APPLICATIONS OF BACTERIAL MINERAL PRECIPITATION: A REVIEW

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Abstract

Bacterial mineralization has become a popular area of research emerging in the current times. The composition, nucleation, morphology and bio minerals are dependent on the metabolic activity of the microorganism. Research has harnessed the application of biologically induced mineralization of metals like Mn, Fe and many metal oxides such as ferrihydrite, hematite, goethite, phosphates. The current review indicates that carbonates are the most common once reported by bacterial biomineralization. This has led to abundant research on bacterially induced calcium carbonate precipitation (MICCP). The wide applications of MICCP are quite multidisciplinary with its growing relevance in fields like Geotechnology, Civil Engineering, Paleobiology and Biotechnology. The current review therefore brings a systematic analysis of various applications of bacterial induced mineral precipitation with special emphasis on MICCP.

Keywords: MICCP, bacterial induced mineral precipitation, biominerals

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Introduction

Bio-mineralization is a kind of microorganism mediated or regulated mineral precipitation process through which specific kind of minerals are formed within a given environmental condition. This process is facilitated by the synergistic biological and chemical modification of the involved organisms in such a way that maximum of the bio minerals can be precipitate out with direct or indirect utilisation of enormous biological agents (Phillips *et al*. 2013). The quantity produced in such methodologies is very miniscule and the entire process of complete mineral precipitation may take a longer time period (Crichton, 2019; Yoshida *et al.*, 2010). Till now six major microbial groups have been identified to validate and carry out the entire process of mineral precipitation and the biomineral deposition in form of precipitate formation may occur within the concerned microbial cell or outside the cell in the surrounding environment depending upon the mechanistic activity of the concerned microbe (Wen *et al.*, 2020; Tang *et al*., 2021). Microbial mediated mineralization is one of the effective techniques that confiscate various toxic pollutants to form a within stabilized solid structural matrix (Tang *et al*., 2021). The mineral precipitation process is initiated with a sequential manner for development of mineral ions from inorganic pollutants and then leading to their compound precipitation step. In contrast to inorganically formed minerals, the microbially precipitated minerals mostly carry their individual structural uniqueness in form of size and shape, density, isotopic value, amorphous or crystalline appearance and many more (Weiner and Dove, 2003). The most widely produced bio mineralization categories include silicification, carbonate precipitation, iron mineralization and calcification (Dupraz *et al*., 2009) giving rise to most of the suitable minerals like nitrates, oxides, calcium oxalates, silicates, apatite, halides, gypsum and phosphates (Chan *et al*., 2009). Microorganism mediated mineralization is enormous and widely utilizes living organisms like Cyanobacteria, bacteria, fungi and algae. Its efficacy rate is maintained by certain factors viz calcium, inorganic carbon, nucleation and pH (Wu *et al*., 2021).

Types of microbial precipitation

Several types of biominerals are being precipitated with the regulated or induced mechanism of microorganisms. Minerals like calcite precipitation (Kang *et al*. 2014; Achal *et al*., 2009; Dhami *et al*. 2014; Karatas *et al*., 2008), calcium carbonate precipitation (Chekroun *et al*., 2004; Ganendra *et al*., 2014; Konstantinou *et al*., 2021), strontium precipitation (Singh *et al*., 2008), iron mineralization (Wang *et al*., 2020), cadmium precipitation (Bai *et al*., 2008), biomineralization of antimony (Huang *et al*., 2022) and Pb (II) biomineralization (Jiaqi *et al*., 2022) are some of the widely available precipitation methodologies, utilising different types of mineralization mechanism for the initiation of the nucleation step.

Microbial precipitation of calcium carbonate

In most cases ureolytic microbes initiates the calcium carbonate precipitation and also act as the nucleation sites for MICCP crystal production. The mechanism of MICCP the anionic cell surface of the microbes facilitates cations for calcium ions accumulation on the cell surfaces (Zhu *et al*., 2015; Wen *et al*., 2020). Enzymatic activity of carbonic anhydrase is found to be the highest at lower temperature. Bacteria induced biomineralization can be facilitated utilising toxic pollutants in any kind of extreme conditions including acidophilic, alkaliphilic, thermophilic, halophilic and anaerobic (Benzerara *et al*., 2014; Achal *et al*., 2015).

The most frequently available biominerals contain the major ion calcium and it is biologically mineralized through precipitation methodology by the physiological metabolism of the concerned prokaryotic organism. Amongst all available calcified minerals, calcium carbonate is one of the potent, widely available mineral creditworthy for almost 4% w/v of earth’s crusts. The mineralization of calcium occur in form of calcium carbonate, which is a well applied methodology, known as microbial precipitation of calcium carbonate (MPCC) and can be seen in soil sediments, water bodies both fresh and marine (Sarayu *et al*., 2014). The mechanism of calcium precipitation can be in an induced form, known as microbially induced calcium carbonate precipitation (MICCP) and microbially controlled calcium carbonate mineralization (MCCCP). The MCCCP mostly occurs due to the interaction of available extracellular polysaccharide matrix with the calcium ions in absence of active involvement of the concerned microbes. In this case the available functional groups deprotonate resulting in anionic charge in the extracellular polysaccharide matrix in the alkaline pH condition. This results in facilitated combination of the metal ions with the selected individual functional groups like carboxylate, amino, sulfates and hydroxyl (Sarayu *et al*., 2014).

Microbially induced calcium carbonate precipitation (MICCP)

The term microbially induced calcium carbonate mineralization is the methodology of biologically calcium carbonate mineral production (Achal *et al*., 2015) due to the active interaction of specific metabolic intermediates in a specific microbe controlled environmental condition. These intermediate products are carbonate and calcium ions (Salman *et al*., 2016). Most of the amorphous structure of calcium carbonate minerals are the form either as monohydrate or dehydrate group with porous calcium framework and interlinked carbonate ions with water particles (Goodwin *et al*., 2010). Microorganisms involved in calcium carbonate precipitation in a controlled condition, are mostly potent enough to change the entire physiological factors of the microenvironment completely or partially.

In the case of microbially controlled calcium carbonate precipitation, in which the biominerals formed contain a very narrow range crystal size distribution. However in the case of microbially induced calcium carbonate precipitation, the development of both crystalline and amorphous calcium carbonate precipitates occurs with broader particle size; whereas in case of microbially controlled calcium carbonate precipitation, the development of narrow sized calcium carbonate crystal precipitates (Silva-Castro *et al*., 2015). In MICCP, among both crystalline and amorphous groups, the amorphous calcium carbonate precipitates are quite unstable and can interconvert to other stable calcite structure, when made soluble in water (Rodriguez-Blanco *et al*. 2011). Bacteria are one of the unique microbes that facilitate mineral precipitation as they help in development of heterogeneous nucleation sites (Rodriguez-Navarro *et al*. 2012).

The microbially induced calcium carbonate precipitation (MICCP) has got several applications including bioremediation of heavy metals and radionucleoids (Kang *et al*., 2014; Yadav *et al*., 2014; Chen *et al*., 2016), self-healing concrete or more widely known as bioconcrete (Achal *et al*., 2015; Siddique *et al*., 2016; Tziviloglou *et al*., 2016), carbon dioxide bio-sequestration (Chough *et al*., 2010; Yadav *et al*., 2014; Okyay and Rodrigues, 2015), improvement of soil quality (Cheng and Cord-Ruwisch, 2012) and many more. The current literature review adapts the systemic review method for analyzing the microbially induced calcium carbonate precipitation and its application by various bacterial agents. Though there are many studies available and still research is going on regarding several types of mineral precipitation; amongst all calcium carbonate precipitation has been studied extensively (Fig 1).

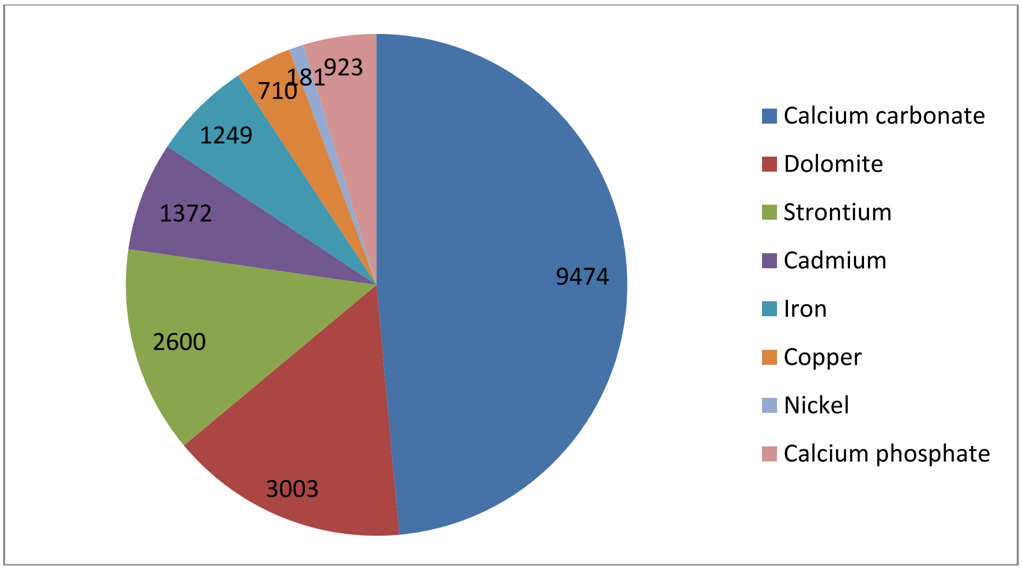

Fig 1: Recent research on different types of mineral precipitation

Within the last ten years many researchers have been working continuously on this aspect to get a clear idea regarding the microbially induced calcium carbonate precipitation. The bibliometric analysis depicts a total publication of papers under bacteria induced and/or controlled mineral precipitation in the SCOPUS database. The trend of research in this domain has extensively increased in the last decade (Fig 2).

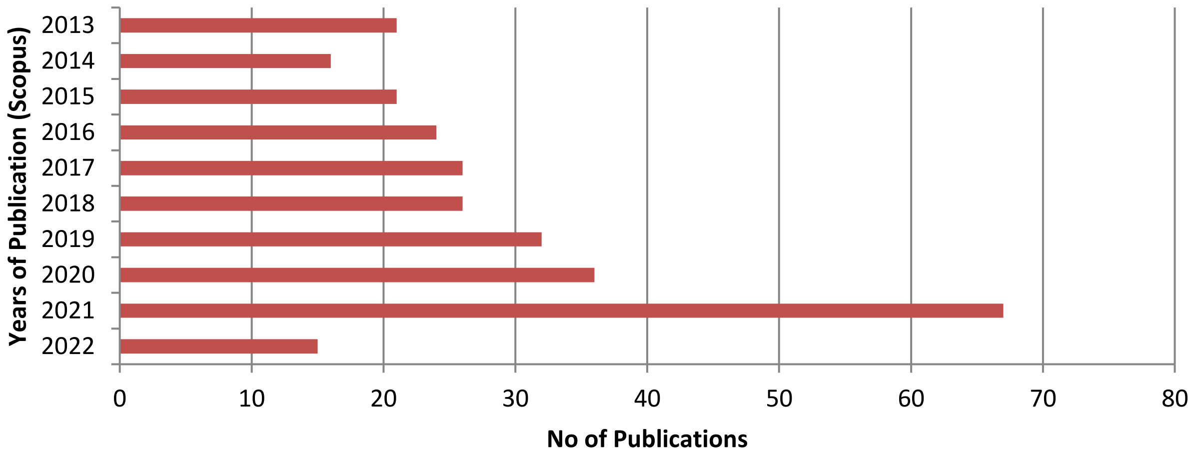

Fig 2: Papers published under "microbially induced calcium carbonate precipitation" (SCOPUS database)

Applications of MICCP

The microbially induced calcium carbonate precipitation (MICCP) has got several applications including bioremediation of heavy metals and radionucleoids (Kang *et al*., 2014; Yadav *et al*., 2014; Chen *et al*., 2016), self-healing concrete (Siddique *et al*., 2016; Achal *et al*., 2015; Tziviloglou *et al*., 2016), carbon dioxide bio-sequestration (Okyay and Rodrigues, 2015; Chough *et al*., 2010; Yadav *et al*., 2014), improvement of soil quality (Cheng and Cord-Ruwisch, 2012), many more. Microbially induced calcium carbonate precipitation methodology has a pivotal feature in different types of functional alternations. This review, however, deals with some of the evident applications as compiled and depicted in Table 1.

Table 1: Data Extraction for the quality papers selected for review under the identified themes

Sl No	Name of Authors with year	Bacteria involved in MICCP	Mechanism of MICCP	Application of MICCP
1	Chekroun *et al*., 2004	*Myxococcus xanthus*	Ammonification	remediate heavy metals and radionuclides, crack remediation and soil improvement
2	Ganendra *et al*., 2014	*Methylocystis parvus*	Denitrification	heritage conservation and self-healing concrete, sealing surrounding matrix
3	Cuthbert *et al*., 2012	*Sporosarcina pasteurii*	Urea hydrolysis	remediate heavy metals, crack remediation and soil improvement
4	Ferrer *et al*. 1988	*Deleya halophila*	Denitrification	heritage conservation and self-healing concrete
5	Sarada *et al*., 2009	*Bacillus pasteurii*	Urea hydrolysis	remediation of heavy metals
6	Pan *et al*., 2005	*Pleurotus ostreatus*	Ammonification	Biosorption of Pb (II), soil improvement and self-healing concrete
7	Puyen *et al*, 2012	*Micrococcus luteus* DE2008	Conversion of organic acid to calcium carbonate	Biosorption of lead and copper, crack remediation and soil improvement
8	Qian *et al*., 2009	*Bacillus pasteurii*	Urea hydrolysis	Biosorption of AS, soil improvement and self-healing concrete
9	Rivadeneyra *et al*., 1996	*Deleya halophila*	Denitrification	soil improvement and self-healing concrete
10	Rivadeneyra *et al*., 1998	*Halomonas eurihalina*	Denitrification	soil improvement and self-healing concrete
11	Rodriguez-Navarro *et al*., 2003	*Myxococcus xanthus*	Ammonification	concrete crack remediation and soil improvement
12	Siddique *et al*., 2008	*Bacillus megaterium*	Urea hydrolysis	soil improvement and self-healing concrete
13	Silver *et al*., 1975	*Bacillus subtilis* and *Escherichia coli*	Urea hydrolysis	concrete crack remediation and soil improvement
14	Fujita *et al*., 2000	ureolytic subsurface bacteria	Urea hydrolysis	soil improvement and self-healing concrete
15	Gorospe *et al*., 2013	*Sporosarcina pasteurii* KCTC 3558	Urea hydrolysis	concrete crack remediation and soil improvement
16	Eryuruk *et al*., 2015	*Sporosarcina pasteurii*	Urea hydrolysis	remediate heavy metals and radionuclides

17	Al-Thawadi and Cord-Ruwisch, 2012	ureolytic bacteria	Urea hydrolysis	remediate heavy metals and radionuclides, sealing surrounding matrix
18	Chunxiang *et al*., 2009	*Bacillus pasteurii*	Urea hydrolysis	Corrosion proof cement, soil improvement and self-healing concrete
19	Ghosh *et al*., 2019	*Sporosarcina pasteurii*	Urea hydrolysis	soil improvement and self-healing concrete, remediate heavy metals and radionuclides
20	Perito *et al*., 2014	*Bacillus subtilis*	Urea hydrolysis	heritage conservation and self-healing concrete
21	Jiang *et al*., 2013	*Synechocystis* sp PCC 6803	Sulfate reduction Photosynthesis	remediate heavy metals and radionuclides, sealing surrounding matrix
22	Martinez *et al*., 2016	*Synechococcus* sp	Sulfate reduction Photosynthesis	remediate heavy metals and radionuclides, sealing surrounding matrix
23	Blondeau *et al*., 2018	Cyanobacteria	Photosynthesis	Improve soil quality and self-healing concrete,
24	Cam *et al*., 2018	Cyanobacteria	Photosynthesis	remediate heavy metals and radionuclides, heritage conservation and self-healing concrete
25	Benzerara *et al*., 2014	Cyanobacteria	Photosynthesis	remediate heavy metals and radionuclides
26	Gray, 2006	*Achromatium*	Sulfate reduction Photosynthesis	self-healing concrete, Improve soil quality
27	Kremer *et al*., 2008	Cyanobacteria	Photosynthesis	self-healing concrete, Improve soil quality, heritage conservation and self-healing concrete,
28	Marvasi *et al*., 2010	*Bacillus subtilis* etfA mutant	Urea hydrolysis	Regulate biofilm formation, self-healing concrete, Improve soil quality
29	Benini *et al*., 2013	*Sporosarcina pasteurii* urease	Urea hydrolysis	remediate heavy metals and radionuclides, heritage conservation and self-healing concrete
30	Zhao *et al*., 2019	*Bacillus licheniformis SRB2*	Urea hydrolysis	remediation of heavy metals
31	Achal and Pan, 2014	*Bacillus sp. CR2*	Urea hydrolysis	Bio-sequestration of carbon dioxide
32	Adzami *et al*., 2018	*Bacillus sphaericus*	Urea hydrolysis	soil improvement and self-healing concrete
33	Achal *et al*., 2012	*Halomonas* sp.	Denitrification	Bioremediation of strontium contaminated aquifer
34	Braissant *et al*., 2007	sulfate reducing bacteria	Sulfate reduction Photosynthesis	remediation of heavy metals
35	Dhami *et al*., 2013	*Bacillus megaterium*	Urea hydrolysis	As biogenic surface treatment agent for green building
36	Dick *et al*., 2006	*Bacillus* sp.	Urea hydrolysis	Layer formation on degraded limestone
37	Helmi *et al*., 2016	*Bacillus licheniformis*	Urea hydrolysis	Bio-sequestration of carbon dioxide, concrete restoration
38	Lian *et al*., 2006	*Bacillus megaterium*	Urea hydrolysis	soil improvement and remediate heavy metals and radionuclides
39	Martin *et al*., 2012	*Sporosarcina pasteurii*	Urea hydrolysis	remediation of heavy metals
40	Ramanan *et al*., 2009	*Citrobacter freundii*	Ammonification	Bio-sequestration of carbon dioxide
41	Seifan et sl., 2016	*Bacillus*	Urea hydrolysis	remediation of heavy metals
42	Sensoy *et al*., 2017	*Sporocarcina pasteurii* ATCC 6453 and *Bacillus aerius* U2	Urea hydrolysis	Layer formation on degraded limestone, Bio-sequestration of carbon dioxide
43	Srivastava *et al*., 2014	*palaeoproterozoic metasediments*	Ammonification	Bio-sequestration of carbon dioxide
44	Zhang *et al*., 2011	*Bacillus mucilaginosus*	Urea hydrolysis	Bio-sequestration of carbon dioxide, concrete restoration
45	Zhu *et al*., 2015	*Synechococcus* PCC8806	Sulfate reduction Photosynthesis	concrete restoration
46	Xu *et al*., 2019	Cyanobacteria	Photosynthesis	Bio-sequestration of carbon dioxide
47	Couradeau *et al*., 2012	microbialite Cyanobacteria	Photosynthesis	Bio-sequestration of carbon dioxide
48	Silva-Castro *et al*., 2015	*Bacillus* sp. and *Virgibacillus* sp.	Urea hydrolysis	Bio-sequestration of carbon dioxide
49	Konstantinou *et al*., 2021	*Sporosarcina pasteurii*	Urea hydrolysis	Formation of biocemented artificial sandstone
50	Barabesi *et al*., 2007	*Bacillus subtilis*	Urea hydrolysis	Bio-sequestration of carbon dioxide

Conclusion & Future Prospects

Although MICCP has got several wide applications and enormously used in various sectors, it still gets some of the major lacunas that can never go unnoticed. The main difficulty is the microbial micro environment. The way the *in vitro* conditions are regulated for a mineral precipitation process, cannot be done in an on-field condition. Several strategies are now available and are used in large scale to overcome the limitation involved in MICCP methodologies.

Depending upon the type of microbial mediated mineral precipitation and the deposition pattern, several applications like bioremediation of heavy metals, organic components binding and sealing the surrounding matrix are possible. The gathered information regarding microbial mediated calcium carbonate bio-mineralization has facilitated the advanced applications of these naturally synthesized minerals for use as biomaterial within medicament industries along with wide application as bio-sequestration of carbon dioxide, heavy metals & radionuclide bioremediation and many more.

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