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Exploring bioengineering strategies to enhance microbial-driven rock weathering for climate mitigation

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Abstract

Enhanced rock weathering has emerged as a promising strategy to accelerate carbon dioxide (CO_2) removal by promoting the dissolution of silicate minerals and the subsequent carbonation reactions. This review synthesizes the current knowledge on microbial contributions to enhanced rock weathering as a climate mitigation strategy. Microorganisms play pivotal roles in facilitating rock weathering processes through diverse physical, chemical, and biological mechanisms. Recent advancements in microbial ecology reveal insights into the diversity and functionality of microbial communities across different environments and substrates. Bioengineering approaches offer opportunities to optimize microbial activities and metabolic pathways, thereby increasing mineral dissolution rates. Future research directions include integrating omics approaches, advancing experimental techniques, and developing sustainable strategies for large-scale implementation. Harnessing the potential of microbially-driven rock weathering presents promising avenues for mitigating climate change and promoting sustainable development.

Keywords: Carbon sequestration, Climate mitigation, Microbial communities, Rock weathering

1. Introduction

Climate change represents one of the most pressing challenges of our time, with profound implications for ecosystems, societies, and economies worldwide. The accumulation of greenhouse gases, particularly carbon dioxide (CO_2), in the atmosphere is a primary driver of global warming and its associated climate disruptions. As efforts intensify to curb emissions and transition to renewable energy sources, the need for innovative strategies to actively remove CO_2 from the atmosphere is becoming increasingly urgent [1].

One such strategy gaining traction in scientific discourse is enhanced rock weathering—a natural process that has the potential to accelerate the removal of CO_2 from the atmosphere by facilitating the dissolution of silicate minerals and the subsequent carbonation reactions [2]. The Earth's surface is dominated by rocks and minerals, which serve as reservoirs for carbon over geological timescales. Weathering of silicate minerals, such as olivine, feldspar, and pyroxene, represents a natural process in which atmospheric CO_2 reacts with mineral surfaces, leading to the formation of carbonate minerals (e.g., calcite and magnesite) and the eventual removal of carbon from the atmosphere [3,4].

In recent years, researchers have been exploring ways to enhance natural weathering processes with the aim to accelerate carbon sequestration and thus mitigate climate change [1,5,6]. Enhanced rock weathering involves the application of finely ground minerals that react with CO_2 and water to form stable carbonate minerals. The efficacy of this approach lies in its potential to offset anthropogenic CO_2 emissions by transforming atmospheric carbon into long-term geological reservoirs [7]. While the concept of enhanced rock weathering holds promise, its practical implementation is hindered by several challenges, including the availability of suitable mineral resources, the vast energy required for the mining and grinding of rock dust, and the potential environmental impacts of large-scale deployment [3]. Moreover, the kinetics of mineral dissolution and carbonation reactions are influenced by various factors, including temperature, moisture, and the presence of catalytic agents [6].

Previous studies have highlighted the role of microbial communities in modulating rock weathering processes and enhancing carbon sequestration rates [8]. Microorganisms colonize mineral surfaces, where they excrete organic acids, enzymes, and other biochemical compounds that facilitate mineral dissolution and carbonate precipitation [9]. Additionally, microbial metabolism produces alkalinity, which buffers the pH of weathering solutions and promotes the formation of carbonate minerals [2]. Understanding these microbial drivers of enhanced rock weathering is essential for optimizing carbon sequestration strategies and developing sustainable solutions to mitigate climate change. The mechanisms by which microorganisms interact with mineral substrates can be harnessed through microbially-driven processes in order to enhance the efficiency and scalability of rock weathering-based carbon removal technologies [10].

The objectives of this review are to present the current knowledge on microbial contributions to enhanced rock weathering as a climate mitigation strategy and to reveal the diversity and activity of microbial communities in weathering environments, elucidate the mechanisms of microbial-mineral interactions, and discuss their implications for carbon sequestration strategies.

2. Section rock weathering and carbon sequestration

Rock weathering is a fundamental geological process that plays a crucial role in the global carbon cycle and the regulation of the Earth's climate. It involves the physical and chemical breakdown of rocks and minerals at or near the surface of the Earth that result from exposure to atmospheric agents, such as water, oxygen, and carbon dioxide [1,8]. Weathering can be classified into two main types: physical weathering, which involves the mechanical breakdown of rocks into smaller particles without altering their chemical composition, and chemical weathering, which entails the alteration of mineral structures through chemical reactions [7]. Chemical weathering processes are of particular interest in the context of carbon sequestration, as they involve the dissolution of silicate minerals and the subsequent uptake of carbon dioxide from the atmosphere. Silicate minerals such as olivine, feldspar, and pyroxene are abundant in the Earth's crust and serve as primary reservoirs for carbon over geological timescales [11]. When exposed to CO_2 and water, these minerals undergo a series of chemical reactions that result in the formation of carbonate minerals, such as calcite, magnesite, and dolomite. This process, known as carbonation, leads to the long-term storage of carbon in stable mineral forms [12], as shown in Figure 1.

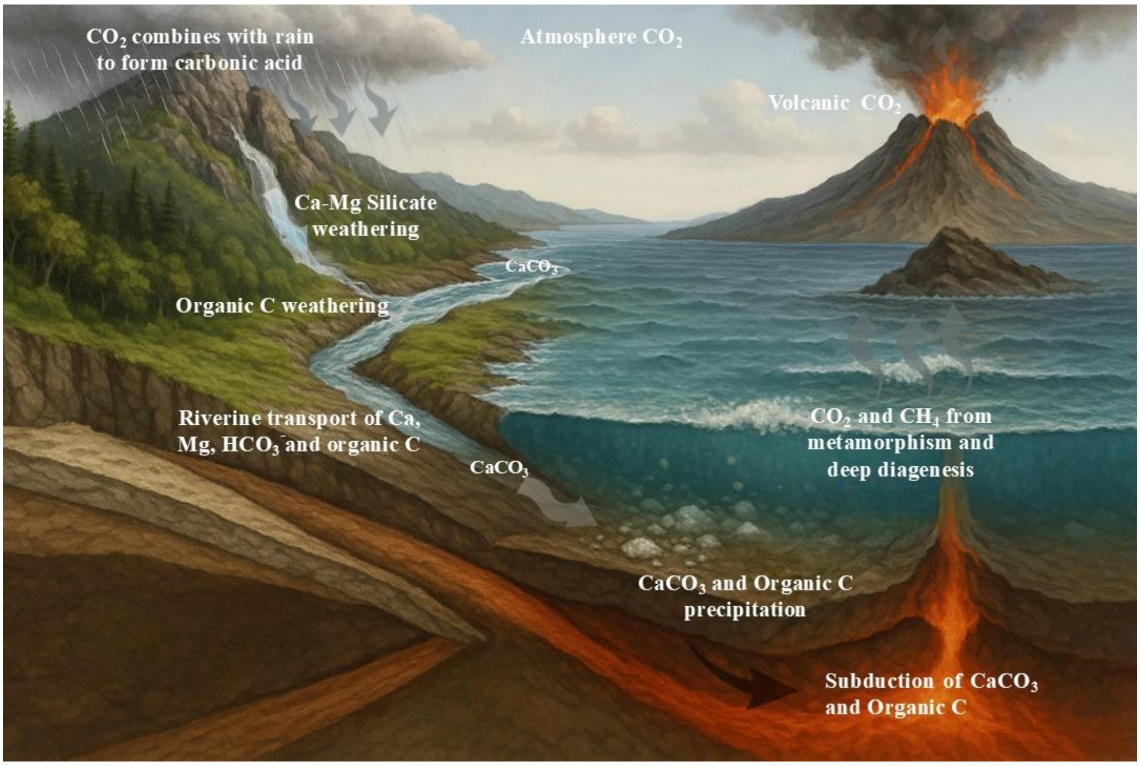

Figure 1 A simplified illustration of the surface-level components of the long-term carbon cycle, highlighting the transfer of carbon between rocks, the oceans, and the atmosphere.

The carbonation of silicate minerals represents a significant sink for atmospheric CO_2 and plays a key role in regulating the Earth's climate over geological timescales [3]. The weathering of silicate rocks consumes CO_2 through chemical reactions with mineral surfaces, effectively acting as a natural carbon capture and storage mechanism [13]. Rocks consist of minerals containing metals that undergo weathering processes over time. Silicate minerals, primarily composed of silica, are a product of the fusion and solidification of magma to form silicate rocks. An example of a chemical reaction in silicate minerals can be illustrated using wollastonite ($CaSiO_3$), as shown in the following equation [13,14].

$$CaSiO_3 + 2CO_2 + 3H_2O \rightarrow Ca^{2+} + 2HCO_3^- + Si(OH)_4 \quad (1)$$

CO_2 and water react to create carbonic acid, which slowly dissolves the silicate minerals and ultimately transforms into bicarbonate (HCO_3^-), which remains stable in surface waters. This dissolution releases Ca^{2+} and Mg^{2+}, marking the onset of chemical weathering as a crucial aspect of the long-term carbon cycle [15]. Rivers serve as snapshots of this long-term carbon cycle by transporting dissolved carbon and metals to the oceans. Here, dissolved carbon combines with the metals resulting from the mineral weathering to form calcium carbonate ($CaCO_3$), a process known as carbonate precipitation, as shown in equation 2 [14].

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O \quad (2)$$

Over time, calcium carbonate settles on the ocean floor, forming limestone, which is a rock containing carbon that once played a role in regulating the atmospheric climate. This geological process unfolds gradually, taking approximately a million years to transform CO_2 into solid rock on the ocean floor [16]. Silicate weathering rates are influenced by temperature, runoff, and the pace of physical erosion. Despite the expectation that warm and moist tropical climates would accelerate the weathering of silicate rocks, the actual rates are often quite sluggish due to the prevalence of dense, well-developed soils in lowland tropical regions [6]. These soils undergo minimal physical disruption and contain primary minerals that have already been transformed into weathering-resistant secondary minerals lacking essential soluble cations (such as Ca^{2+}, Mg^{2+}, Na^+, K^+) that are crucial for plant growth [17].

Basalts are a type of silicate rock that is particularly prone to weathering. Despite covering less than 5% of the continental area, they contribute approximately 35% of the current CO_2 consumption through silicate weathering [18]. Introducing freshly ground basalt into tropical soils could address the challenges related to mineral availability, unlocking the geochemical capacity of tropical regions to capture and store atmospheric CO_2. This process can be further facilitated by the release of organic acids and CO_2 during root respiration, as well as by the acidification of the rhizosphere [19]. Studies conducted at the catchment scale indicate that vegetation can enhance weathering rates by a factor of five or more compared to barren areas nearby. These factors render the warm, highly productive tropics into an ideal environment for employing enhanced weathering as a method of CO_2 capture [5,6,20].

Biological weathering is a prevalent geochemical phenomenon that involves the breakdown, deterioration, and disintegration of rocks and minerals in a process facilitated by living organisms. This process holds pivotal significance in the liberation of nutrients from rocks and is linked to overarching climate and environmental shifts on a global scale [19]. Microorganisms stand out as the primary agents of weathering, actively participating in the breakdown of rocks and the creation of soil. Additionally, microbes play a crucial role in supplying essential nutrients such as phosphorus, potassium, and silicon that support plant growth by influencing environmental factors such as pH and oxidation-reduction potential, thereby enhancing the solubilization of minerals [10,11].

3. Microbial diversity and activity in rock weathering

Microorganisms play a crucial role in facilitating rock weathering by interacting with mineral surfaces and catalyzing biogeochemical reactions. Weathering environments, including soils, sediments, and rock substrates, harbor diverse microbial communities adapted to survive and thrive under extreme conditions [10]. The diversity of microbial communities in weathering environments is influenced by various factors, including pH, temperature, moisture, mineralogy, and organic carbon availability [21,22].

Acidic environments, such as mine tailings and acid mine drainage sites, often support specialized acidophilic microbial communities adapted to low pH conditions. These acidophilic microorganisms play a crucial role in mineral dissolution and metal mobilization, contributing to the weathering of sulfide minerals and the release of metals into the environment [23]. Autotrophic microorganisms, including *Acidithiobacillus*, *Sulfolobus*, *Acidianus*, and *Leptospirillum*, are recognized for their role in the bioleaching process, which involves the dissolution of metals from sulfide ores [24]. Additionally, heterotrophic bacteria belonging to the genus Bacillus and fungi such as *Aspergillus* and *Penicillium*, also contribute to metal leaching. This contribution may occur through enzymatic reduction of metal compounds or the secretion of organic acids and phenolic derivatives into the culture medium, involving processes such as acidolysis, complexolysis, redoxolysis, and bioaccumulation [24,25].

In contrast, neutral to alkaline environments, such as carbonate-rich soils, host microbial communities adapted to circumneutral pH conditions. These communities are involved in the weathering of carbonate minerals and the precipitation of secondary carbonates, such as calcite and dolomite [26]. Ureolytic bacteria, such as *Sporosarcina pasteurii*, *Pseudomonas calcis*, *Bacillus* spp., and *P. denitrificans*, are commonly found in soil and are capable of inducing carbonate precipitation. Moreover, *Myxococcus*, typically inhabiting organic-rich soils with decaying matter, can precipitate calcium carbonate regardless of its metabolic state, though this process may result in various forms of calcite [27].

In dry ecosystems, the biological soil crust composed of lichens, mosses, and cyanobacteria serves as a crucial factor in facilitating microbial weathering of natural rock surfaces [9]. The collaboration of cryptogamic litho-biotic communities, encompassing cyanobacteria, lichens, green algae, fungi, and other heterotrophic organisms, has been identified as a driving force behind microbial weathering [28]. Exploring rock samples from the Tsauchab River in Namibia, Genderjahn et al. (2021) [29] discovered 28 isolates spanning three major phyla—Proteobacteria, Actinobacteria, and Firmicutes. These potentially active lithic microorganisms were observed to contribute to the weathering of limestone, quartz-rich shale, and quartz-rich sandstone under challenging climatic conditions. Moreover, microbial diversity in dryland rocks was investigated using paired culture-independent ribosomal ribonucleic acid (rRNA) 16S rRNA gene amplicon sequencing along with culture-dependent techniques (isolation of bacteria). The bacteria isolated from these rocks were found to participate in rock weathering. Chen et al. (2022) [30] examined the evolution of fungal, bacterial, and archaeal communities within carbonate weathering rinds as a function of time, as shown in Figure 2, providing significant insight into the carbonate rock weathering process. Actinobacteria (37.03%) and Proteobacteria (23.07%) were the two main bacterial phyla in carbonate rock rind communities. Notably, the relative abundance of Actinobacteria increased over time, whereas Proteobacteria showed a significant decrease as weathering progressed. Ascomycota (96.25%) dominated the fungal communities within carbonate rock rinds, yet their relative abundance decreased significantly over time. In archaeal communities, Euryarchaeota (44.28%) and Thaumarchaeota (38.49%) were the dominant phyla within carbonate rock rinds.

On the other hand, research on microbial ecology in ice sheets and glaciers, particularly in East Antarctica and the Western Himalayas, has unveiled a rich diversity of microorganisms. Sanyal et al. (2020) [31] documented 86 yeast strains in these extreme environments, with a notable percentage demonstrating the capacity to produce extracellular enzymes that enable the degradation of diverse compounds. The findings underscore the importance of comprehending the intricate microbial dynamics within these unique biomes, offering valuable insights into their ecological roles and potential applications in extreme environment.

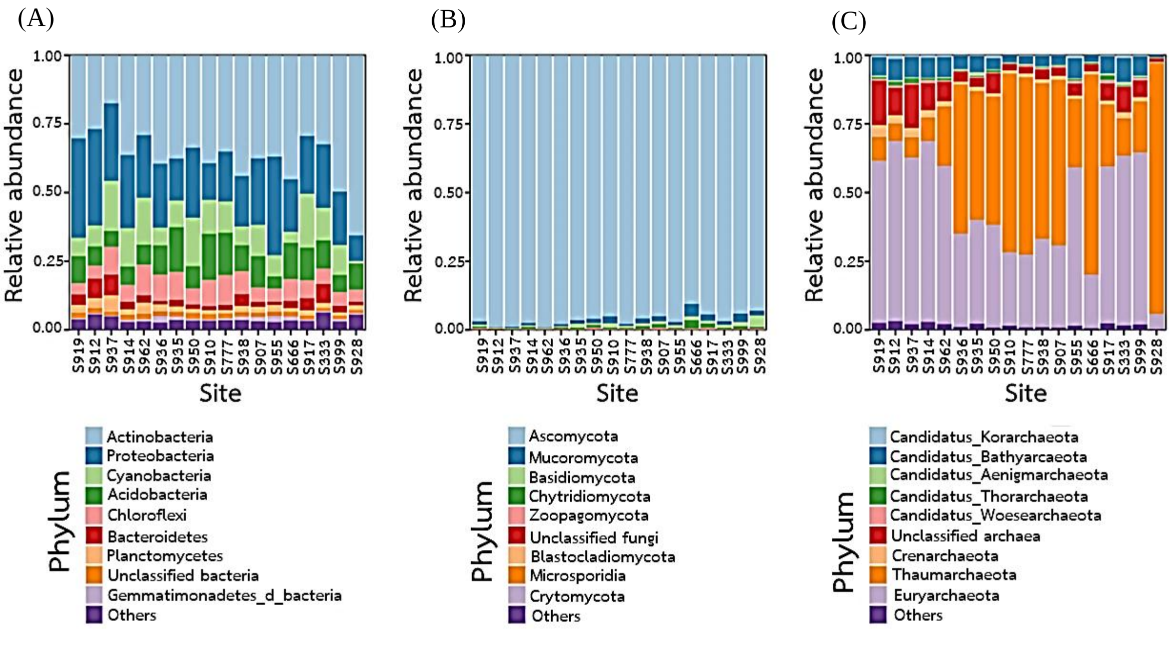

Figure 2 The proportional prevalence of various taxa at the phylum taxonomic level is depicted, with the top 10 relative abundances displayed for (A) Bacteria, (B) Fungi, and (C) Archaea. Adapted from Chen et al. (2022) [30], under the terms of the Creative Commons Attribution License (CC-BY 4.0).

Microorganisms participate in rock weathering processes through a variety of mechanisms, including physical, chemical, and biological pathways, as demonstrated in Figure 3. According to previously published works [9, 32], microbial carbonate rock weathering involves four primary mechanisms as follows:

1. Colonization of microorganisms on rock surfaces: Microorganisms proliferate on rock surfaces and within crevices, leading to bio-corrosion, erosion, and boring. This colonization expedites rock decomposition and weathering.

2. Microscopic mechanical degradation: Microbial colonies create intricate networks of borings, enhancing the surface area for chemical weathering and facilitating mechanical erosion. The breakdown of cementation structures within rock particles accelerates mineral decomposition.

3. Microbial water retention and acidification: This encompasses microbial water retention, the precipitation of organic acids secreted by microorganisms, and the release of CO_2 due to microbial respiration onto rock surfaces.

4. Influence of microbial metabolites: Microorganisms derive nutrients from rock surfaces, generate complex biochemical compounds, and facilitate the release of mineral elements during their growth and metabolic processes.

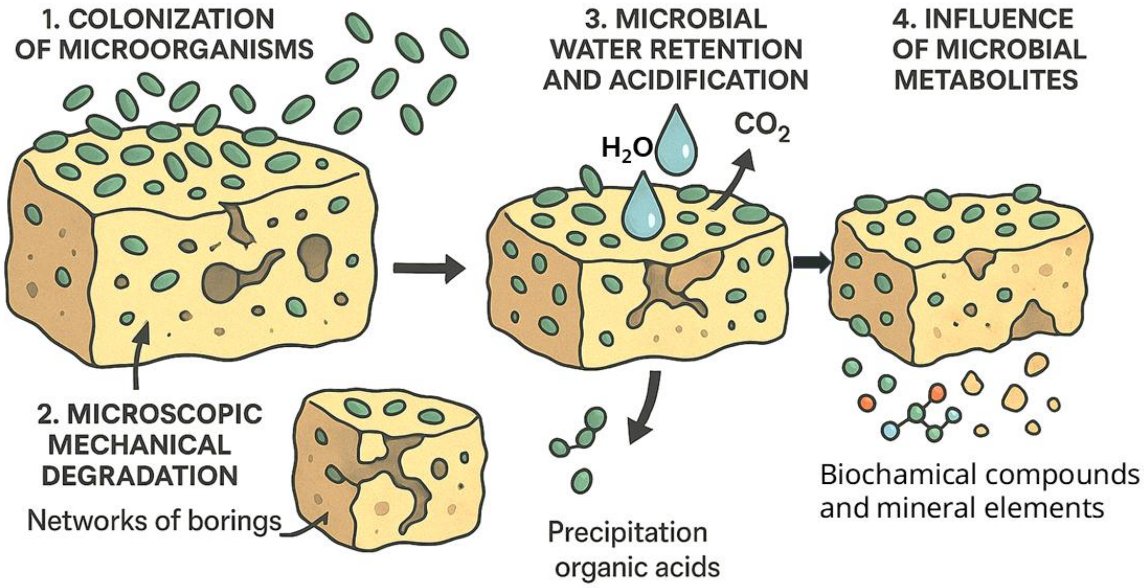

Figure 3 Biological rock weathering mechanism.

One of the key mechanisms by which microorganisms interact with minerals is through the production and excretion of organic acids such as citric acid, oxalic acid, and gluconic acid, which are among the most common metabolites produced by microorganisms during weathering reactions [33]. Siderophores and organic acids serve as the primary chelating agents. Siderophores, specifically, act as chelators for ferric ions, being secreted particularly under iron-deprived conditions. These non-ribosomal peptides are categorized into various types, including catecholate, hydroxamate, carboxylate, and mixed forms, which differ in their ability to dissolve iron silicates and other iron-rich minerals [21]. Additionally, extracellular enzymes such as phosphatases, proteases, and cellulases catalyze the hydrolysis of organic and inorganic substrates, releasing nutrients and facilitating microbial growth [34]. Microbial organic acids facilitate the weathering of silicate minerals and the uptake of carbon dioxide from the atmosphere by enhancing the solubility of minerals. Moreover, organic acids can serve as carbon sources for other microorganisms, further fueling microbial activity and carbon cycling in weathering environments [21].

Previous work [35] reported that arbuscular mycorrhizal (AM) fungi are essential partners for most terrestrial plant species, forming obligatory symbiotic relationships as shown in Figure 4. AM fungi colonize plant roots and extend into the soil, where they scavenge for vital nutrients such as phosphate, ammonium, potassium, and zinc, while depending on their host plants for carbon and energy supplies. Plants allocate significant amounts of carbon belowground to acquire nutrients and other essential resources. Particularly in agricultural contexts, the carbon released by roots constitutes a significant portion of total soil carbon inputs, thereby profoundly influencing ecosystem functioning. Plant roots release carbon dioxide and organic acids, altering soil conditions to facilitate the breakdown of silicate minerals. Research involving maize plants demonstrated that these fungi enhance plant growth and increase the overall carbon flow belowground [36].

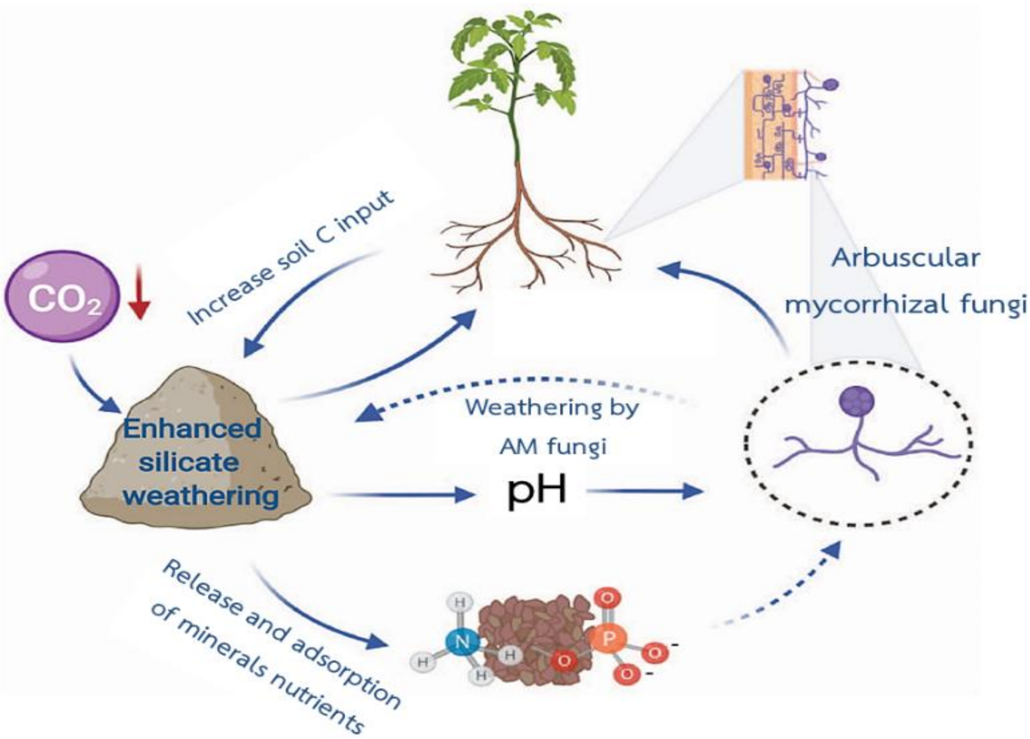

Figure 4 Diagram illustrating the expected interactions among silicate application, *arbuscular mycorrhizal (AM)* fungi, and weathering processes in agricultural soils. Blue arrows represent predicted positive impacts, while dashed arrows highlight important pathways that require further investigation. Adapted from Verbruggen et al. (2021) [35], under the terms of the Creative Commons Attribution License (CC-BY 4.0).

4. Bioengineering microbial communities for enhanced rock weathering

Bioengineering strategies aim to optimize microbial activities and metabolic pathways in order to increase the rates and extent of mineral dissolution and carbonate precipitation [26]. These approaches involve the selection, manipulation, and engineering of microbial taxa with specific traits related to weathering processes, as well as the modification of environmental conditions to promote microbial growth and activity [10]. Various recent studies offer valuable perspectives on the functional diversity and metabolic pathways that drive microbial-induced weathering mechanisms, necessitating distinct genes and enzymes. These genes regulate the expression of extracellular compounds, proteins, and enzymes, subsequently influencing the metabolic pathways essential for mineral dissolution, as shown in Table 1.

Table 1 Microbial genes/enzymes and mechanisms involved in enhanced rock weathering.

Microorganism	Enzyme/Gene	Mechanism/Pathway	Function	Reference
Bacillus subtilis	Oxydoreductase enzyme	Redox reaction	Transformation of serpentine and acid production	[37]
Burkholderia cenocepacia 71-2	*eno* gene	Acidification reaction	Phosphate solubilization	[38]
Enterobacter cloacae S71	*poxB, pta, and ackA*	Acidification reaction	Acid production	[39]
Priestia aryabhattai SK1-7	*maeA-1* gene and malic enzyme	Redox reaction	Potassium solubilization	[11]
Pseudomonas aeruginosa	*pvdS* gene	Chelation reaction	Siderophore production	[40]
Pseudomonas azotoformans F77	*gcd* and *adh* genes	Acidification and Biofilm Synthesis	Acid and biofilm production to enhance mineral weathering	[41]
Pseudomonas azotoformans F77	*potF, nuoF, and gdtO* genes	Acidification reaction	Acid Production	[42]
	potF, nuoF, and gdtO genes	-	Acid Tolerance	
Schizophyllum commune	Laccase enzyme	Chelation reaction	Siderophore production to enhance the dissolution of quartz phases and create a new secondary mineral phase	[43]

The molecular mechanisms underlying the interaction between *Bacillus subtilis* and serpentine were investigated by Liu et al. (2021) [37], who employed quantitative proteomics technology to demonstrate an increased secretion of oxidoreductases, which facilitated the transformation of serpentine and promoted the synthesis of organic acids, thus expediting the weathering of serpentine. Recent studies have highlighted the importance of microbial–mineral interactions in shaping carbon cycling dynamics in terrestrial environments, and the manipulation and optimization of mineral–microbe interactions were investigated by Yang et al. (2023) [11] through transcriptomic sequencing analysis. The results revealed that *Priestia aryabhattai* SK1-7 responds to mineral-induced reactive oxygen species (ROS) scavenging stress by upregulating the expression of antioxidant genes as a passive defense mechanism. Additionally, the overexpression of malic enzyme results in the secretion of pyruvate, which contributes to the generation of ROS and enhances the dissolution of feldspar, thereby releasing potassium, aluminum, and silicon into the surrounding medium. This study lays the groundwork for enhancing microbial mineral weathering capabilities through genetic manipulation in future applications.

Genetic engineering approaches offer another avenue for enhancing microbial weathering activity through the manipulation of metabolic pathways and enzymatic functions. Researchers are able to engineer microorganisms to overexpress genes encoding enzymes involved in mineral dissolution, such as phosphatases, proteases, and organic acid transporters. A phosphate-solubilizing bacterial strain, *Burkholderia cenocepacia* 71-2, was isolated through genetic analysis of 16S rRNA and *recA* genes by Liu et al. (2019) [38]. They investigated the phosphate-solubilizing mechanisms of strain 71-2, and mutants with reduced phosphate solubilization activity were generated using the EZ-Tn5 transposon. The results revealed a putative protein with 65.26% identity to enolase from *Escherichia coli*, indicating its likely role as an enolase enzyme. Complementation analysis confirmed that this gene, named *eno*, was responsible for phosphate solubilization in *B. cenocepacia* strain 71-2. This study represents the first identification of *eno* involvement in phosphate solubilization in *B. cenocepacia*. The genes *poxB*, *pta*, and *ackA* were found to have distinct effects on bacterial growth, mineral weathering activity, and acetate production during the weathering of biotite in *Enterobacter cloacae* S71. The research revealed that *E. cloacae* S71 primarily utilized acetate production. Notably, the *ackA* gene played a more significant role in bacterial growth, acetate production, and the release of elements from biotite. This investigation provided more detailed insights into the molecular mechanisms underlying the interactions between *E. cloacae* S71 and silicate minerals [39].

Wang et al. (2020) [41] studied the interactions between biotite and the highly effective mineral-weathering bacterium *Pseudomonas azotoformans* F77. The findings indicate that *gcd* and *adh* genes, related to gluconic acid metabolism and pilus formation, had distinct impacts on the mineral-weathering process and exerted crucial and differential effects on bacterial growth, gluconic acid production, and cell attachment to mineral surfaces. Moreover, Wang et al. (2021) [42] employed a multi-omics approach combining genomics, transcriptomics, and genetics to unravel the molecular mechanisms underlying mineral weathering activity and acid tolerance in *P. azotoformans* F77. Biotite was utilized as the silicate mineral for investigating mineral weathering. Analysis of the F77 genome revealed upregulation of the *tkt*, *tal*, and *gntP* genes associated with gluconic acid metabolism, flagellar assembly, pilus biosynthesis, as well as the acid tolerance-related genes (*potF*, *nuoF*, and *gdtO*) in the presence of biotite. Mutant strains lacking the key genes involved in gluconic acid metabolism and acid tolerance showed reduced mineral weathering activity and bacterial growth. Furthermore, iron (Fe) and aluminium (Al) concentrations increased significantly in the F77-inoculated medium, while pH values remained slightly acidic. The release of Al and Fe was notably diminished in certain mutant strains, indicating the importance of these genes in mineral weathering.

Lemare et al. (2022) [40] engineered a metabolic strain of *P. aeruginosa* in which iron no longer inhibited pyoverdine (siderophore) production. Remarkably, the optimized strain exhibited a sevenfold increase in pyoverdine production when exposed to asbestos waste, leading to significantly enhanced dissolution of magnesium and iron from the chrysotile fibers present in the waste. This novel mineral weathering process can thus aid in removing toxic iron from asbestos fibers.

In a study by Kirtzel et al. (2019) [43], the wood-rotting basidiomycete *Schizophyllum commune* was examined for its ability to degrade black slate, a carbon-rich rock. They explored biophysical weathering mechanisms, focusing on hyphal pressure and extracellular polymeric substances. Additionally, the fungus was found to secrete siderophores and organic acids, contributing to biochemical weathering in addition to enzymatic activity. While it was previously believed that laccase targeted the organic matter within black slate, leading to the release of metals, this study found that overexpression of laccase actually resulted in enhanced quartz dissolution, forming a new mineral phase.

5. Future directions and research challenges

The future of research on microbial-driven rock weathering presents a multifaceted landscape of challenges and opportunities. While bioengineering strategies offer promising avenues for enhancing microbial-driven rock weathering as a means of climate mitigation, significant challenges persist. Understanding metabolic pathways, genetic regulation, and microbial interactions is crucial for engineering microbial strains and consortia optimized for mineral weathering. Overcoming technical hurdles in genetic modification and ensuring the long-term stability of bioaugmented microbial communities are essential for effective CO_2 sequestration. Furthermore, scaling up these techniques for real-world applications requires cost-effective and scalable methods. Thus, future research should aim to optimize microbial consortia for enhanced mineral weathering. This will involve identifying synergistic interactions among various microbial species and engineering consortia with complementary metabolic pathways. Integrating omics approaches, molecular biology techniques, and geochemical analyses will facilitate the unraveling of the genetic, biochemical, and physiological basis of microbial weathering activities. In addition, understanding the genetic and metabolic diversity of these microbial communities will help with the design of tailored bioengineering strategies for enhanced mineral dissolution. Therefore, the diversity and functionality of microbial communities across different environments and substrates are essential for predicting carbon sequestration rates and designing targeted interventions.

In recent years, synthetic biology has gained increasing importance across various fields due to its wide range of applications [44]. It is a promising approach that enables scientists to precisely engineer microbial genomes, allowing for the customization of metabolic pathways to enhance mineral weathering capabilities. For instance, genes encoding enzymes involved in organic acid production or metal ion transport can be inserted, deleted, or modified to optimize microbial activity. Synthetic biology also facilitates the construction of modular genetic circuits that can be assembled and fine-tuned for the achievement of specific functions. This modular approach enables the design of microbial consortia with diverse metabolic functions that are tailored to target particular minerals or environmental conditions. The advent of genome editing tools such as clustered regularly interspaced short palindromic repeats (CRISPR) CRISPR-Cas9 has revolutionized synthetic biology by providing efficient and precise methods for modifying microbial genomes. These tools allow for targeted gene editing, pathway optimization, and the construction of complex genetic circuits, thereby accelerating the development of engineered microbial strains that can be used for mineral weathering [45]. Metagenomic sequencing has further enhanced researchers' understanding by allowing them to survey the genetic diversity of microbial communities in natural environments. Subsequently, researchers can pinpoint microbial species through the analysis of environmental Deoxyribonucleic acid (DNA) samples that possess desired traits, such as the ability to weather specific minerals or tolerate extreme conditions.

The advancement of experimental approaches, including laboratory, field, and computational modeling studies, is crucial for overcoming technical challenges and scaling up microbial-driven weathering strategies. Long-term monitoring and observational studies are therefore needed in order to track changes in microbial communities and carbon sequestration rates over time and across space. Moreover, developing sustainable and cost-effective strategies for large-scale implementation requires leveraging natural weathering processes, exploring alternative mineral substrates, and integrating microbial-driven weathering into sustainable land management practices. Carbon storage capacity and ecosystem resilience can be optimized by coupling microbial-driven weathering with regenerative agricultural practices, such as agroforestry and soil conservation [46]. By addressing these challenges and harnessing the potential of microbial-driven rock weathering, promising avenues for mitigating climate change and fostering sustainable development can be provided [47].

6. Summary

The study of microbial involvement in rock weathering offers promising climate mitigation strategies by enhancing carbon sequestration. Microorganisms employ various mechanisms, such as organic acid secretion and enzymatic activities, that present opportunities for optimizing weathering processes. Bioengineering advances enable tailored solutions to enhance weathering rates. However, challenges remain, including the need to better understand microbial diversity and metabolic potential, improve experimental techniques, and address concerns about scalability, resource availability, energy requirements, and environmental impacts. Therefore, integration of omics approaches and modeling efforts is crucial for informed decision-making and policy development in order to fully realize the potential of microbial-driven rock weathering.

7. Author Contributions (CRediT)

Noppadol Panchan: Conceptualization; Investigation; Data curation; Formal analysis; Visualization; Writing – original draft; Writing – review & editing.

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9. Conflict of Interest

The author declares no competing financial or personal interests that could have influenced this work.

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