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Mini Review

Biomineralization Ability of Cave Microorganisms

Rachna Rautela[1]*, Seema Rawat[2]

[1]*Department of Botany and Microbiology, Hemvati Nandan Bahuguna Garhwal University, Srinagar Garhwal, Uttarakhand, India*

[2]*School of Life Science, Central University of Gujarat, India*

***Corresponding author:** Rachna Rautela, Department of Botany and Microbiology, Hemvati Nandan Bahuguna Garhwal University, Srinagar Garhwal, Uttarakhand, India.

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Abstract

Biomineralization in cave environments is a dynamic process where microorganisms play a critical role in the formation of various minerals under extreme conditions. These microorganisms contribute to the development of speleothems, such as stalactites and stalagmites, by precipitating minerals like calcium carbonate, gypsum, silica, iron oxides, and manganese oxides. The processes of Biologically Induced Mineralization (BIM) and Biologically Controlled Mineralization (BCM) are key mechanisms in this context, leading to the formation of intricate and diverse mineral structures. This study explores the mineralization pathways facilitated by cave microorganisms and their implications for understanding geological processes, microbial ecology, and potential applications in biotechnology and environmental science. Future research in this area holds promise for advancing our knowledge of life in extreme environments and developing innovative biotechnological applications, including sustainable construction and bioremediation.

Keywords: Cave, Biomineralization

Biomineralization in Cave Environments

The occurrence of bacteria and fungi in cave sediments and water suggests the participation of microorganisms in the deposition of cave speleothems such as carbonate speleothems [1] and saltpeter [2]. The discovery of chemolithotrophic microorganisms made it clear that light is not the only energy source for growth; several inorganic minerals can also be used as an energy source. Cave microorganisms acquire energy by oxidizing/reducing metals, fixation of gases, and transformation of aromatic compounds [3]. The number of features observed within the cave, like multilayer biofilms, colorful patches, stalactites, stalagmites, and others, served as footprints of microbial activities. The sustainability of these structures for millions of years is really intriguing, as the forces behind the maintenance of these structures remain unclear. Many researchers have confirmed the presence of microbes in cave structures and have highlighted their role in the formation of cave structures. Biomineralization in cave environments is diverse and complex, involving both Biologically Induced Mineralization (BIM) and Biologically Controlled Mineralization (BCM) processes driven by microorganisms [4,5] (Figure 1). BCM refers to the process where organisms actively regulate the formation of minerals, using specific biochemical mechanisms to control the size, shape, and composition of the resulting minerals. This results in highly organized structures, often tailored to the organism's needs [6,7]. In contrast, biologically induced mineralization occurs when organisms unintentionally cause mineral precipitation as a byproduct of their metabolic activities. This process is driven by environmental changes like pH shifts or ion concentration alterations caused by the organism, resulting in less controlled and more variable mineral deposits [8]. These mechanisms enable microorganisms to thrive in the nutrient-poor and extreme conditions of caves, playing a crucial role in shaping the mineralogy of these subterranean environments.

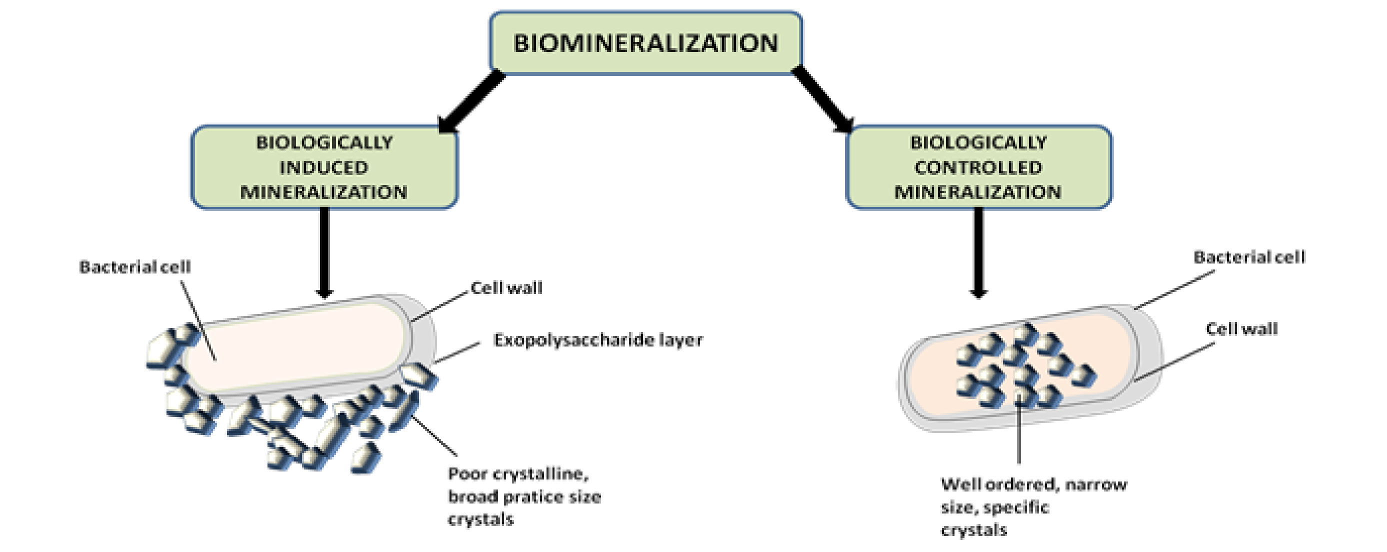

Figure 1: Types of microbial mediated mineralization.

Minerals Precipitated by Cave Microorganisms

Cave microorganisms play a critical role in the precipitation of various minerals, leading to the formation of intricate and diverse cave formations. One of the most prevalent minerals produced by these microorganisms is calcium carbonate ($CaCO_3$), which occurs in different crystalline forms, primarily as calcite and aragonite [9-11]. These forms are responsible for creating iconic speleothems such as stalactites, stalagmites, flowstones, and cave pearls. Some researchers believe that the precipitation is a specific process with ecological benefits for the mineralizing organisms [12,13], while others think that the precipitation is an undesirable and accidental product of microbial metabolism [14]. The precipitation of calcium carbonate is often facilitated by bacteria that metabolize organic compounds, producing carbon dioxide, which combines with calcium ions in the cave water to form $CaCO_3$. *Growth, et al.* [15] demonstrated that many cave bacteria, including a large number of actinobacteria, were capable of crystal formation. *Laiz, et al.* [16] reported that 61% of the Actinobacteria isolated from caves were capable of producing crystals in culture media. In addition to calcium carbonate, gypsum ($CaSO_4 \bullet 2H_2O$) is another common mineral formed in caves, particularly in drier environments where evaporation is significant. Gypsum is often deposited by sulfate-reducing bacteria, which can convert sulfates in the cave water into sulfides, subsequently leading to gypsum formation when conditions favor oxidation [17,18]. Cave microorganisms also contribute to the formation of silica (SiO_2) deposits, such as opal and chalcedony, through the weathering of silicate minerals or the biological mediation of dissolved silica in groundwater [19,20]. These silica minerals often form as coatings or thin layers on cave walls and are sometimes associated with microbial mats.

Many studies have revealed the presence and association of bacteria with iron mineralization in caves by applying metagenomics and scanning electron microscopy [21-26]. Deposits and biosignatures of biogenic iron in caves can provide information related to the source of energy in dark and nutrient-poor environments for supporting microbial life and microbial metabolism [27]. In cave ecosystems, iron-oxidizing microbes have received rare but increasing attention. Microorganisms are responsible for the precipitation of iron oxides [28], including goethite (FeO(OH)) and hematite (Fe_2O_3), which give rise to reddish or brownish stains and coatings on cave surfaces. *Peck* [29] identified *Gallionella ferruginea* and *Leptothrix* sp. from mud and wall crusts, which were involved in iron precipitation in Level Crevice Cave in Iowa. “Rusticles” of iron oxides and organic filaments in Lechuguilla Cave, New Mexico, were identified by *Davis, et al.* [30] using scanning electron microscopy. Later on, *Provencio and Polyak* [31] studied these structures and reported them as fossilized *Clonothrix* sp. or similar iron-oxidizing bacteria. *Baskar, et al.* [32] suggested that the iron-oxidizing bacteria, namely *Leptothrix* sp., *Siderooxidans* sp., *Crenothrix* sp., *Comamonas* sp., and *Dechloromonas* sp., were involved in the formation of iron precipitates in Bora Caves of India. Manganese oxides like birnessite and pyrolusite are also commonly precipitated by cave microorganisms, particularly those capable of oxidizing manganese ions. These manganese oxides often manifest as black, dendritic patterns or form delicate structures known as “cave flowers” or “cave corals,” which are prized for their aesthetic appeal. Additionally, iron oxides often coexist with manganese oxides, resulting in the formation of multicolored ferromanganese deposits [33,34]. These iron minerals result from the oxidation of ferrous iron by iron-oxidizing bacteria in aerobic conditions. In caves, *Gallionella ferruginea* [35] is notably associated with iron oxidation, while *Leptothrix* species [36] are recognized for their ability to oxidize both iron and manganese. Additionally, other less common minerals precipitated by cave microorganisms include barite ($BaSO_4$), formed through the microbial mediation of barium and sulfate ions, and various phosphates like hydroxylapatite, often associated with bat guano deposits. Together, these minerals contribute to the unique and varied mineralogy of caves, reflecting the diverse metabolic capabilities of cave-dwelling microorganisms and the geochemical conditions of their environment. The study of these biominerals not only enhances our understanding of cave formation processes but also provides valuable insights into microbial life in extreme environments.

Future Perspectives of Biomineralization Inside Caves

The future of biomineralization research in caves holds great promise for advancing our understanding of microbial processes and their applications across multiple scientific disciplines. One of the most exciting areas of future research is the exploration of cave biomineralization as a model for understanding life in extreme environments, including potential extraterrestrial habitats. The ability of microorganisms to thrive and precipitate minerals under the nutrient-poor, light-deprived conditions of caves provides valuable insights into how life might exist on other planets, such as Mars or the icy moons of Jupiter and Saturn, where similar conditions may prevail. Additionally, advancements in molecular biology and omics technologies, such as metagenomics, metatranscriptomics, and proteomics, will allow for a more comprehensive characterization of the microbial communities involved in cave biomineralization, revealing the genetic and metabolic pathways that drive these processes. Another important future perspective is the potential application of biomineralization processes in biotechnological and industrial contexts. For example, Microbial-Induced Calcium Carbonate Precipitation (MICP) is being explored for use in sustainable construction practices, such as self-healing concrete, where microorganisms could be harnessed to repair cracks and enhance the durability of building materials. Similarly, the ability of cave microorganisms to precipitate heavy metals and other pollutants suggests potential applications in bioremediation, where these processes could be used to clean up contaminated environments. Furthermore, understanding the biomineralization mechanisms in caves could lead to the development of new materials with unique properties, inspired by the naturally occurring minerals and structures found in these subterranean ecosystems. As research in this field progresses, interdisciplinary collaborations will be crucial in addressing the challenges of studying cave biomineralization, such as the difficulty of accessing remote cave environments and replicating their unique conditions in the laboratory. Innovations in remote sensing, imaging technologies, and in situ experimentation will likely play a key role in overcoming these obstacles. Ultimately, the continued exploration of biomineralization in caves will not only deepen our understanding of microbial ecology and geochemistry but also pave the way for novel applications in environmental science, astrobiology, and materials engineering.

Conclusion

Biomineralization in cave environments represents a remarkable intersection of biology and geology, where microorganisms play a pivotal role in the formation of intricate and diverse mineral structures. The study of these processes not only enhances our understanding of the complex interactions between life and minerals but also offers valuable insights into the broader implications for various scientific fields. As research continues to uncover the mechanisms and pathways of biomineralization, the potential applications in biotechnology, environmental remediation, and even astrobiology become increasingly evident. The unique conditions of caves provide an unparalleled natural laboratory for exploring these processes, and future advancements in technology and interdisciplinary research will undoubtedly expand our knowledge and open new avenues for innovation. Ultimately, the study of cave biomineralization serves as a powerful reminder of the profound influence of microbial life on our planet's geology and the potential it holds for future scientific and practical applications.

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Conflict of Interest

None.

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