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Silent Architects of the Earth: Microbial Agents in Rock Weathering and Biodiversity Shaping Dynamics -A Review

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ABSTRACT

Microorganisms play a vital role in shaping Earth's surface through their interactions with minerals and rocks. As key agents of rock weathering, they facilitate mineral dissolution, nutrient release, soil formation, and the cycling of essential elements that sustain terrestrial ecosystems. Microbial weathering occurs through several interconnected mechanisms, including organic and inorganic acid production, biofilm formation, siderophore-mediated metal mobilization, and symbiotic associations with plants and fungi. These processes alter mineral structures, enhance nutrient availability, and influence the transformation of geological materials within the Earth's critical zone. Environmental factors such as temperature, moisture, pH, nutrient availability, and rock composition strongly regulate the efficiency of microbial weathering and the composition of microbial communities. Beyond its geochemical significance, microbial weathering contributes to ecosystem productivity, biodiversity maintenance, and long-term carbon cycling. Recent advances in geomicrobiology have highlighted the importance of microbial-mineral interactions in carbon sequestration, ecosystem restoration, and sustainable environmental management. Emerging research also suggests that enhanced rock weathering supported by microbial activity may offer innovative approaches for climate change mitigation through increased carbon dioxide capture and storage. Understanding the mechanisms and ecological consequences of microbial weathering is therefore essential for advancing Earth system science and developing nature-based solutions to contemporary environmental challenges.

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1. Introduction

Microorganisms represent one of the most fundamental drivers of interactions between the biosphere and lithosphere. Through their metabolic activities, they mediate the release of essential elements from minerals, thereby sustaining life and regulating global biogeochemical cycles. Geological evidence suggests that microbes have influenced mineral evolution and weathering processes throughout Earth's history (Hazen et al., 2013). In contemporary environments, microbial communities dominate processes occurring within the Earth's critical zone, where rock, soil, water, and living organisms interact (Wild et al., 2022). Recent advances further demonstrate that microbial weathering contributes not only to geochemical cycling but also to carbon sequestration and ecosystem functioning through microbial weathering processes in the critical zone (Wild et al., 2022).

2. Microbial Mechanisms of Rock Weathering

Microbial rock weathering involves a complex interplay of chemical, physical, and biological processes. These mechanisms operate simultaneously and often synergistically, enhancing the overall efficiency of mineral transformation. Microbial weathering is a fundamental process that influences the breakdown and alteration of rocks, contributing significantly to soil formation and landscape development. Through their metabolic activities, microorganisms release nutrients locked within minerals, making them available for plant growth and ecosystem functioning. These processes regulate important

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biogeochemical cycles, including the cycling of carbon, nitrogen, phosphorus, and other essential elements. Microbial interactions with minerals also facilitate carbon sequestration and play a role in mitigating climate change through long-term carbon storage. Understanding these mechanisms provides valuable insights into ecosystem sustainability and Earth surface dynamics. Moreover, microbial weathering has practical applications in environmental remediation, sustainable agriculture, mine waste management, and the development of nature-based solutions for environmental challenges.

2.1. Acid Production

Acid production is one of the most significant mechanisms through which microorganisms promote mineral dissolution. Acidophilic bacteria such as *Acidithiobacillus ferrooxidans* oxidize sulfide minerals, generating sulfuric acid that accelerates weathering reactions (Adams and Pennington, 1995). In addition to inorganic acids, heterotrophic microorganisms produce a variety of organic acids, including oxalic, citric, gluconic, and acetic acids, which chelate metal ions and destabilize mineral structures (Adeleke et al., 2017). The dissolution of minerals by microbial metabolites has been widely documented in natural environments (Welch and Vandevivere, 1994).

2.2. Oxidation–Reduction Reactions

Redox reactions form the basis of microbial energy metabolism and play a crucial role in mineral transformation. Microorganisms utilize minerals as electron donors or acceptors, resulting in changes in oxidation states and mineral composition. Such redox-driven transformations are essential for understanding the mobility of trace metals and the formation of secondary mineral phases.

For instance, iron-oxidizing bacteria catalyse the oxidation of ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}): $Fe^{2+} \rightarrow Fe^{3+} + e^-$. Similarly, manganese-oxidizing bacteria promote the oxidation of manganese: $Mn^{2+} \rightarrow Mn^{4+} + 2e^-$. Conversely, under anaerobic conditions, certain microorganisms can reduce ferric iron according to the reaction: $Fe^{3+} + e^- \rightarrow Fe^{2+}$.

These microbial redox processes influence mineral stability, nutrient availability, and carbon cycling in soils and sediments (Zhang and Furman, 2021). Such redox-driven transformations are essential for understanding the mobility of trace metals, the formation of secondary mineral phases, and the overall functioning of biogeochemical cycles.

2.3. Biofilm Formation

Biofilms are structured microbial communities embedded in extracellular polymeric substances that adhere to mineral surfaces. These structures enhance weathering by concentrating microbial activity at specific sites and creating localized microenvironments characterized by altered pH and redox gradients. Biofilm associated polymers can significantly influence mineral dissolution rates and weathering efficiency (Welch and Vandevivere, 1994). Recent research further highlights the role of microbial communities in weathering processes within porous geological media (Welch and Vandevivere, 1994).

2.4. Siderophore Production

Siderophores are low molecular weight organic compounds produced by microorganisms under iron-limited conditions. They bind strongly to ferric iron (Fe^{3+}), enhancing its solubility and bioavailability. Beyond iron acquisition, siderophores contribute to mineral dissolution and weathering by mobilizing metal ions from mineral surfaces (Uroz et al., 2009). This process plays an important role in geochemical cycling and nutrient acquisition by microorganisms (Uroz et al., 2009).

2.5. Symbiotic Interactions

Symbiotic relationships between microorganisms and plants significantly enhance weathering processes. Mycorrhizal fungi extend the root system and increase the surface area available for mineral interaction. Biological interactions in the rhizosphere have long been recognized as important drivers of mineral dissolution and nutrient release (Banfield et al., 1999). Recent molecular studies have further revealed that weathered rocks host specialized microbial communities with unique metabolic capabilities, including lanthanide-dependent enzymes (Voutsinos et al., 2024).

3. Environmental Factors Influencing Microbial Weathering

Rock composition, nutrient availability, moisture, temperature, and pH collectively regulate microbial activity and weathering intensity. The influence of microbial communities on weathering varies according to environmental conditions and ecosystem characteristics (Uroz et al., 2009). Recent studies emphasize that complex microbial interactions significantly enhance weathering processes and ecosystem functioning (Uroz et al., 2009).

4. Geochemical Implications

Microbial rock weathering is a fundamental biogeochemical process that contributes to mineral dissolution, secondary mineral formation, elemental cycling, and long-term ecosystem development. Microorganisms, including bacteria, fungi, archaea, and lichens, accelerate weathering through a variety of mechanisms such as the production of organic acids, chelating compounds, extracellular polymeric substances (EPS), and redox active metabolites. These agents enhance the dissolution of primary minerals, thereby releasing essential nutrients and trace elements into the surrounding environment.

The dissolution of silicate minerals may be represented by the generalized reaction:

$$CaSiO_3 + 2CO_2 + 3H_2O \rightarrow Ca^{2+} + 2HCO_3^- + H_4SiO_4$$

where atmospheric or soil derived carbon dioxide reacts with silicate minerals, resulting in the release of dissolved cations and bicarbonate ions. Microbial activity significantly accelerates this process by increasing mineral surface reactivity and generating localized acidic microenvironments.

Microbial weathering also promotes the formation of secondary minerals such as clays, iron oxides, and carbonates. For example, dissolved calcium and magnesium released from mineral weathering may subsequently precipitate as carbonate minerals according to:

$$\begin{aligned} Ca^{2+} + CO_3^{2-} &\rightarrow CaCO_3(s) \\ Mg^{2+} + CO_3^{2-} &\rightarrow MgCO_3(s) \end{aligned}$$

These reactions contribute to the stabilization and long-term storage of carbon in geological reservoirs.

Beyond mineral transformation, microbial weathering plays a crucial role in regulating soil carbon dynamics and nutrient turnover. The release of phosphorus, potassium, iron, magnesium, and other micronutrients from mineral matrices supports plant productivity and microbial metabolism, thereby influencing terrestrial carbon cycling and ecosystem functioning. Weathering-driven nutrient availability can enhance biological productivity, increase organic matter inputs to soils, and affect rates of carbon sequestration and decomposition (Wild et al., 2022).

Recent studies have highlighted the potential of bio accelerated weathering of ultramafic rocks, such as peridotite and serpentinite, as a promising strategy for climate change mitigation. Ultramafic rocks are particularly rich in magnesium bearing minerals, which readily react with carbon dioxide to form stable carbonate minerals. A simplified carbonation reaction is:

$$Mg_2SiO_4 + 2CO_2 \rightarrow 2MgCO_3 + SiO_2$$

Microorganisms enhance these reactions by increasing mineral dissolution rates and facilitating carbonate precipitation. Consequently, bio-accelerated weathering can significantly increase carbon mineralization, transforming atmospheric CO_2 into thermodynamically stable carbonate phases that remain sequestered over geological timescales. This process represents a promising nature-based approach for long-term carbon dioxide removal and contributes to global efforts aimed at mitigating anthropogenic climate change (Wild et al., 2022).

Therefore, microbial rock weathering is increasingly recognized not only as a key driver of geochemical cycling and soil formation but also as an important component of emerging enhanced weathering technologies designed to promote sustainable carbon sequestration and ecosystem resilience.

5. Ecological Implications

Microbial weathering supports biodiversity by releasing essential nutrients, creating habitats, and strengthening ecosystem resilience. Weathering driven nutrient release in the rhizosphere promotes plant growth and microbial diversity (Banfield et al., 1999). Enhanced rock weathering has also been shown to improve ecosystem multifunctionality through strengthened microbial networks (Wild et al., 2022).

6. Applications of Microbial Rock Weathering

6.1. Bioremediation

Microorganisms play a pivotal role in environmental remediation by transforming, detoxifying, or removing pollutants from contaminated environments through their metabolic activities. In biomining and bioleaching applications, acidophilic microorganisms such as *Acidithiobacillus ferrooxidans* and *Leptospirillum ferrooxidans* facilitate the extraction of valuable metals from low-grade ores and mining wastes, thereby reducing reliance on energy-intensive conventional extraction methods and minimizing environmental impacts.

Recent advances in microbial consortia, metabolic engineering, and synthetic biology have further enhanced the efficiency, selectivity, and scalability of bioremediation technologies, expanding their applications in the treatment of metal-contaminated soils, industrial effluents, and acid mine drainage (Johnson, 2014; Rawlings and Johnson, 2007; Jerez, 2017).

6.2. Ecosystem Restoration

Microbial communities play a crucial role in restoring degraded ecosystems. Biological soil crust technologies enhance soil stability, water retention, nutrient cycling, and ecological recovery, particularly in karst and arid regions (Wild et al., 2022).

6.3. Agriculture

Microbial weathering plays a significant role in sustainable agriculture by enhancing soil fertility and increasing the availability of essential plant nutrients. Weathering microorganisms, including phosphate-solubilizing bacteria and fungi, release organic acids, protons, and chelating compounds that dissolve mineral-bound phosphorus, potassium, and micronutrients, making them more accessible for plant uptake. These microbial processes improve nutrient cycling, promote plant growth, and reduce dependence on synthetic chemical fertilizers, thereby supporting environmentally sustainable and resource-efficient agricultural practices (Rodríguez and Fraga, 1999; Uroz et al., 2009; Sharma et al., 2013).

6.4. Climate Change Mitigation

Enhanced rock weathering has emerged as a promising strategy for carbon dioxide removal. By accelerating natural weathering processes, microbes facilitate CO_2 sequestration while improving soil health (Wild et al., 2022). Such approaches offer significant potential for climate change mitigation and sustainable land management.

7. Challenges and Opportunities

Despite significant advances in geomicrobiology, many aspects of microbial rock weathering remain poorly understood because of the extraordinary diversity and complexity of microbial communities. Natural weathering environments contain highly diverse microbial assemblages that interact synergistically with minerals, making it challenging to distinguish the specific contributions of individual taxa to mineral dissolution and biogeochemical cycling. Recent molecular and metagenomic studies have revealed that microbial weathering is governed by complex community interactions rather than by single microbial species (Uroz et al., 2009; Wild et al., 2022).

Environmental heterogeneity presents another major challenge for understanding microbial weathering processes. Variations in temperature, moisture, pH, nutrient availability, and mineralogical composition strongly influence microbial community structure and metabolic activity, resulting in considerable spatial and temporal variability in weathering rates. Consequently, findings obtained under controlled laboratory conditions cannot always be extrapolated directly to natural ecosystems, emphasizing the importance of long-term field investigations and ecosystem-scale studies (Wild et al., 2022; Gadd, 2017).

The application of microbially enhanced rock weathering as a climate change mitigation strategy also faces practical limitations. Important uncertainties remain regarding large-scale deployment, economic feasibility, environmental sustainability, long-term carbon storage efficiency, and the ecological impacts of widespread rock amendment. Addressing these issues will require comprehensive life-cycle assessments, rigorous environmental monitoring, and multidisciplinary evaluation before enhanced weathering technologies can be implemented on a commercial scale (Beerling et al., 2020; Taylor et al., 2016).

At the same time, these challenges present substantial opportunities for future research and technological innovation. Advances in metagenomics, metabolomics, single-cell genomics, and high-resolution microscopic imaging are providing unprecedented insights into microbial–mineral interactions and the functional diversity of weathering microorganisms. Furthermore, integrating artificial intelligence, remote sensing, machine learning, and predictive Earth system modelling has the potential to improve the quantification of microbial weathering processes under changing environmental conditions. These interdisciplinary approaches may transform microbial weathering from a largely descriptive discipline into a predictive science capable of supporting ecosystem restoration, sustainable resource management, and climate change mitigation strategies (Wild et al., 2022; Gadd, 2017).

8. Research Gaps and Future Directions

Although substantial progress has been made in geomicrobiology, several important research gaps remain. Most existing studies have focused on laboratory experiments or isolated microbial species, whereas natural weathering is driven by complex multispecies communities interacting under variable environmental conditions. More ecosystem-scale investigations are therefore required to understand how microbial networks regulate mineral transformation in situ.

Another area requiring attention is the role of poorly understood microorganisms, particularly archaea and uncultivable bacteria, whose contributions to rock weathering remain largely unknown. Advances in molecular biology may reveal novel metabolic pathways that significantly influence mineral dissolution and nutrient cycling.

The interactions between microbial weathering and global climate change also deserve greater investigation. Rising temperatures, altered precipitation patterns, and increasing atmospheric carbon dioxide concentrations are likely to modify microbial community structure and weathering rates, yet these feedback mechanisms remain poorly quantified.

Future research should also focus on optimizing enhanced rock weathering technologies for carbon sequestration while minimizing ecological risks. Integrating geomicrobiology with environmental engineering, biotechnology, and Earth system modelling could facilitate the development of sustainable strategies for carbon removal, soil restoration, and resource management.

Collaborative research involving geologists, microbiologists, ecologists, environmental engineers, and climate scientists will be essential for translating fundamental discoveries into practical solutions. Such interdisciplinary efforts have the potential to expand the role of microbial weathering from a natural geological phenomenon to a key component of sustainable environmental management.

9. Conclusion

Microbial rock weathering is a fundamental Earth system process that links geological, biological, and climatic dynamics. Through the production of organic acids, redox transformations, biofilm formation, siderophore mediated metal mobilization, and symbiotic interactions, microorganisms actively participate in mineral dissolution and transformation (Adams and Pennington, 1995; Uroz et al., 2009). These processes contribute to nutrient cycling, soil formation, and the maintenance of ecosystem productivity.

Recent research has highlighted the broader significance of microbial weathering in carbon sequestration, ecosystem multifunctionality, and environmental restoration (Wild et al., 2022). Enhanced rock weathering technologies, supported by microbial activity, offer promising opportunities for long-term carbon dioxide removal and sustainable climate change mitigation (Wild et al., 2022).

As understanding of microbial-mineral interactions continues to advance, microorganisms are increasingly recognized as indispensable agents shaping Earth's surface environments. Their role as "silent architects" extends beyond rock transformation to influencing biodiversity, ecosystem resilience, and global biogeochemical cycles. Harnessing these natural processes may provide innovative solutions to some of the most pressing environmental challenges of the twenty first century.

CRediT statement

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The author declares that he has no known competing financial interests or personal relationships that could influence the work reported in this paper.

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During the preparation of the manuscript, the author used AI tools to improve the language and readability. After using this tool, the author reviewed the content and made changes whenever necessary. The author takes full responsibility for the contents of this publication.

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