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Biogenic Nanomineral Formation: Exploring the Role of Microbial Metabolism in Shaping Subsurface Geochemistry

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Abstract

This study explores the mechanisms, pathways, and geochemical implications of biogenic nanomineral formation driven by microbial metabolism within subsurface environments. Microorganisms—including bacteria, archaea, and fungi play a crucial role in generating nanominerals through biologically controlled and biologically induced mineralization processes, mediated by complex metabolic reactions such as iron and sulfate reduction, sulfur oxidation, and redox cycling. These microbial activities give rise to structurally and chemically distinct nanominerals such as magnetite, greigite, pyrite, manganese oxides, carbonates, and metal sulfides, which differ significantly from their abiotic counterparts in crystallinity, morphology, and reactivity. At the nanoscale, extracellular polymeric substances, cell wall functional groups, and metabolic by-products act as catalytic interfaces for nucleation, growth, dissolution, and stabilization of mineral nanoparticles. The study highlights how microbial redox transformations regulate metal mobility, influence geochemical gradients, and shape the mineralogical evolution of sediments, soils, and aquifers. Furthermore, it demonstrates that biogenic nanominerals serve essential functions as redox buffers, contaminant immobilizers, nutrient reservoirs, and biosignatures in both modern and ancient environments. These nanoscale products also contribute to larger processes such as bioremediation, biomineral-based energy cycling, and the long-term stabilization or mobilization of metals.

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Overall, the findings underscore microbial nanomineral formation as a major driver of subsurface geochemistry, emphasizing the need to integrate microbiology, mineralogy, and geochemical modeling to understand elemental cycling, environmental transformation processes, and the evolution of Earth's mineral diversity.

Keywords: Biogenic nanominerals; microbial metabolism; biomineralization; redox processes; geochemical cycling.

1. Introduction

Potential new avenues for producing materials for application in environmental cleanup, vehicles, photovoltaics, airplanes, medical imaging, and medical implants are made possible by biological synthesis of nanomaterials Reference [1, 2, 3]. The method of producing nanomaterials using biochemical reactions and biomolecules from bacteria, fungi, plants, and viruses is known as "biogenic synthesis." Natural microbes have the ability to create nanoscale compounds like silicates and magnetosomes [1]. The profusion and diversity of life (from micro-to macro-organisms) entwined with literally millions of organic and inorganic compounds and materials made from atoms across the periodic table make the earth system unbelievably complicated, according to [4]. However as stated by [5], geomicrobiology research over the past 20 years has shown that microorganisms are active agents that catalyze the precipitation, dissolution, and transformation of minerals through a variety of metabolic pathways. Henry Ehrlich was one of the first to combine microbiology and geochemistry, according to [6]. When a colleague sparked his interest in the bacterial facilitation of pyrite oxidation during his academic training as a microbiologist, he discovered a fortuitous union with geology. Earth's nanomaterial (NM) cycle, for instance, has recently been recognized and presented, and additional Earth cycles and components are being investigated as a result of the expansion of methodologies and tools available for studying the Earth system [4]. The NM cycle, like all cycles, includes, at least in theory, the locations of NM as well as their formation, distribution, and eventual loss or consumption as a new generation of nano-components emerges across the Earth system. These biological processes often produce biogenic nanominerals, which are mineral phases at the nanoscale that differ greatly from their abiotic counterparts in terms of appearance, content, and reactivity [7].

According to [8], natural nano-minerals (NNMs) are derived from nature and have at least one dimension smaller than 100 nm in size. The significance of these nanominerals goes beyond their size because of their high surface-to-volume ratios, catalytic potential, and reactive interfaces, they significantly influence redox reactions, metal mobility, and nutrient cycling in subsurface systems [9]. Microorganisms, such as bacteria, archaea, and fungi, help form tiny minerals called nanominerals in two main ways. One way is by using enzymes to change the chemical state of elements, like changing iron from a higher to a lower form. Another way is by producing substances during their normal activities that change the environment around them, such as the acidity, the ability to gain or lose electrons, and how ions are present in the area. For example, some bacteria that reduce iron, like Geobacter metallireducens and Shewanella oneidensis, cause magnetite nanoparticles (Fe_3O_4) to form by changing iron oxides into iron in a lower form. Similarly, bacteria that reduce sulfate help create tiny metal sulfide minerals such as pyrite (FeS_2) by producing hydrogen sulfide [10, 11, 12]. Microbially mediated nanominerals possess distinctive structural and chemical signatures that serve as biosignatures in ancient terrestrial and extraterrestrial materials, underscoring their significance in early Earth and astrobiological studies [13]. At the nanoscale, microbe–mineral interactions are governed by extracellular polymeric substances, cell wall groups, and metabolic intermediates that promote mineral nucleation and nanoparticle stabilization. These processes influence geochemical gradients and drive biogeochemical cycling of elements such as iron, manganese, sulfur, and carbon Reference [14]. Microbial redox reactions thereby regulate metal mobility, porosity, and contaminant fate within subsurface environments. This study will therefore explore the intricate mechanisms by which microbial metabolism drives nanomineral formation and influences the geochemical evolution of subsurface environments.

2. Microbial Metabolism and its Role in Geochemical Transformations

The notion that the distribution of microbial activity in aquifers follows a thermodynamic ladder, an energy hierarchy of electron-accepting activities. There are numerous distinct nanostructures that microorganisms can create [5, 15]. Because of this, scientists are increasingly interested in using these microorganisms to create nanostructures for a variety of uses. According [15] connoted that bacteria and fungi can produce inorganic compounds through biologically mediated and induced synthesis. However, nanostructures with desired compositions and geometries can be created by regulating the biological production. The biological synthesis of nanoparticles is nevertheless constrained in terms of particle geometry controllability and process scalability, notwithstanding the accuracy of the nanoparticle physicochemical synthesis. However, physiologically induced synthesis has enabled researchers to produce inorganic nanoparticles with a range of compositions using common metal precursors [16]. Metal ions are transported through the cell wall during intracellular synthesis, where the positively charged ions interact with the negatively charged wall. These ions are reduced to metal nanoparticles by cellular enzymes. The creation of gold nanoparticles using Lactobacillus kimchicus bacteria is depicted in Figure 1.

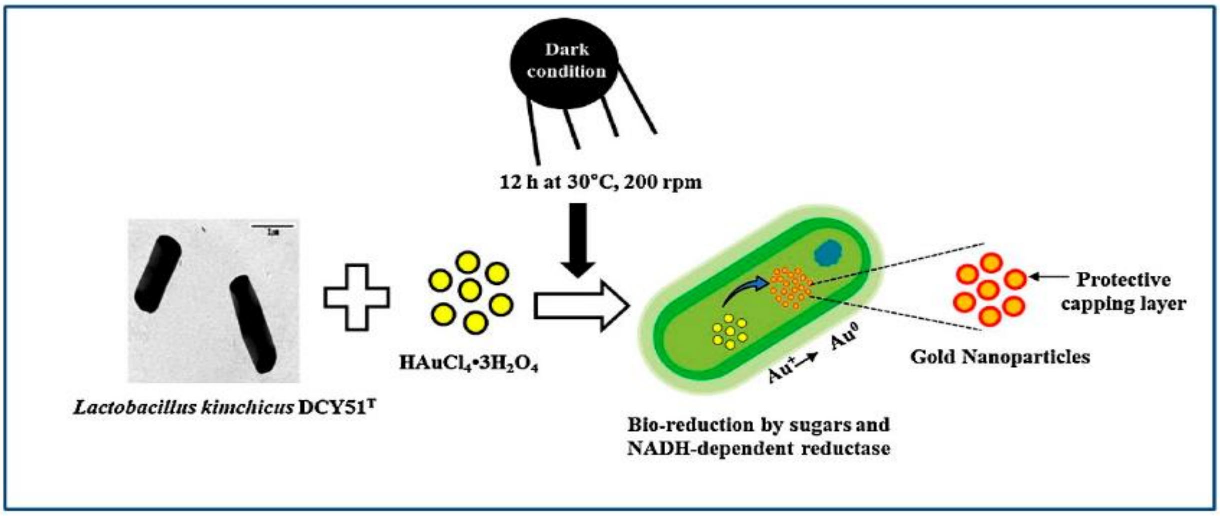

Figure 1: The process by which gold nanoparticles (AuNPs) are synthesized within cells using L. Kimchicus

DCY51^T [15,17] stated that NPs can be produced by physical, chemical, and biological means, as illustrated in Figure 2. According to multiple researchers, microbial communities can use biological synthesis mechanisms to produce inorganic nanostructures like metal or metal-oxide nanoparticles. These biogenic nanoparticles have unique compositions and forms that are regulated by extracellular metabolites, cellular surfaces, and microbial enzymes [18].

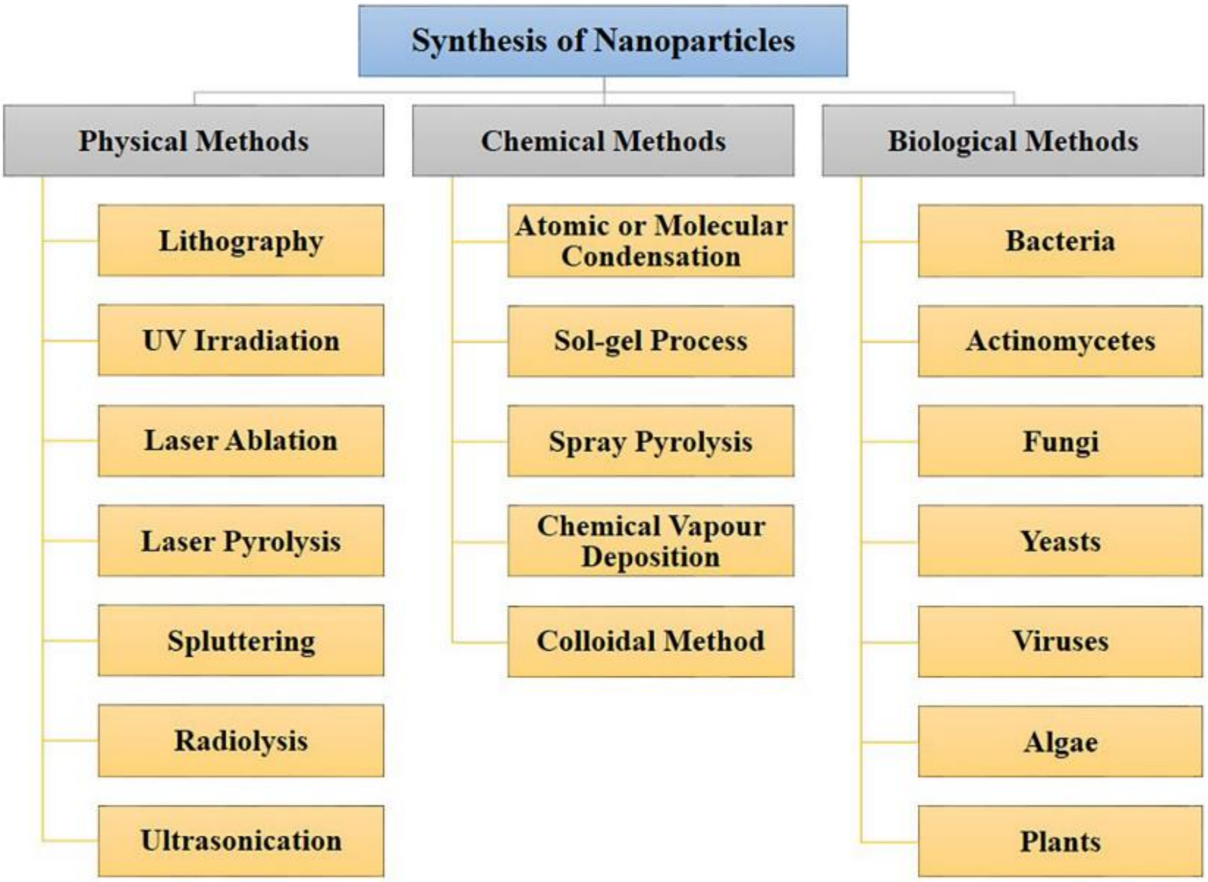

Figure 2: Several methods for creating nanoparticles [18]

Similarly, [19] connoted that microbial metabolism plays a central role in geochemical transformations as shown in Table 1 by providing reactive surfaces, altering redox potentials, and modulating element sorption or precipitation. Microbes can reduce metal ions intracellularly or at the cell surface, producing zero-valent or oxide nanoparticles, effectively forming a “microbial nanofactory” that drives element cycling [15, 16]. However, in aquifer and sedimentary systems, Fe(III) reduction releases Fe^{2+}, which precipitates as magnetite or siderite or interacts with trace metals, altering mobility and geochemical gradients [18, 20, 21]. In accordance with recent research, [11] opined that sulfate-reducing bacteria produce H_2S, which combines with dissolved metals to form sulfide nanoparticles (PbS, ZnS), immobilizing metals and creating ore deposits. In addition, microbial nanoparticle formation of Au, Ag, Cu, or ZnO adds a nanoscale dimension, influencing mineral formation and element cycling [1, 4, 11]. Microbial exudates, including organic acids, siderophores, and extracellular polymeric substances, further regulate mineral dissolution, metal chelation, and nanoparticle stabilization [22].

Table 1: Microbial Metabolic Processes and Their Roles in Geochemical Transformations and Nanostructure Formation

Microbial Metabolic Process	**Mechanism**	**Resulting Nanostructure / Mineral**	**Geochemical Implications**
Iron reduction ($Fe^{3+} \rightarrow Fe^{2+}$)	Microbial electron transfer to Fe^{3+} from organic C/H_2	Fe^{2+}-bearing nanoparticles, magnetite	Mobilisation of trace metals, redox zone modification
Sulfate reduction ($SO_4^{2-} \rightarrow H_2S$)	Organic C oxidation coupled to SO_4^{2-} reduction	Metal-sulfide nanoparticles (e.g., PbS, ZnS)	Metal immobilisation, ore genesis
Microbial nanoparticle synthesis	Enzymatic reduction of metal ions intra/extra-cellular	Au, Ag, Cu, ZnO nanoparticles	Enhanced reactivity, metal detoxification, catalytic surfaces
Sulfur oxidation (S^{2-} / $S^0 \rightarrow SO_4^{2-}$)	Lithotrophic bacteria oxidise sulfide/elemental S	Sulfate minerals, elemental S nanoparticles	Acidification, metal mobilisation
Manganese reduction/oxidation	Mn(IV)/Mn(II) redox cycling	Biogenic Mn oxides	Trace element sequestration, reactive surfaces, secondary mineral

2.1 Microbial Reduction and Oxidation Processes

According to [23] a substantial amount of iron (Fe) is present in soils, as well as freshwater, marine and subsurface sediments. Microbial Fe(III) reduction can reduce Fe(III) minerals, and in turn provide Fe(II) as either a dissolved or solid phase electron donor for Fe(II)-oxidizing bacteria. Under acidic and pH-neutral conditions, aerobic and microaerophilic Fe(II)-oxidizing bacteria can use O_2 as an electron acceptor for oxidation of Fe(II) to Fe(III). Microbial oxidation and reduction processes play a crucial role in connecting microbial metabolism to geochemical changes in both terrestrial and aquatic environments. In oxygen-poor habitats, such as oxygen-deficient regions of oceans, lakes, deep sea, and deep continental crust, these redox reactions enable microbes to utilize various electron donors and acceptors. This energy hierarchy can be visualized as a thermodynamic "ladder," where oxygen, nitrate, manganese(IV), iron(III), sulfate, and carbon dioxide act as terminal electron acceptors under increasingly reducing conditions. These processes highlight the versatility and adaptability of microbes in thriving within diverse environmental conditions.

However, in reduced subsurface sediments, for instance, bacteria such as Shewanella oneidensis mediate both ferrous oxidation and nitrate reduction under anaerobic conditions, thereby linking iron and nitrogen cycles in complex ways [24]. Similarly, it has been found that a variety of microbial taxa can oxidize sulfide produced by microbial sulfate reduction back to sulfate, linking sulfur redox cycling with arsenic or iron transformations and so influencing trace-metal mobility [25]. The way these reactions work together changes how stable minerals are, like when iron oxides form or break down. They also change the chemistry of the fluids, including things like pH, redox conditions, and the amount of dissolved substances. This affects how elements move around. For example, when microbes reduce iron compounds, they can free up iron and other metals. On the other hand, when microbes oxidize sulfide minerals, they can create acidic conditions and bring metals back into solution. These microbes also help form new mineral surfaces, control how new minerals grow, and create areas with different redox conditions, which can divide sediments and groundwater into different chemical zones [9,24,25].

2.2 Microbial Biomineralization Pathways

Biominerals are minerals produced by organisms through the process of biomineralization, which has profoundly influenced the functional biology, evolutionary trajectories, and biogeochemical impacts of diverse animal, plant, and protist lineages as shown in Figure 3 [26, 27]. Though initially driven by predation pressures, biomineralized structures have evolved multiple functions, such as locomotion, buoyancy, grinding, reproduction, and sensing gravity, magnetic fields, or light (Table 2). Biominerals frequently serve more than one purpose, with calcium carbonate ($CaCO_3$) armor acting as lenses in chitons, antimicrobial shields in ants, and detoxification mechanisms in most phyla. The genetic recipes underlying these complex, functional biominerals are a testament to the power of evolution [28, 29,27], state that biomineralization has also been taken into consideration for extensive environmental uses, like sealing geologic formations created by hydraulic fracturing and Microorganisms generate a wide range of biominerals, such as phosphates, silicates, carbonates and oxides, and sulfates and sulfides of different metals, from soils to sediments, aquifers to hot springs, lakes to seas. The structure, size, crystallinity, isotopic, and trace element content of biominerals can be significantly different from those of their inorganically generated counterparts. However, according to a number of studies, microbial biomineralization pathways comprise a range of metabolic and physicochemical interactions that allow microorganisms to convert dissolved ions into solid mineral phases, significantly influencing geochemical environments as shown in Table 3 Reference [15, 19, 30]. According [31], the first is biologically controlled mineralization (BCM), where organisms have a great deal of control over the formation of minerals. In BCM, microbes precisely regulate nucleation and crystal growth intracellularly. One example of this is magnetotactic bacteria, which produce uniform magnetite or greigite nanocrystals for navigation [32]. The second, on the other hand, is biologically induced mineralization (BIM), in which organisms have little to no influence over the creation of minerals. Metabolic byproducts, such as alkalinity from ureolysis or sulfide from sulfate reduction, cause biologically induced mineralization (BIM), which is the precipitation of carbonates, phosphates, or metal sulfides in supersaturated microenvironments Reference [31, 33]. Redox-driven pathways, common in Fe- and Mn-cycling bacteria, rely on enzymatic electron transfer that alters metal valence states, enabling the formation of nanominerals such as Fe(III) oxides or mixed-valence Mn oxides critical in subsurface element mobility [31, 34]. Besides that, the sticky substances outside microbes in biofilms have special chemicals that can stick to metal ions. These substances help form new minerals and keep small mineral particles together. Together, these processes create many different types of minerals made by living things. These minerals affect how sediments change over time, how harmful substances stay trapped, and how important chemical cycles work across large areas. This shows that microbes play a major role in shaping the variety of minerals found on Earth.

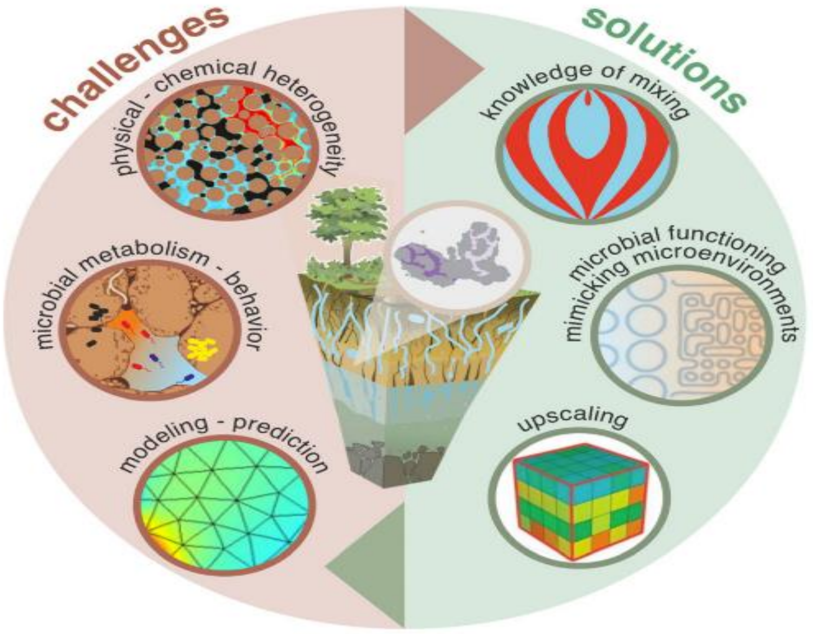

Figure 3: Microbial biomineralization in nature controlled by flow, chemistry, minerals, heterogeneity [27]

Table 2: Examples of biomineral functions in various organisms

Biomineral	**Function**	**Organism(s)**
Calcium carbonate	Structural support, protection, lenses, microbial shields	Mollusks, corals, chitons, foraminifera, sponges, ants
Silica	Structural support, nutrient uptake regulation	Diatoms, sponges, higher plants
Magnetite	Magnetoreception	Bacteria (e.g., magnetotactic bacteria), birds, fish
Aragonite	Structural support, protection	Corals, mollusks, some species of algae
Calcium phosphate	Structural support, energy storage, cellular signaling	Vertebrates (bones, teeth), some invertebrates (e.g., sea urchin teeth)
Iron sulfide	Energy storage, detoxification	Bacteria (e.g., sulfate-reducing bacteria), some plants
Hydroxylapatite	Structural support, hardness, and strength	Vertebrates (bones, teeth), some invertebrates
Gypsum	Water storage, structural support	Desert plants (e.g., cacti), some bacteria
Pyrite	Energy storage, environmental redox buffer	Sulfate-reducing bacteria, certain fungi
Siderite	Detoxification, environmental redox buffer	Iron-reducing bacteria, certain fungi

Table 3: Major Microbial Biomineralization Pathways

Pathway	**Key Microbial Group(s)**	**Mechanism**	**Typical Nanominerals Formed**
Biologically Controlled Mineralization (BCM)	Magnetotactic bacteria, diatoms	Cells regulate nucleation, growth, and morphology within compartments	Magnetite (Fe_3O_4), greigite (Fe_3S_4), silica frustules
Biologically Induced Mineralization (BIM)	Sulfate-reducing bacteria, ureolytic bacteria	Metabolism alters local pH, redox, or ion saturation, driving passive precipitation	Carbonates, sulfides, phosphates
Redox-Driven Mineralization	Iron- and manganese-reducing/oxidizing microbes	Electron transfer changes metal valence, controlling dissolution or precipitation	Fe(III)/Fe(II) minerals, Mn oxides
EPS-Mediated Mineralization	Biofilm-forming bacteria and archaea	Extracellular polymeric substances bind metals and act as nucleation templates	Carbonates, clays, metal oxides

2.3 Types of Biogenic Nanominerals

Although there are several instances of large-scale commercial microbial synthesis methods for organic bioproducts, [35] mentioned that few research have addressed the clear potential for microbial systems to create inorganic functional biomaterials at scale. Furthermore, mineral precipitation is dependent on the availability of anions, cations, and pH in addition to nucleation sites. Microbial biomineralization in subsurface environments reveals intricately linked pathways by which bacteria convert dissolved ions into nanominerals that have a major impact on geochemical cycles as shown in Table 4 [32, 36]. However, sulfate-reducing bacteria (SRB), an anaerobic bacterial group, have been shown in pure culture to transform Fe(III)-phosphate nanoparticles into pyrite (FeS_2) spherules hundreds of nanometers wide inside extracellular polymeric substance (EPS) layers via an intermediate mackinawite (FeS) and greigite (Fe_3S_4) phases. Sulfate, elemental sulfur or metals, and fermenting nitrate are examples of electron donors from which SRB obtains energy. It is the main bacterial group responsible for souring, biofouling, and microbiologically influenced corrosion (MIC) issues in oil and gas production facilities, as well as transportation and storage facilities [37, 38]. This mechanism depends heavily on the iron source which involved dissolved Fe^{2+} yields mostly mackinawite encrusting cell walls, but nanoparticulate Fe(III)-phosphate leads to pyritization via polysulfide-mediated oxidation. A similar biogenic process was observed in a mixed sulfate-reducing consortium from Lake Pavin, where rapid pyrite formation occurred within weeks much faster than previously assumed — likely driven by local enrichment of polysulfides around SRB cells [28]. These results match with bigger ideas about how microbes and sulfur processes create small areas that help pyrite form in a stable way. Another type of bacteria called *Geobacter sulfurreducens* can make pyrite when there's the right mix of iron and sulfur. In these experiments, tiny sulfur particles act as a starting point for forming pyrite spheres through a process that involves polysulfides. However, studies show that small sulfur areas are key places where pyrite spheres begin to form, and that bacteria other than sulfate-reducing ones can also make very small pyrite particles through chemical reactions and uneven precipitation. The small structure and different chemical and physical properties of these naturally made sulfides are important for understanding the types of minerals found in sediments and signs of life [11, 35, 39].

Reference [18] demonstrated that magnetotactic bacteria produce intracellular magnetite (Fe_3O_4) nanocrystals through a highly regulated biomineralization process. Utilizing X-ray absorption spectroscopy, it has been observed that the formation of these nanocrystals involves a disordered, phosphate-rich ferric hydroxide intermediate. This intermediate subsequently transforms into magnetite through ferric (oxyhydr)oxide phases inside specialized organelles called magnetosomes. The precise biological control of this mineralization process ensures uniform particle size, morphology, and magnetic functionality, which significantly impacts various geobiological aspects [9, 18, 28, 40].

Table 4: Biogenic Nanomineral Studies in Subsurface / Sedimentary Environments

Nanomineral	**Microbes (or Consortium)**	**Mechanism**	**Outcomes & Implications**	**Reference(s)**
Pyrite (FeS_2) spherules	*Desulfovibrio desulfuricans* (SRB)	Reduction of nanoparticulate Fe(III)-phosphate → mackinawite → greigite → pyrite via polysulfide oxidation in EPS	Hundreds-of-nm pyrite spherules, EPS-encrusted, strong biosignature, iron/sulfur cycling control	[11]
Pyrite (FeS_2) framboids	Mixed SRB + sulfur-reducing consortium	Rapid sulfur cycling, local polysulfide enrichment	Fast pyritization in weeks, potential analog for sedimentary pyrite formation	[41]
Pyrite (FeS_2) spherules (via Geobacter)	*Geobacter sulfurreducens*	Elemental S template + polysulfide pathway	Spherulitic pyrite on sulfur particles, microenvironment nucleation	[42]
Magnetite (Fe_3O_4) nanoparticles	Magnetotactic bacteria	Intracellular biomineralization via ferric (oxyhydr)oxide intermediates in magnetosomes	Uniform magnetite nanocrystals, magnetic functional particles	[43]
Magnetite (Fe_3O_4) in sediments	Methanogenic archaea / iron-reducing microbes	Microbial iron reduction in subsurface sediments	Magnetite-rich sediment layers, link between metabolic iron reduction and magnetic mineral accumulation	[40]

2.4 Geochemical Significance of Microbial Nanomineral Formation

Microbes are crucial to the movement of these elements between environmental reservoirs. As a dynamic link between microbial metabolism and mineral cycle, microbial nanomineral production has significant geochemical implications in subsurface and larger environmental systems [44]. First, according to ,[45 41], microorganisms like iron- and sulfate-reducers drive the precipitation of Fe- and S-bearing nanominerals (such as mackinawite, greigite, pyrite, and iron (oxy)hydroxides) that act as sinks or redox buffers for dissolved metals, thereby influencing metal mobility, trace metal sequestration, and redox gradients in sediments. Because iron exists in two primary redox states in the environment—ferric iron (Fe(iii)), which is poorly soluble at circumneutral pH, and ferrous iron (Fe(ii)), which is usually more soluble and thus more bioavailable such biogenic Fe-S minerals also act as reservoirs for phosphorus or other nutrients by adsorbing or co-precipitating with biological ligands, further changing nutrient cycles. Iron has a complex network of biogeochemical interactions, including a close interplay of biotic and abiotic reactions, while having just two naturally occurring redox states [46, 47]. Iron-oxidizing bacteria have been found to generate amorphous or crystalline iron (hydr)oxides, which can immobilize heavy metals through adsorption, co-precipitation, or structural incorporation. This bacterial process serves as a natural attenuation mechanism for contaminants in environments like acid mine drainage systems. Furthermore, under oxic and alkaline conditions, cyanobacteria have demonstrated the ability to biomineralize Fe(III)-, Mn(IV)-, and even Si-rich amorphous nanoscale phases. This challenges the traditional view that authigenic Fe/Mn enrichments result solely from reducing conditions. Instead, these microbes actively scavenge Fe and Mn, impacting the interpretation of redox conditions from sedimentary records and contributing to elemental cycling in oxygenated systems [30, 36, 38]. Fourth, in metal-rich subsurface nodules (e.g., deep-sea ferromanganese sediments), microbial communities mediate Mn oxidation to higher-valent oxides that serve as nanomineral repositories, redox platforms, and barriers for trace-element fluxes, thus facilitating long-term metal stability and cycling under energy-limited conditions. According to [45], biogenic magnetite nanoparticles can function as "biogeobatteries." These nanoparticles, which are made of mixed-valence iron, can store and release electrons during cycles of microbial oxidation and reduction. This process not only affects how microbes gain energy but also impacts the chemical changes of contaminants, nutrients, and minerals that microbes help create. Microbes are important in making both natural and man-made materials, which can have very different properties. They also play a role in developing biogeobatteries as a new type of energy source [6,46]. These diverse functions show that microbial nanomineralization is more than a biomarker. Before genetic data became available, microbes were described using pure cultures and the isolation of individual microbial species using particular electron donor-acceptor combinations under carefully regulated physicochemical conditions. With consequences for bioremediation, paleoenvironmental reconstructions, and subsurface habitability, it is a crucial geochemical engine that shapes elemental distributions, redox regimes, and the stability of mineral phases throughout time [6].

3. Mechanisms and Controls of Microbial Nanomineral Formation

The biology of bacteria, their surroundings, their cellular processes, and the kinds of minerals they interact with all influence how they produce minuscule minerals [18]. These elements operate in both natural and artificial systems, regardless of size. Whether microbes break down minerals, begin to form new ones, or cause them to settle out depends on a number of factors, including the environment's acidity or basicity (pH), the amount of electricity available (redox potential), temperature, the amount of salt present, and the types of chemicals microbes can use for energy [6, 24]. While variations in redox conditions alter the forms of metals like iron, manganese, sulfur, and uranium, which in turn affect how nanoparticles form, pH variations affect how readily metals dissolve or adhere to one another. According to recent studies, shifting redox conditions in soil and water can help bacteria alter metals through a process known as bioreduction and produce bursts of iron nanoparticles. Extracellular polymeric substances (EPS), organic acids, siderophores, and oxidation state-changing enzymes are examples of chemical compounds produced by bacteria that have a significant impact on the formation and growth of nanominerals at the microbial level. These materials adhere to metal ions, alter local chemical concentrations, and produce distinct chemical environments. In particular, EPS functions as a barrier that slows down the flow of materials and aids in the formation of nanoparticle structures. As demonstrated by naturally occurring iron and manganese oxide nanoparticles, this aids in maintaining the stability of nanoparticles and regulates their clumping behavior, crystal structure, and reactivity [27, 32, 37]. Microorganisms govern redox equilibrium, transport metals, and produce nanoparticles at the cellular and genetic levels. They employ mechanisms that remove metals from the cell as well as membrane-bound enzymes including oxidases and reductases. Biomineralization processes within the cell, such as the production of magnetite by magnetotactic bacteria or gold nanoparticles by lactic acid bacteria, rely on genetically regulated ion transporters and enzyme pathways that maintain optimal redox conditions. This contributes to the nanominerals' extremely consistent morphology. Additionally, the cell wall's functional groups act as locations for metal ions to adhere, resulting in the surface production of nanoparticles Reference [23]. The chemical composition of the cell wall and the metabolic activity of the cell determine this process. Mineralogy, pore connectivity, and hydrological flow control how microbial communities colonize substrates and where nanominerals develop up in porous subsurface systems (soils, sediments, aquifers, building materials). Sharp pH/Eh gradients produced by heterogeneous pore architectures stimulate localized biomineralization processes such Fe(III) reduction, sulfate reduction, or Mn(IV)/Mn(II) redox cycling, which result in the creation of highly reactive Fe-oxide, metal sulfide, and Mn-oxide nanoparticles [34, 44]. However, the size of the nanoparticles, the coatings (such as proteins and EPS) on their surfaces, their susceptibility to variations in oxidation and reduction conditions, and their interactions with dissolved organic matter all have an impact on the durability of biogenic nanominerals. Because biogenic nanoparticles are coated with living molecules and frequently have more structural flaws than non-biological ones, they are typically more reactive and transient. The ability of these nanoparticles to dissolve, reform, enlarge, or transform into more structured minerals can have an impact on how metals travel through the environment and how geochemical processes evolve over time. These factors environmental, biochemical, genetic, mineral-related, and stability-related all show that microbial nanomineral formation is not only a consequence of metabolism but rather an active, controlled, and responsive process that profoundly affects subterranean geochemistry.

4.Conclusion

This study demonstrates that microbial metabolism is a central force in the formation, transformation, and stabilization of biogenic nanominerals that shape subsurface geochemistry. By mediating redox reactions, altering local pH and saturation states, and producing organic ligands and extracellular matrices, microorganisms create highly reactive nanomineral phases that regulate metal mobility, nutrient availability, and redox gradients within soils, sediments, and aquifers. The diversity of microbial biomineralization pathways from biologically controlled intracellular mineral production to environmentally driven precipitation in extracellular microenvironments—reveals the complexity and breadth of microbial influence on mineral formation. The resulting nanominerals, including iron oxides, iron sulfides, manganese oxides, carbonates, and phosphates, possess distinct structural and chemical signatures that not only affect modern geochemical processes but also serve as important biosignatures in the geological record. Ultimately, understanding microbial nanomineral formation enhances our ability to interpret subsurface processes, develop improved bioremediation strategies, and harness microbial systems for sustainable nanomaterial synthesis.

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