Research Progress and Hotspots of Bacterially Induced Carbonate Mineralization Based on Bibilometrix

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ABSTRACT. — *The study of bacterially induced carbonate mineralization can reveal the fixation process, fixation mechanism and fixation contribution of biological carbon sequestration. It is also of great significance for soil remediation, water remediation and radionuclide pollution of heavy metal pollution. Now it has become a hot research issue. This paper analyzed, integrated, summarized and sorted out 2354 literature in Web of Science from 2012 to 2022 by using Bibliometrix. By analyzing the number of literature, citations, the most influential journals, the most influential authors, international cooperation, historical citations and keyword clustering, this paper combs the knowledge structure, research progress and hot topics in the field of bacterially induced carbonate mineralization. The study found that: (1) In recent ten years, the field of bacterially mineralization has developed rapidly, showing a trend of interdisciplinary, interdisciplinary and multi-disciplinary development. (2) The number of Chinese literature published ranks the first in the field of bacterially mineralization, and has established a stable and close international cooperation network. However, the average number of citations is low, and the academic influence is weak compared with the European and American countries. (3) Through the analysis of highly cited literature and keyword cluster analysis, it is found that the research hotspots of bacterially induced carbonate mineralization mainly focus on four aspects: Study on the formation mechanism of dolomite; Study on MICP by hydrolyzation of urea; Study on the mechanism of bacterially induced carbonate mineralization; Study on the influence of medium environment on the species and morphology of carbonate minerals.*

KEYWORDS: Biomineralization; Bacteria; Carbonate minerals; WOS; Bibliometrix

1. Introduction

Biomineralization is the process by which organisms are strictly regulated by organisms to synthesize minerals with highly ordered hierarchical structure and special biological functions(Mann, 2001). Various organic-inorganic minerals with excellent performance generated under biological regulation are endowed by organisms with properties such as mechanical support (Oaki and Imai, 2005), gravity sensor (Aizenberg *et al*, 2001) and calcium storage (Faivre and Godec, 2015). It has successfully attracted the attention of researchers in geomicrobiology, geochemistry,

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life science, environmental ecology and medicine. The mineralization process with the participation of microorganisms is called microbially induced mineralization. Microbially induced mineralization is mainly through the following two ways: one is control biomineralization, that is, microorganisms strictly control the formation of inorganic phase crystals with specific morphology or advanced structure through metabolites (Weiner and Dove, 2003); the second is induced biomineralization, that is, microorganisms use the microenvironment created by their own metabolic activities to promote the formation of minerals (Dhami *et al.*, 2013). The most common type of induced biomineralization is the bacterially induced carbonate mineralization. The induction pathway mainly involves two regulatory mechanisms: alkalinity engine (Gallagher *et al*., 2012) and cell surface nucleation (Tourney and Ngwenya, 2014). In addition, extracellular polymers secreted by bacteria can also enrich calcium ions and provide nucleation sites to promote the production of carbonate minerals (Tourney and Ngwenya, 2014). Therefore, bacterially induced carbonate mineralization is a process with specific biological function products that is not actively regulated by internal genes, but a passive mineralization process driven by bacterially metabolic activities (Lian *et al*., 2006), which has become one of the research hotspots in microbiology and mineralogy (Zhang *et al*., 2018).

Carbonate mineral is the most common type of biominerals, widely distributed in all spheres of the earth and an important component of sedimentary rocks in geological environment (Guo *et al*., 2013). Studies have shown that carbonate minerals in the earth's supergene environment and shallow sea sediments are mainly controlled by bacterially growth and metabolism (Bundeleva *et al*., 2012; Dupraz *et al*., 2009). Almost all bacteria in nature can promote the formation of mineral precipitation under appropriate conditions (Couradeau *et al*., 2012; Li *et al*., 2014). At present, scientific research results have confirmed that the types, morphology, structure and elemental composition of bacterially induced carbonate mineralization products are mainly influenced by bacterially activities, bacterially cells, metabolites and media components (Prywer *et al*., 2012; Zhang *et al*., 2015; Li *et al*., 2017). However, the specific regulation mechanism in the biomineralization process remains to be further explored by the majority of scientific researchers. In addition, bacterially induced carbonate mineralization also has great potential in concrete repair (Wang *et al*., 2012), Heavy metal pollution control (Mitchell *et al*., 2010) and Protein stability (Yang *et al*., 2015). However, the current studies mainly focuse on indoor mineralization experiment (Xu *et al*., 2016), biomimetic mineralization experiment (Huang *et al*., 2019) and material performance improvement experiment (Yang *et al*., 2015). Few studies have systematically combed and summarized the results of bacterially induced carbonate mineralization in recent years. Bibliometrix is a scientific literature measurement software based on R language. At present, foreign

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scholars have used Bibliometrix for statistical analysis, index calculation, data visualization analysis and knowledge mapping of literature (Aria and Cuccurullo, 2017), but domestic scholars have little research on this software. In view of the great significance of bacterially induced carbonate mineralization in geochemical cycle, global environmental change and practical production and application, this paper used Bibliometrix to integrate, summarize and organize relevant literatures with big data, and summarized the history, current situation, development trend and hot research fields of bacterially carbonate minerals. This can not only improve the understanding of bacterially mineralization, but also provide ideas for the follow-up work of biological mineralization researchers all over the world.

2. Research methods

2.1 Research tools

This study mainly used HistCite and Bibliometrix for data analysis and processing. HistCite software was only used for the screening of early keywords and the locking of important literatures, and Bibliometrix was used as the main application software of this study. Bibliometrix is a scientific software based on R language. It is open-source and free, and supports the import of Web of Science (WOS), Scopus, Diensions, PubMed and other databases. It was co-developed by Massimo Aria, associate professor of economics and statistics department of Naples Federico II, University of Italy. Bibliometrix has good expansion performance and can be used for scientific literature analysis and visual demonstration of the whole process (Aria and Cuccurullo, 2017). Therefore, Bibliometrix can realize literature statistical analysis, index calculation, data visualization analysis and knowledge map drawing, which is an effective method to solve this research.

2.2 Data statistics and analysis

In this study, HistCite software and Bibliometrix are based on the WOS database for literature analysis and retrieval. With the help of HistCite software, the three keywords of Bacteria, Carbonate and Biomineralization were extracted, and 50 literatures were exported respectively according to LCS (Local citation score) and LCR (Local cited references). A total of 2354 subject-related literatures from 2012 to 2022 were retrieved from the WOS by using the pairwise combination of three keywords retrieved by HistCite software. The knowledge structure of related research fields is analyzed by Bibliometrix, mainly including data collection, data analysis and data visualization. The specific process is shown in Figure 1.

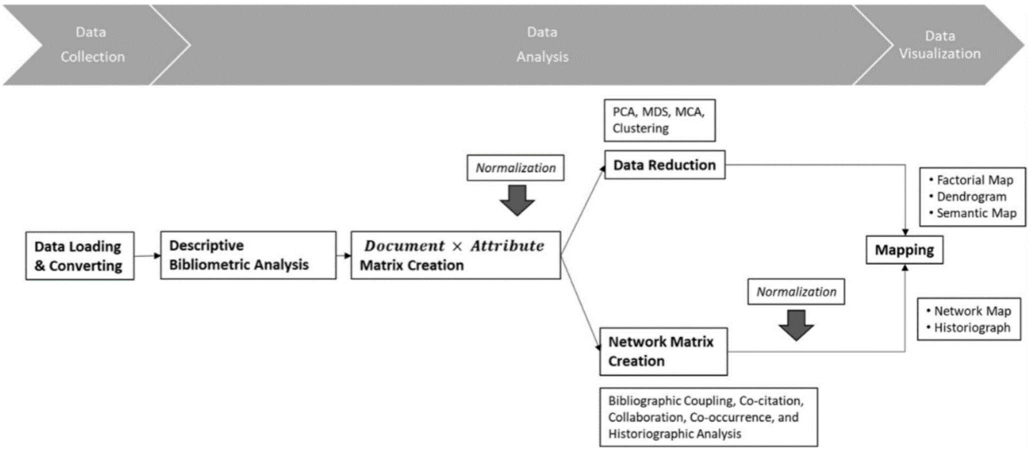

Figure 1. Data analysis flow chart of Bibliometrix

3. Results and analysis

3.1 Structural analysis in the research field of bacterially induced carbonate mineralization

3.1.1 Statistics of publications and citations

The change of publications with year is an important index to measure academic output and field development. As shown in Figure 2, since 2012, the research field of bacterially induced carbonate mineralization has shown three stages of development trend, namely slow growth period (2013-2016), rapid growth period (2017-2019) and extreme growth period (2022-present). According to Bibliometrix analysis results, the annual average growth rate of publications is 13.2%, indicating that the research field of bacterially induced carbonate mineralization shows a prosperous trend as a whole.

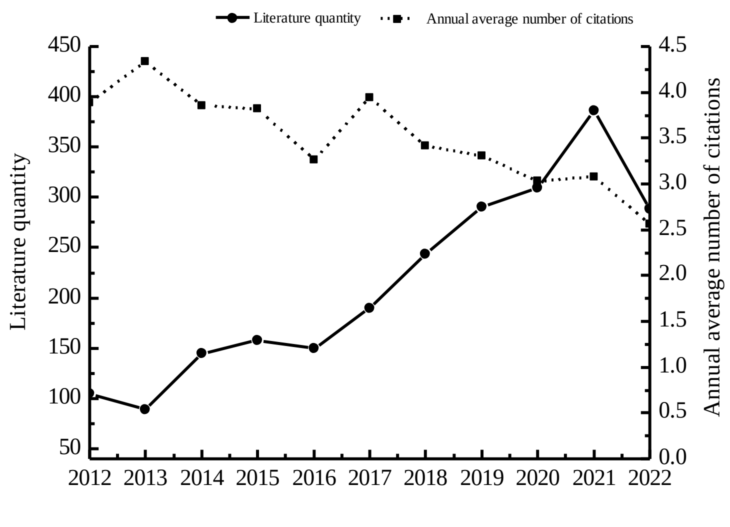

Figure 2. Variation trend of publications and annual average number of citations

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from 2012 to 2022

The change of annual average number of citations with year is an effective indicator to measure the recognition degree of scientific research literature. According to the analysis results of Bibliometrix, the average growth rate of the annual average citation is -3.4%, showing a downward trend as a whole. The average number of citations was 3.9 in 2012, and the average number of citations was only 2.6 in 2022. On the one hand, it reflects the growth trend in the research field of bacterially mineralization, on the other hand, it also reflects the problems such as immature technology caused by the rapid development of the field. In addition, the average number of citations reached two small peaks in 2013 and 2017, 4.3 and 3.9 respectively. The analysis found that the peak in 2013 was mainly related to the slight decline in field development, while the peak in 2017 indicated that the research field had entered a mature and prosperous period.

3.1.2 Journal influence analysis

Table 1 lists the information of the top 10 authoritative journals in the field of bacterially mineralization. The top 10 journals have published a total of 505 papers in the past ten years, accounting for 21.5% of the total citations. Geomicrobiology Journal topped the list with 112 publications in the past decade, followed by Chemical Geology and Frontiers in Microbiology. H index refers to that H articles published in a journal that have been cited at least H times, which is an important indicator to evaluate academic output and output level. Geochimica et Cosmocchimic Acta, Geobiology and Chemical Geology rank among the top three in the H index. The top three journals in total citations are Ecological Engineering, Geomicrobiology Journal and Chemical Geology. Looking forward to the future, Geomicrobiology Journal and Chemical Geology are journals that need to be focused on, and more and more weighty papers will appear.

It can be seen from Table 1 that bacterial mineralization is not only closely related to traditional microbiology, geology and ecology, but also integrated with geochemistry, building materials science, biotechnology and other fields, showing a trend of interdisciplinary, interdisciplinary and multidisciplinary development. However, a centralized proprietary journal group has not yet been formed.

Table 1. Information of the Top 10 most influential journals in the research field

Journal	H-index	G-index	publications	Accumulative	Total citations
Geomicrobiology Journal	18	33	112	112	1404
Chemical Geology	21	35	62	174	1350
Frontiers in Microbiology	17	29	62	236	988
Construction and Building Materials	16	29	55	291	890
Geochimica et Cosmocchimic Acta	22	34	44	335	1233

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Geobiology	21	29	42	377	891
Minerals	11	17	39	416	373
Applied Microbiology and Biotehnology	11	20	31	447	410
Sedimentology	16	30	30	477	952
Ecological Engineering	17	28	28	505	1492

3.1.3 Analysis of publications and international cooperation network

The number of publications and citations in a country is a key indicator to measure the quantity, quality and influence of a country's academic output. Figure 3 lists the top 10 countries in the field of bacterially mineralization in terms of number of articles published and citations in recent ten years. China ranks first with 469 articles in related fields, and the United States ranks second with 322 articles, followed by India, Germany and France. In the total citations, the United States ranks first with 7,473 citations, and China ranks second with 4,441 citations, followed by Germany, France and Italy. The top five countries in the average number of articles cited are the United States, The United Kingdom, Spain, Germany and France, with 23.2, 20.3, 18.8, 18.6 and 17.9, respectively, all from European and American countries, while The average number of articles cited in China is only 9.5, ranking the ninth. It can be seen that although China ranks first in the number of publications in the field of bacterially mineralization, the average number of citations is relatively low, and its academic influence is weak compared with European and American countries, which is mainly related to China's lack of innovation, emphasizing quantity over quality, scientific history and other factors. Therefore, it is the most important measures to further enhance the influence of academic papers to vigorously cultivate scientific research innovation system, optimize resource allocation to the maximum, develop and perfect high-quality Chinese core database, and carry out cooperation and exchange with foreign high-level scientific research institutions.

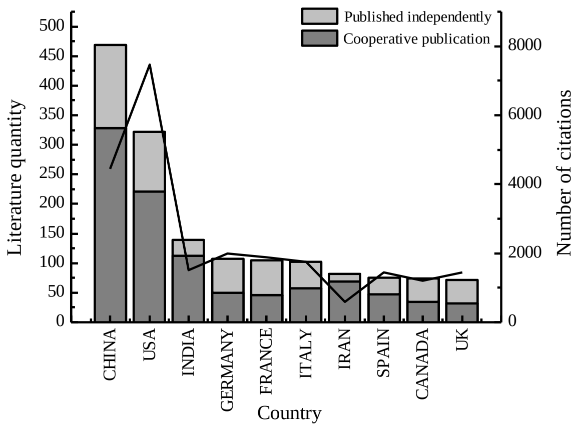

Figure 3. Number of l publications and citations by countries

Cooperation between countries means that researchers from different countries work together to explore new scientific knowledge. International cooperation helps to

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improve the level and capacity of scientific research of both sides. In the international cooperation network map in Figure 4, the node size, line connection and line depth can all reflect the degree of communication between countries. International cooperation network map can be divided into three groups, among which the United States, China, Britain, Australia and Canada have the most close cooperation, and China and the United States have established long-term friendly relations. Germany, Spain and Italy have the most frequent exchanges. France, the Netherlands and Belgium have the most in-depth contacts. As the country with the largest number of publications in the field of bacterially mineralization, China has significantly improved its international cooperation and established a stable and close international cooperation network, especially with the United States. However, there is still room for further improvement in its cooperation and exchange with Germany and France. Domestic scholars should explore new cooperative countries to comprehensively promote the development of the field of bacterially mineralization.

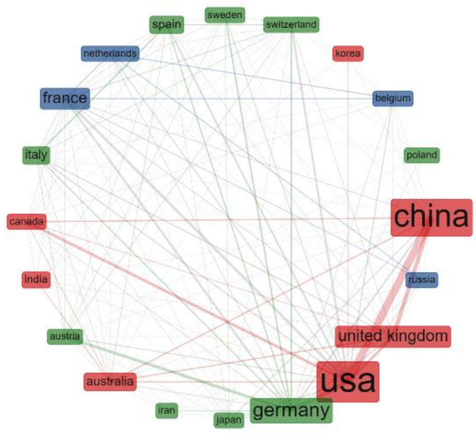

Figure 4. International cooperation network map

3.2 Structural analysis in the research field of bacterially induced

Table 2 lists the Top 10 key citations. There are two statistical indicators LCS (Local Citation Score) and GCS (Global Citation Score). LCS refers to the number of citations in the current database. GCS refers to the total number of citations of documents in the whole wos database. From 2000 to 2009, "Microbial Carbonate Precipitation as a Soil Improvement Technique"(Whiffin *et al*., 2007) and "Bacterial Induced Mineralization of Calcium Carbonate in Terrestrial Environments: The Role of Exopolysaccharides and Amino Acids"(Braissant *et al*., 2003) ranked among the top two in LCS indicators. The former paper mainly focuses on the study of MICP (Microbially Induced Calcite Precipitation), while the latter paper mainly studies the effects of bacterially extracellular polysaccharides and amino acids on bacterially induced carbonate crystallization. "Microbial carbonates: the geological record of

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calcified bacterial-algal mats and biofilms"(Robert, 2000) and "Processes of carbonate precipitation in modern microbial mats" (Dupraz *et al*., 2009) rank the top two in GCS indicators. The former paper mainly deals with the factors affecting carbonate precipitation in microbial mineralization process, The latter paper focuses on the specific role of microorganisms and extracellular polymers in various mineralization processes (freshwater, marine, high salt and terrestrial microbial mats).

Table 2. List of key historical direct citation and number of historical direct citation

Years	Literatures	doi	LCS	GCS
2000	Robert R. Microbial carbonates: the geological record of calcified bacterial-algal mats and biofilms [J]. Sedimentology, 2000, 47(s1): 179-214.	10.1046/j.1365-3091.2000.00003.x	96	877
2003	Braissant O, Cailleau G, Dupraz C, Verrecchia E P. Bacterially Induced Mineralization of Calcium Carbonate in Terrestrial Environments: The Role of Exopolysaccharides and Amino Acids [J]. Journal of Sedimentary Research, 2003, 73(3): 485-490.	10.1306/111302730485	135	288
2004	Dupraz C, Visscher P T, Baumgartner L K, Reid R P. Microbe-mineral interactions: early carbonate precipitation in a hypersaline lake (Eleuthera Island, Bahamas) [J]. Sedimentology, 2004, 51(4):745-765.	10.1111/j.1365-3091.2004.00649.x	77	313
2007	Whiffin V S, van Paassen L A, Harkes M P. Microbial Carbonate Precipitation as a Soil Improvement Technique [J]. Geomicrobiology Journal, 2007, 24(5): 417-423.	10.1080/01490450701436505	145	517
2007	Braissant O, Decho A W, Dupraz C, Glunk C, Przekop K M, Visscher P T. Exopolymeric substances of sulfate-reducing bacteria: Interactions with calcium at alkaline pH and implication for formation of carbonate minerals [J]. Geobiology, 2007, 5(4): 401-411.	10.1111/j.1472-4669.2007.00117.x	84	310
2008	Anbu P, Kang C H,Y Shin Y J, So J S. Formations of calcium carbonate minerals by bacteria and its multiple applications [J]. SpringerPlus, 2016, 5(1): 1-26.	10.1016/j.conbuildmat.2006.12.011	79	238
2009	Dupraz C, Reid R P, Braissant O, Decho A W, Norman R S, Visscher P T. Processes of carbonate precipitation in modern microbial mats [J]. Earth ence Reviews, 2009, 96(3): 141-162.	10.1016/j.earscirev.2008.10.005	120	709
2010	Muynck W D, Belie N D, Verstraete W. Microbial carbonate precipitation in construction materials: A review [J]. Ecological Engineering, 2010, 36(2): 118-136.	10.1016/j.ecoleng.2009.02.006	148	468
2013	Dhami N K, Reddy M S, Mukherjee A. Biomineralization of calcium carbonates and their engineered applications: a review [J]. Frontiers in Microbiology, 2013a, 4: 1-13.	10.3389/fmicb.2013.00314	74	179
2016	Anbu P, Kang C H, Shin Y J, So J S. Formations of calcium carbonate minerals by bacteria and its multiple applications [J]. 2016, 5(1): 1-26.	10.1186/s40064-016-1869-2	61	130

From 2012 to 2022, there are mainly three citations with high indicators of LCS and GCS, namely "Microbial carbonate precipitation in construction materials: A review"(Muynck *et al*., 2010), "Biomineralization of calcium carbonates and their engineered applications: a review"(Dhami *et al*., 2013) and "Formations of calcium carbonate minerals by bacteria and its multiple applications"(Anbu *et al*., 2016). These three papers are reviews on MICP, respectively introducing the application of MICP technology in the field of building materials, the application of MICP technology in the field of biological mineralization, the advantages of MICP technology and the limitations of commercial application. The historical direct citation network map in the field of bacterially mineralization is shown in Figure 5.

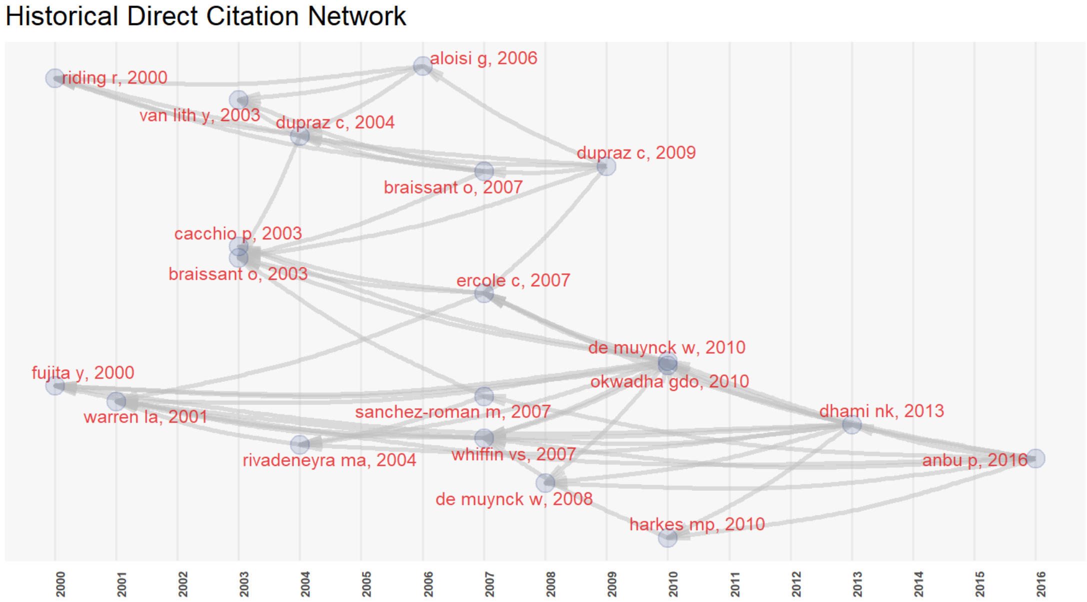

Figure 5. Historical direct citation network map

3.3 Analysis of key words in the field of bacterially induced carbonate mineralization

The key words are a high summary of the current hot research contents and topics. The literature is clustered by using Bibliometrix for MCA (Multiple Correspondence Analysis) combined with K-means clustering method. It can be seen from Figure 6 that the hot research in the field of bacterially induced carbonate mineralization can be divided into the following four aspects (I~IV): Cluster I: The keywords are liquid media, nucleation, $CaCO_3$, crystallization, morphology, vaterite, etc. The content includes the influence of medium environment on the morphology and types of calcium carbonate and the exploration of the mechanism of calcium carbonate nucleation. Cluster II: The keywords are dolomite, calcium carbonate, precipitation, sulfate reducing bacteria, oxidation, etc. It mainly involves using anaerobic and aerobic bacteria to explore “dolomite problem”. Cluster III: The key words are microorganisms, biomineralization, calcium carbonate precipitation, calcite, bacteria, etc. It mainly focusing on the study of microbially induced calcium carbonate precipitation represented by bacteri. Cluster IV: The key words are urease, ureolytic bacteria, Sporosarcina pasteurii, bioremediation, remediation, etc. The content is mainly about the bioremediation research of urease secreted by ureolytic bacteria to catalyze the production of calcium carbonate, and the representative ureolytic bacteria is Sporosarcina pasteurii.

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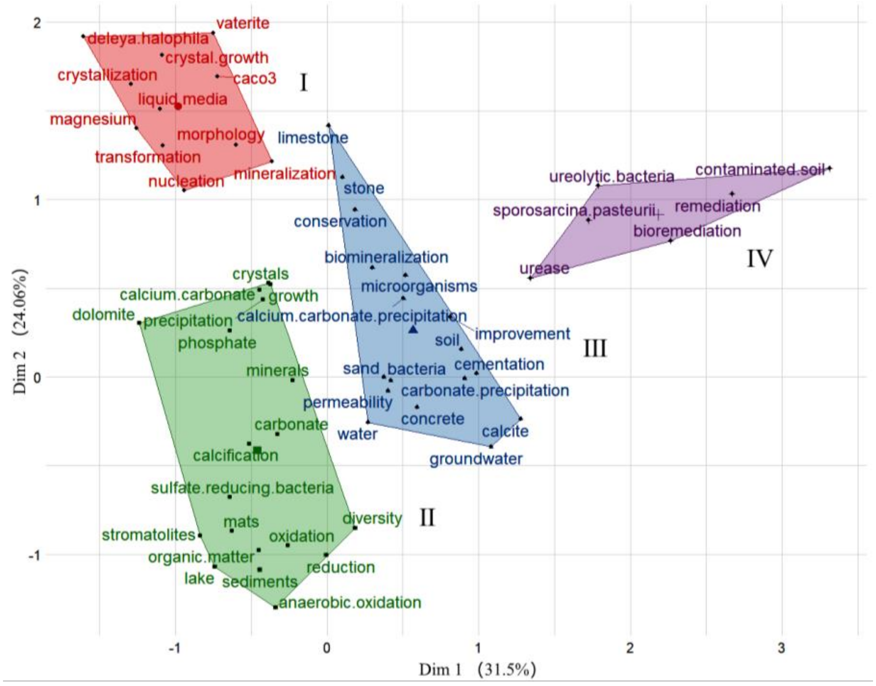

Figure 6. Keyword clustering diagram

4. Analysis of hotspots in the research field of bacterially induced *carbonate mineralization*

Through the analysis of highly cited literature and keyword cluster analysis, it is found that the research hotspots of bacterially induced carbonate mineralization mainly focus on four aspects: Study on the formation mechanism of dolomite; Study on MICP by hydrolyzation of urea; Study on the mechanism of bacterially induced carbonate mineralization; Study on the influence of medium environment on the species and morphology of carbonate minerals.

4.1 Study on the formation mechanism of dolomite

Dolomite [$MgCa(CO_3)_2$] refers to carbonate minerals with magnesium calcium ratio of 1:1. Its formation mechanism has always been the focus of research in the field of mineralogy and sedimentology. The “dolomite problem” has also been a scientific problem that has puzzled geologists for generations(Baniak *et al*., 2014). As an important component mineral of sedimentary carbonate, dolomite has the characteristics of dynamic obstacles such as low ionic activity, low CO_3^{2-} concentration, high hydration energy of Mg^{2+}, and SO_4^{2-} inhibition. That makes it difficult to simulate the synthesis of dolomite at room temperature in modern seawater environment or laboratory conditions (Huang *et al*., 2019). With the proposal of microbial dolomite formation model (Vasconcelos *et al*., 1995), early scientists found anaerobic bacteria such as sulfate reducing bacteria (Warthmann *et al*., 2000),

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methanogenic archaea (Roberts *et al*., 2004) and anaerobic bacteria (Zhang *et al*., 2015) can induce the formation of dolomite at room temperature in the laboratory. With the further research, scientists found that moderately halophilic aerobic bacteria such as Virgibacillus marismortui and Halomonas meridiana can also induce the formation of Dolomite Precipitation under aerobic conditions (Sánchez-Román *et al*., 2009). In recent years, the exploration of the formation mechanism of low-temperature dolomite induced by aerobic bacteria has become a hot research content. Liu *et al*. (2019) found that dolomite mainly occurred in the bioreactor of pure isolates of aerobic bacteria and Halophilic bacteria in the lake water through the indoor mineralization experiment simulating the high sulfate salt lake. Sánchez-Román *et al*. (2011) conducted mineralization experiments with Halophilic bacteria and found that most of the environments where dolomite occurs are very rich in aqueous Mg compared to Ca. By isolating different biomass components in aerobic bacterial cultures, scientists found that high concentration and density of carboxyl and phosphoryl groups on the bacterial biomass may be the key factors to promote the formation of disordered dolomite. This provides a new idea for non-metabolically active bacterial biomass components to promote dolomite precipitation (Huang *et al*., 2019). However, the microbially dolomite model still has two limitations: one is that the microbial action is limited to the high salinity environment (Lumsden, 1988; Zhang *et al*., 2018), and the other is that the microbially induced dolomite lack the superstructure-derived rays of natural samples (Wright and Wacey, 2005). At present, with the accuracy of Mg isotope testing technology, Mg isotope geochemistry has become a new method for the study of tdolomite formation (Huang *et al*., 2015). Studies on Mg isotope fractionation during dolomite formation mainly include theoretical calculation (Rustad *et al*., 2010), simulation experiment (Li *et al*., 2015) and actual observation (Mavromatis *et al*., 2014). The latest research is to quantitatively simulate the dolomitization process by establishing the Advective Flow-AF Model and the Diffusion Advection Reaction-DAR Model (Huang *et al*., 2015; Peng *et al*.,2016).

4.2 Study on Microbially Induced Calcite Precipitation by hydrolyzation of urea

Carbonate minerals are formed in an extremely slow geological period under natural conditions, and the search for microorganisms that create conditions for carbonate precipitation in a short time has been widely concerned by all walks of life (Dhami *et al*., 2013a). The ureolytic bacteria catalyze the hydrolysis of urea to precipitate carbonate minerals by secreting urease, which has the potential to produce a large number of carbonate rocks in a short time (Muynck *et al*., 2010). The topic of MICP by hydrolyzation of urea is a hot research issue at present, and screening new

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ureolytic bacteria with high urease activity and high environmental adaptability is a key research field that scientists have been committed to (Sun Y *et al*., 2015; Sun Y *et al*., 2017). The ureolytic bacteria involve many genera of bacteria, including pseudomonas, bacillus, sporosarcina, and myxococcus , etc. Scientists through a large number of experiments found that Bacillus megaterium (Dhami *et al*., 2013b), Lysinibacillus medium (Kang *et al*., 2014) and Sporosarcina pasteurii (Gorospe *et al*., 2013) have strong urease activity, calcium carbonate production capacity and environmental adaptability, and is widely used in the research of microbially induced calcium carbonate precipitation technology. Environmental conditions affecting urease activity are also the focus of current research in addition to screening ureolytic bacteria, (Anbu *et al*., 2016). Okwadha and Li (2010) conducted factor experiments on Sporosarcina pasteurii and found that bacterial cell concentration, initial urea concentration and Ca^{2+} concentration affected $CaCO_3$ precipitation and CO_2 separation by controlling urease activity. Mortensen *et al*. (2011) found that ammonium concentration, oxygen availability, as well as the ureolytic activities of viable and lysed cells had no or limited effect on the urease activity of Sporosarcina pasteurii during urea hydrolysis. The catalytic effect of urease on urea is also closely related to temperature. Mitchell and Ferris (2005) found that the optimum temperature of most ureases is between 20~37℃. Dhami *et al*. (2014) found that urease is completely stable at 35℃, but when the temperature rises to 55℃, the enzymatic activity decreases by nearly 47%. In addition, the ureolytic bacteria also have great potential in the field of building material consolidation and repair. Currently, the popular directions include the study of MICP by urea hydrolysis to improve the overall performance of concrete such as compressive strength, permeability, water absorption and chloride ion absorption (Siddiquea and Chahal, 2011). The study of MICP by urea hydrolysis to repair concrete surface defects and cracks by urea hydrolysis micp (Qian *et al*., 2016); The study of MICP by urea hydrolysis to improve the mechanical properties of porous materials (Harkes *et al*., 2010); The study of MICP by urea hydrolysis cemented calcium Sand strength test and strength dispersion research (Wang *et al*., 2018).

4.3 Study on the mechanism of bacterially induced carbonate mineralization

The study found that in the Ca^{2+}-Mg^{2+}-CO_3^{2-}-H_2O/Ca^{2+}-CO_3^{2-}-H_2O system, the pH value of the medium, the supersaturation of carbonate and sufficient nucleation sites are necessary conditions for the formation of precipitates (Wang *et al*., 2013). Bacterially induced carbonate mineralization mainly includes two regulatory mechanisms: One is alkalinity engine of bacteria, bacteria through their own metabolic activities such as urea hydrolysis, sulfate reduction and anaerobic sulfide

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oxidation change the surrounding environment, by increasing the pH value and supersaturation of culture medium to precipitation of carbonate mineral, namely homogeneous nucleation (Gallagher *et al*., 2012). The other is the nucleation of bacterial cells and extracellular polymers. Both cell surface and extracellular polymers can provide nucleation sites to promote carbonate precipitation, namely heterogeneous nucleation(Tourney and Ngwenya, 2014). Guo *et al*. (2013) believe that multiple nucleation mechanisms may coexist in the same experimental system. Plate-like minerals may be the result of uniform nucleation at a particular site, dumbbell-shaped minerals may be formed with bacteria as the template, and irregular minerals may be formed with extracellular polymers as the template. The mineralization mechanism and nucleation mechanism of bacteria induced carbonate has always been a hot research issue in the field of biomineralization.

4.3.1 The alkalinity engine of bacteria

4.3.1.1 The pH value of culture medium

The pH value of culture medium plays an important role in the process of carbonate precipitation, and bacteria can change the pH value of medium environment through their own metabolic activities. The scientists found that for most of the experiments, the pH value of culture medium continued to decrease in the early stage and and the pH value began to increase in the middle and late stages. Researchers generally believe that the increase of pH value is closely related to the ammonia produced by microorganisms. Xu *et al*. (2016) summarized the main reasons for pH changes: (1) Bacteria secrete low-molecular-weight organic acids (LMWOAs); (2) Bacterial respiration produces CO_2 dissolved in water; (3) The autolysis of dead bacteria cells; (4) The degradation of tryptone into ammonia by facultative bacteria. Therefore, the increase of pH value may be due to the autolysis of dead bacterial cells and the degradation of tryptone into ammonia by facultative bacteria in the middle and late stage. Zhuang *et al*. (2018) also confirmed that Bacillus cereus MRR2 can produce ammonia by degrading the beef extract and tryptone in the culture medium. In addition, the sulfate reducing bacteria can reduce SO_4^{2-} while consuming H+ to increase the pH of the medium (Castanier *et al*., 1999). The ureolytic bacteria increase the pH value of the culture medium by secreting urease to catalyze the hydrolysis of urea to produce NH4+and CO_3^{2-} (Fujita *et al*., 2008). Pan *et al*. (2019) found that the release of ammonia and the activity of carbonic anhydrase could increase the pH value of the culture medium to about 9.0. However, by drawing pH curves based on NH4+ concentration, it was found that ammonia is not the most reasonable explanation for the increase of pH value, and there may be other factors. Guo *et al*.

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(2013) believe that the increase of pH value is a prerequisite for carbonate precipitation. Xu *et al*. (2016) conducted biological experiments with Arthrobacter sp. strain MF-2 and found that there was a significant positive correlation between the precipitation amount and pH value. The higher the pH value, the more favorable the carbonate precipitation. Zhang *et al*. (2018) found that the quality of Arthrobacter sp. strain MF-2 induced carbonate precipitation was significantly positively correlated with pH regardless of the change in Mg/Ca, suggesting that an increase in pH is one of the necessary physicochemical conditions for carbonate precipitation. It can be seen that ammonia is indeed closely related to pH value, but the specific reasons need to be further explored. It can be clear that pH value directly affects the process of carbonate precipitation, and the increase of pH value is a necessary condition for carbonate precipitation.

4.3.1.2 Degree of supersaturation

The supersaturation of carbonate is a necessary condition for the formation of precipitation. The saturation index SI can be defined by the ratio of the ion activity product to the solubility product of the corresponding mineral. When SI>1, it indicates that the solution reaches the supersaturated state and carbonate precipitation can be spontaneously precipitated (Dupraz *et al*., 2009). See the following formula for details.

$$SI=\log[IAP/Ksp]$$

$$IAP=[Ca^{2+}]x[Mg^{2+}](1-x)[CO_3^{2-}]/IAP=[Ca^{2+}]x[CO_3^{2-}]$$

SI: saturation index; IAP: the ion activity product; Ksp: the solubility product of the corresponding mineral; x: The mole fraction of Ca in Mg-rich carbonate minerals/calcium carbonate

According to the saturation formula, the concentrations of Ca^{2+} and Mg^{2+} and the concentration of soluble inorganic carbon are the two key factors affecting the saturation. Microorganisms induce carbonate homogeneous nucleation by changing these two factors. In the study of bacteria affecting the concentrations of Ca^{2+} and Mg^{2+}, the following reasons can affect the Ca^{2+} concentration and Mg^{2+} concentration: (1) The functional groups in the cell surface and extracellular polymers: the functional groups in an alkaline environment make the extracellular polymers have total negative charge through deprotonation. The characteristics of functional groups are the key in the process of mineral formation, and the calcium binding ability of different functional groups is different. The functional groups with strong calcium binding ability can reduce the activities of Ca^{2+} and Mg^{2+} and thus reduce the saturation of carbonate to inhibit the precipitation of carbonate (Sutherland, 2001, Braissant, 2007). Bianchi (2007) found that –COOH, –OH, $–NH_2$, $–O–SO_3H$, $–SO_3H$ and -SH can

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strongly complex with metal ions (including Ca^{2+} and Mg^{2+}), but –COOH and –O–SO_3H are generally considered to be the most important ligands in extracellular polymers (Dupraz *et al*., 2009). The functional groups with weak calcium binding ability can enrich Ca^{2+} and Mg^{2+} and promote their homogeneous nucleation with CO_3^{2-}. Zhuang *et al*. (2018) found that the negatively charged oxygen atom of the glycoside group (–C–O–C–) fixed on the exopolysaccharide can adsorb a large amount of Ca^{2+}, thereby promoting the combination of Ca^{2+} and CO_3^{2-} to form calcium carbonate. The functional groups with different calcium binding abilities promote the formation of different types of minerals (Zhou *et al*., 2010). (2) The dissolved organic carbon (DOC) secreted by extracellular polymer: Tourney and Ngwenya (2009) conducted mineralization experiments on Bacillus licheniformis S-86 and found that DOC released from the extracellular polymer of the strain can complex Ca^{2+} and reduce its activity, thus reducing the saturation of carbonate. The low saturation is conducive to the precipitation of polycrystalline calcite with poor solubility and more stability, rather than vaterite. (3) Molecular interaction: Bacterial mineralization involves controlled nucleation process at the interface between template macromolecules and minerals, such as the recognition process of inorganic-organic molecules (Suga and Nakahara, 1991). The molecular interaction at the interface may affect the "availability" of functional groups to bind Ca^{2+} and Mg^{2+}. At a given pH value, The binding of Ca^{2+} and Mg^{2+} may not be proportional to the abundance of functional groups (Dupraz *et al*., 2009). According to the intrinsic characteristics of extracellular polymer, it can inhibit or promote the formation of carbonate which has dual effects. (4) Microbial degradation: Microbial degradation of extracellular polymers will reduce the number of cation binding sites and release cations such as Ca^{2+} and Mg^{2+} (Perri *et al*., 2017).

In the study of bacteria affecting soluble inorganic carbon, the following reasons can affect the concentration of inorganic carbon: (1) Carbonic anhydrase: scientists found that carbonic anhydrase secreted by bacteria can increase the concentration of HCO_3^- and CO_3^{2-} in the culture medium. Carbonic anhydrase widely exists in bacteria of many genera, such as Bacillus (Zhou *et al*., 2010), Arthrobacter (Zhang *et al*., 2018) and Citrobacter (Han *et al*., 2013). Li *et al*. (2013) found that Bacillus cereus secreted carbonic anhydrase to improve the hydration conversion coefficient of CO_2 and promote the formation of carbonate precipitation. Pan *et al*. (2019) explored the mechanism of biomineralization by using Halomonas smyrnensis WMS-3 and found that a large amount of HCO_3^- and CO_3^{2-} catalyzed by carbonic anhydrase can further increase the fluid supersaturation to precipitate carbonate minerals. In addition, the activity of carbonic anhydrase was significantly positively correlated with the

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concentration of bacterial cells (Xu *et al*., 2016). and a large amount of carbonic anhydrase could be produced during the growth and reproduction stage of bacteria to provide conditions for mineral precipitation. (2) Urease: Ureolytic bacteria can secrete highly active urease to catalyze urea hydrolysis and rapidly increase the CO_3^{2-} concentration in the microenvironment around the bacteria. Medium environments such as pH value (Bang *et al*., 2001), calcium source species (Abo-El-Enein *et al*., 2012) and urea concentration (Mortensen *et al*., 2011) can all change urease activity and affect carbonate precipitation. Omoregie *et al*. (2017) studied the culture conditions affecting urease activity and found that the optimal urease activity was 25℃ -30℃, the pH value of 6.5-8.0, 24h culture time and 6%-8%(w/v) urea concentration. (3) Sulfate reduction: Sulfate reducing bacteria will consume organic acids to produce H2S, and also generate HCO_3^- and CO_3^{2-} to increase the concentration of soluble inorganic carbon (Castanier *et al*., 1999). The cation concentration, pH value of culture medium, temperature and oxygen content can all affect the reduction rate of sulfate reducing bacteria, and then affect the concentration of soluble inorganic carbon (Neal *et al*., 2001). (4) Organic acids in extracellular polymers: Organic acids such as uronic acid and nucleic acid in extracellular polymers affect the supersaturation of carbonate due to the existence of ionization equilibrium, thereby affecting the formation of precipitates.

4.3.2 Nucleation

4.3.2.1 Nucleation of bacterial cells

Bacterial cells induce carbonate mineralization nucleation sites mainly because bacterial cells as solid-phase impurities reduce the liquid-solid interface energy and promote mineral non-uniform nucleation (Huang *et al*., 2019). There seem to be two different mineralization pathways for bacterial cell nucleation: One is the distribution of phospholipid bilayers and glycoproteins on the cell surface or cell surfaces, which are rich in negatively charged functional groups (carboxyl, hydroxyl, phosphorylation groups, etc.), with which Ca^{2+} and Mg^{2+} form coordination complexes, forming nucleation sites for amorphous particles, it can be absorbed through the active ion exchange process through the cell membrane (Wacey *et al*., 2007). The other is the bacterial cell surfaces can serve as a kind of heterogenous nucleation template that either adsorb or nucleate amorphous $CaCO_3$ (ACC), which then transforms into the metastable vaterite toward the periphery. With prolonged experimental time, the calcium carbonate shells on the cell surfaces continued to grow while also accumulating aggregates of other nanoparticles from solution, to fully encase the calcified bacteria within macroscale crystal aggregates. Thus, propose that calcifying

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bacteria can erve as a kind of structural unit in MICP (Lyu *et al*., 2021).

Guo *et al*. (2013) suggested that minerals using cells as nucleation template present dumbbell and cauliflower shapes due to the fact that bacteria have more negatively charged groups at the ends than in the middle (Aloisi *et al*., 2006), Ca^{2+} and Mg^{2+} act as "cation bridges" to attract CO_3^{2-} and cause fine crystals to the aggregation rate at the ends is faster than at the middle part, showing a dumbbell shape and then a cauliflower shape.

However, it has also been suggested that the cell surfaces are not sufficient as nucleation sites. Deng *et al*.(2010) used sulfate reducing bacteria and halophilic bacteria to induce dolomite precipitation and found that extracellular polymers may act as sites for dolomite nucleation, while heat-killed cells did not produce dolomite precipitation suggesting that the cell surface may not be sufficient as a nucleation site.

4.3.2.2 Nucleation of extracellular polymers

Extracellular polymers are mainly composed of sugars, proteins and a small amount of uronic acid and nucleic acid (Xu *et al*., 2009; Ozturk *et al*., 2014). The view that extracellular polymers are the nucleation sites of biomineralization has been widely accepted by researchers (Robert *et al*., 2000; Dupraz *et al*., 2004). Yatsunenko (2012) believes that extracellular polymers secreted by bacteria can enrich calcium ions and provide nucleation sites to promote the formation of carbonate minerals. Zhang *et al*. (2015) studied the effect of extracellular polymer on calcium carbonate precipitation by using anaerobic bacteria and sulfate reducing bacteria, and found that extracellular polymer has a catalytic effect on the formation of disordered dolomite in Ca-Mg carbonate solutions. Pan *et al*. (2019) suggested that extracellular polymers can serve as nucleation sites for monohydrocalcite. The above studies generally believe that extracellular polymers play an important role in the process of bacterial mineralization. When all functional groups of extracellular polymers are occupied by bound cations, that is, the cation binding sites are supersaturation, and under the condition of high concentration of CO_3^{2-} and high pH value, it can enrich free Ca^{2+} and provide nucleation sites to promote the formation of carbonate precipitation. The nucleation of precipitated minerals is controlled by the extracellular polymeric properties and the saturation state of the precipitated minerals (Dupraz *et al*., 2009). In addition, bacterial species, growth stage and temperature can all affect the composition of bacterial extracellular polymers (Tourney and Ngwenya, 2014), which in turn directly affects the types and morphology of minerals (Braissant O *et al*., 2003). Kawaguchi and Decho (2002) found that differences in the biochemical composition of extracellular polymers can lead to the formation of different types of calcium carbonate precipitates. The Extracellular polysaccharides of non-fossilized

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layers of stromatolites induce calcite precipitation, while the extracellular polysaccharides of fossilized layer of stromatolites with higher content of uronic acid and carbohydrate induce aragonite precipitation. Zhang *et al*. (2012) believed that extracellular polysaccharides can weaken the high hydration energy of Mg^{2+}, reduce the energy barrier of dehydration of Mg^{2+}–water complex on the carbonate surface, enhance the combination of Mg^{2+} and carbonate precipitation, and promote the formation of disordered dolomite. Braissant *et al*. (2003) emphasized that the type of amino acids can affect the type and morphology of minerals, and aspartic acid and glutamate are more conducive to the formation of spherical morphology of vaterite. Pan *et al*. (2019) found that bacteria can provide the nucleation sites of exopolysaccharides and reduce the nucleation energy barrier to promote precipitation, and also proved that amino acids play an important role in the nucleation process. There may be other organic compounds in extracellular polymers, and its specific mechanism needs to be further explored.

4.4 Research on the medium environment and its influence on the species and morphology of carbonate minerals

The species and morphology of carbonate minerals are influenced by several factors, which have been described in detail above for bacterial cells (Guo *et al*., 2013), cell surfaces (Han *et al*., 2017; Zhang *et al*., 2017), and extracellular polymers (Kawaguchi and Decho, 2002; Braissant *et al*., 2003; Zhang *et al*., 2012; Zhang *et al*., 2015) on the types and forms of minerals, and here we focus on the influence of the medium environment. It was found that the bacteria species are the same, but the media composition is different, and the precipitation ratio and time are also different (Sánchez-Román *et al*., 2011). Bacteria can influence the physicochemical parameters in their local environment through their own activities (Guo *et al*., 2013), while the media environment such as biological factors (bacterial cell concentration, extracellular polysaccharides, carbonic anhydrase, urease) (Xu *et al*., 2016; Zhuang *et al*., 2018), chemical factors (pH value, supersaturation, Mg^{2+} concentration, Ca^{2+} concentration, Mg/Ca) (Sánchez-Román *et al*., 2011; Zhang *et al*., 2018) and physical factors (temperature, magnetic field, ultrasound) (Alimi *et al*., 2009; López-Periago *et al*., 2009; Zhou *et al*., 2010)can influence the mineralization of bacteria by affecting their growth and metabolic activities. The whole process is extremely complex and variable, and there are still many unknown areas to be explored. The effects of the chemical composition of the medium such as Mg^{2+} concentration, Ca^{2+} concentration and Mg/Ca on carbonate mineral species and morphology have been the subject of hot research.

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4.4.1 Influence of medium environment on carbonate mineral species

The carbonate minerals produced by bacteria can be broadly classified as Mg-rich carbonates and calcium carbonate variants. Sánchez-Román *et al*. (2011) studied the morphology and structure of Mg-rich carbonates by halophilic bacteria in different Mg^{2+} concentrations (18.7-187 mM), Ca^{2+} concentrations (5.7-22 mM) and Mg/Ca (2-11.5), it was found that in the medium environment with the lowest Ca^{2+} concentration (5.7 mM), struvite was the first precipitate; in the medium environment with medium Ca^{2+} concentration (11 mM), hydromagnesite precipitated before Mg-calcite, dolomite and struvite; in the medium environment with higher Ca^{2+} concentration (17-22 mM), dolomite precipitates before hydromagnesite and struvite. The results indicated that the increase of Ca^{2+} concentration favored carbonate minerals over struvite precipitation, while bacteria could reduce the Mg/Ca precipitation of carbonate minerals. Zhuang *et al*. (2018) found that as Ca^{2+} concentration increased, more Ca^{2+} was used mainly for calcite formation. It can be seen that the increase of Ca^{2+} concentration in the medium environment is necessary for the formation of carbonate minerals. Magnesium is an important modifier of carbonate species, morphology and growth during bacterial mineralization, and different concentrations of Mg^{2+} affect the formation of different species of carbonate minerals by bacteria. Numerous studies have shown that the adsorption and high hydration energy of Mg^{2+} can inhibit the formation of calcite, and the Mg^{2+} can also inhibit calcite nucleation and thus interfere with crystal growth (Davis *et al*., 2000; Choudens-Sanchez and Gonzalez, 2009). Rushdi *et al*. (1992) have reported that low concentrations of Mg^{2+} in solution are conducive to the formation of calcites, whereas high concentrations of Mg^{2+} promote the formation of aragonite. Choudens-Sanchez and Gonzalez (2009) suggested that at low Mg/Ca, calcite was the dominant precipitant, and as solution Mg/Ca increased, aragonite became the dominant mineral phase, mainly because Mg^{2+} controlled carbonate minerals by decreasing precipitation rate of calcite, but had no effect on aragonite precipitation rate. Davis *et al*. (2000) concluded that at moderate Mg^{2+} concentrations ($2<Mg/Ca<5.3$), Mg-calcite and aragonite co-precipitate; at higher Mg^{2+} concentrations ($Mg/Ca>5.3$), only aragonite precipitates; It shows that high Mg^{2+} concentrations favor entry into the calcite lattice, change the thermodynamic properties of the crystal, inhibit calcite growth, and promote aragonite precipitation. Zhang *et al*. (2018) found that when Mg^{2+} concentration is (Mg=0.3; Mg/Ca=6), Mg-calcite and aragonite co-precipitation; when Mg^{2+} concentration is (Mg=0.45; Mg/Ca=9), no aragonite precipitation, and Mg-calcite and dolomite co-precipitation; high Mg^{2+} concentration (Mg=0.60; Mg/Ca=12) is not favorable for Mg-calcite and dolomite precipitation. It has also

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been suggested that the dolomitization of calcite is formed through Mg-calcite as an intermediate phase (Krause *et al*., 2012). High Mg/Ca facilitates the formation of Mg-calcite and dolomite, mainly because high Mg/Ca removes H+ from the carbonate surface and also reduces the dehydration energy of ions and ion pairs (Krause *et al*., 2012). Therefore, the precipitation of aragonite may require a specific Mg/Ca, and the medium environment has a positive effect on the formation and stability of aragonite when it reaches a certain comprehensive condition (Zhang *et al*., 2018). High concentration of Mg^{2+} is conducive to the transformation of Mg-calcite as an intermediate phase to dolomite, but too high concentration of Mg^{2+} will affect the formation of minerals by inhibiting the growth and reproduction of bacteria.

In addition, the concentration of Ca^{2+} in the medium environment will affect the change of intracellular Ca^{2+} concentration. Zhuang *et al*. (2018) found that extracellular Ca^{2+} is transported to the cell along the concentration gradient through diffusion. When the intracellular Ca^{2+} concentration exceeds a critical threshold (Benzerara *et al*., 2014), Bacillus cereus MRR2 can generate intracellular amorphous nanospheres. According to the new view of aggregation mechanism nucleation, amorphous nanospheres may be clusters before calcium carbonate nucleation, and then crystallize to form other stable minerals (Gebauer *et al*., 2008, Zhuang *et al*., 2018). Recent studies have found that Mg^{2+} concentration also affects changes of intracellular Ca^{2+} concentration. Pan *et al*. (2019) found that Mg^{2+} concentration in the medium strongly affects the diffusion of Ca^{2+}, leading to a significant decrease in intracellular Ca^{2+} concentration, possibly because Mg^{2+} with a smaller radius passes through ion channels more easily than Ca^{2+}. The role of intracellular Mg^{2+} needs to be further investigated.

4.4.2 Influence of medium environment on the morphology of carbonate minerals

Bacterially induced carbonate mineralization with complex and variable morphologies, such as dumbbell-shaped, rhombohedral-shaped, cauliflower-shaped, spindle-shaped, spherical-shaped, rod-shaped, and plate-shaped (Guo *et al*., 2013; Gilis *et al*.,2014; Mercedes-Martín *et al*.,2016). Numerous studies have found that the production of different crystal morphologies is apparently also related to hetero-ions in the crystal lattice and surrounding source solution (Raz *et al*., 2000; Guo *et al*., 2013). Chen *et al*. (2005) found that Mg^{2+} can cause an increase in crystal surface roughness and deformation of crystals. Sánchez-Navas experimentally found that the promotes the formation of spherulitic and dumbbell-like morphologies under conditions of high magnesium/calcium (Mg/Ca) molar ratios. Zhang *et al*. (2018) used Arthrobacter sp. strain MF-2 to conduct culture experiments with different Mg/Ca molar ratios (R=0,1.5,3,6,9,12) and found that at higher Mg^{2+} concentrations

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(Mg>0.15M, R>3), the mineral morphology changed from complex to simple (mainly spherical-shaped and lamellar-shaped). He suggested that increasing Mg^{2+} concentration in the environment affects the polymorph and morphology of carbonate formation by controlling the metabolism and carbonic anhydrase activity of Arthrobacter sp. strain MF-2. Han *et al*. (2017) found that the crystallinity of calcite minerals decreases with the increase of Mg/Ca molar ratio. Park *et al*. (2008) have studied the effect of Mg^{2+} ions on the crystal elongation of aragonite and concluded that the longitude and aspect ratio of aragonite crystals decreases with the increasing of Mg^{2+} ions concentration. This shows that Mg^{2+} can easily adsorb on the surface of minerals and further incorporate into the crystal structure, thus destroying the crystal structure of minerals (Long *et al*., 2014). Han *et al*. (2017) performed thermogravimetry–derivative thermogravimetry (TG–DTG) analysis of the mineral precipitates induced by S.PCC6803 cells and found that the thermal stability of mineral precipitation gradually decreased with increasing Mg/Ca molar ratio. This is because the more stable the crystal structure is, the more heat is absorbed when being decomposed, and Mg^{2+} can increase the irregular part of the crystal, and the structural stability of this irregular part is lower than that of the regular part. Therefore, the thermal decomposition temperature of irregular crystals is lower than that of regular crystals, which leads to the thermal stability of the mineral precipitates declined gradually with the increase of Mg^{2+} concentration, thus affecting the crystallization process of carbonate mineral precipitates. It can be seen that the different crystal forms of minerals are closely related to the Mg^{2+} and Mg/Ca molar ratios, and Mg2+ can easily adsorb on the crystal surface to increase the irregularity of the crystal structure and reduce the thermal stability of minerals, which in turn affects the crystallization process of mineral precipitation.

5. Conclusion

(1) Through the analysis of knowledge structure in the field of bacterial mineralization by using Bibilometrix software, it was found that the research field as a whole showed a boom from 2012 to 2022. Bacterial mineralization was developing at the intersection and dispersion of microbiology, geochemistry, building materials science, mineralogy, and ecology. Geomicrobiology Journal and Chemical Geology are the journals that need to be focused on in the future. With the continuous deepening of research, a number of excellent scientific researchers emerged at home and abroad. Foreign scholars represented by Visscher, Muynck, Sánchez-Román, SO and Mortense and domestic scholars represented by Qian C.X., Zhou G.T., Han Z.Z., Li F.C. and Li Y., all of whom have made outstanding contributions in the field of

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bacterial mineralization. China tops the list of publications in the field of bacterial mineralization and has established a stable and close international cooperation network with the United States, the United Kingdom, Australia and Canada, but the average number of citations is low and the academic influence is weak relative to that of European and American countries. Therefore, focusing on fostering a scientific research innovation system, maximizing resource allocation, establishing high-quality Chinese core databases, and exploring new cooperative countries are important measures to promote the overall development of the field of bacterial mineralization.

(2) By mapping the literature history citation network and keyword clustering, it was found that in 2000-2022, the highly cited articles mainly focus on: (i) The study of the application and limitations of MICP technology in the field of construction materials. (ii) The study of the effect of bacterial extracellular polymer on carbonate crystallization. (iii) The study of factors affecting bacterially induced carbonate precipitation. Based on the MCA combined with the K-means clustering method, the bacterial mineralization keywords can be divided into four clusters: The research on the influence of medium environment on the morphology and types of calcium carbonate and the exploration of the mechanism of calcium carbonate nucleation (I). The investigation of the "dolomite problem" using anaerobic and aerobic bacteria (II). The study of microbially induced calcium carbonate precipitation represented by bacteri (III). The research of urease secreted by ureolytic bacteria to catalyze the production of calcium carbonate for bioremediation (IV).

(3) Through the analysis of highly cited literature and cluster analysis of key words in the field, it is found that the hot spots of bacterial mineralization mainly focus on four aspects: Study on the formation mechanism of dolomite; Study on MICP by hydrolyzation of urea; Study on the mechanism of bacterially induced carbonate mineralization; Study on the influence of medium environment on the species and morphology of carbonate minerals.

After further hot spot summary and inductive classification, bacterially-induced carbonate mineralization can be specifically divided into the following seven directions: ① Research on the mechanism of aerobic microbially-induced low-temperature dolomite formation; ② Application of Mg isotope geochemistry in dolomite problems; ③ Screening of new ureolytic bacteria with high urease activity and high environmental adaptability; ④ Research on environmental conditions affecting urease activity of ureolytic bacteria; ⑤ Research on urea hydrolysis MICP on consolidation and restoration of construction materials; (6) Study on the mechanism of mineral nucleation by bacterial cells and extracellular polymers; (7) Study on the effect of media environment on carbonate mineral species and

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morphology.

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