

Article

Mechanistic Insights and Engineering Pathways of Enhanced Rock Weathering for Carbon Neutrality in Mountainous Mine Ecological Restoration

Yanzhao Yuan ^{1,2,3,4,5,6} , Fenghao Duan ^{1,*}, Yanjun Shen ¹, Bailei Shi ¹ and Chao Zheng ³¹ School of Intelligent Construction and Traffic Engineering, Henan University of Urban Construction, Pingdingshan 467036, China; yyz@huuc.edu.cn (Y.Y.)² Key Laboratory of Ecological Geology and Disaster Prevention, Ministry of Natural Resources, Xi'an 710054, China³ Technology Innovation Center for Geological Disaster Prevention and Ecological Restoration in Western China, Ministry of Natural Resources, Chengdu 610059, China⁴ College of Environmental Science and Engineering, Ocean University of China, Qingdao 266100, China⁵ Henan Key Laboratory of Engineering Materials and Hydraulic Structures, Zhengzhou University, Zhengzhou 450001, China⁶ Key Laboratory for Geo-Hazard in Loess Area, Ministry of Natural Resources, Xi'an Center of China Geological Survey, Xi'an 710119, China

* Correspondence: chddfh@163.com

Abstract

Ecological restoration of abandoned mountainous mines remains challenging because of complex geological conditions, severe substrate degradation, and long-term environmental impacts. Conventional restoration strategies primarily emphasize vegetation establishment and slope stabilization, while the potential contribution of carbon sequestration is often insufficiently considered. Enhanced Rock Weathering (ERW) has recently emerged as a promising negative-emission technology that accelerates the natural weathering of silicate minerals to remove atmospheric CO₂ while improving soil quality. This paper synthesizes current knowledge on ERW and proposes a conceptual framework for integrating this technology into the ecological restoration of abandoned mountainous mines. The framework comprises four complementary dimensions: (1) Physical Restoration, utilizing fragmented rock materials to improve slope stability and substrate structure; (2) Acid–Base Neutralization, exploiting alkaline silicate minerals to alleviate acid mine drainage (AMD) and regulate geochemical conditions; (3) Pedogenic Optimization, promoting soil formation, improving soil physicochemical properties, and facilitating CO₂ infiltration and mineral carbonation; and (4) Biological Synergy, enhancing plant–microbe–mineral interactions to accelerate weathering processes and support long-term ecosystem development. Drawing on existing evidence, we discuss how the use of on-site waste rock as reactive substrates may simultaneously reduce restoration-related carbon emissions, provide essential mineral nutrients (e.g., Ca, Mg, and K), and enhance carbon sequestration potential. Overall, this synthesis suggests that integrating ERW into abandoned mine restoration has the potential to simultaneously advance ecological rehabilitation and climate-change mitigation. The proposed framework provides a theoretical basis for future experimental validation, field-scale implementation, and the development of low-carbon strategies for sustainable mine restoration.



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conditions of the [Creative Commons](#)[Attribution \(CC BY\) license](#).**Keywords:** enhanced rock weathering; abandoned mine restoration; carbon sequestration; synergistic restoration; nature-based solutions

1. Introduction

In response to the increasing impacts of climate change, many countries have incorporated carbon mitigation into their long-term development strategies. In 2020, China announced its national commitment to peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060, commonly referred to as the “dual carbon goals [1–3].” These targets have accelerated the transition from fossil-fuel-dependent industries toward low-carbon development and are expected to result in the gradual closure of numerous mining operations [4–6]. Consequently, ecological restoration of abandoned mines has become an increasingly important component of both environmental remediation and climate-change mitigation.

Restoration is particularly challenging in mountainous mining regions, where steep topography, fragmented geological formations, difficult accessibility, and diverse pollution sources considerably increase engineering complexity [7,8]. According to incomplete statistics, abandoned mountainous mines account for more than 40% of all abandoned mines in China (Figure 1) and are mainly distributed across southwestern, northwestern, and northern China, particularly in Sichuan, Guizhou, Yunnan, Shaanxi, and Shanxi provinces. These sites include abandoned metal mines (e.g., copper, lead–zinc, mercury, and molybdenum), non-metallic mines (e.g., limestone and basalt), and coal mines. Owing to decades of intensive extraction and inadequate post-mining management, many of these sites have become environmentally degraded landscapes characterized by severe soil erosion, acid mine drainage (AMD), heavy-metal contamination, unstable slopes, and poor soil fertility [9–12]. Such conditions substantially increase both the technical difficulty and economic cost of ecological restoration.

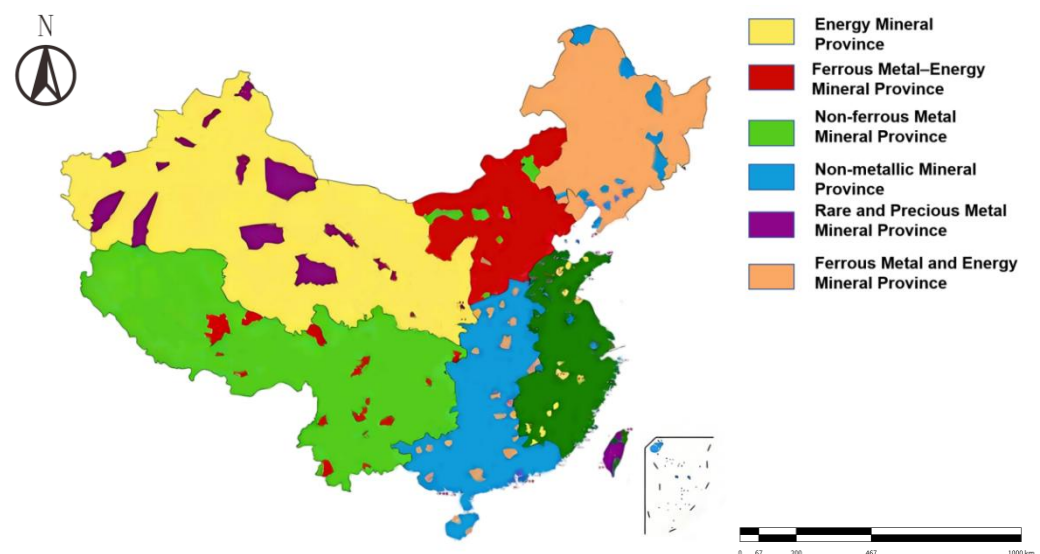


Figure 1. Distribution of Major Mineral Provinces in China, all maps in this article use the standard base map from the Ministry of Natural Resources of the PRC (map approval no. GS(2019)1822). Projection WGS84 (EPSG:4326). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article) date form [13] <https://geocloud.cgs.gov.cn/geological/> (accessed on 18 July 2026).

Restoration is particularly challenging in mountainous mining regions, where steep topography, fragmented geological formations, difficult accessibility, and diverse pollution sources considerably increase engineering complexity [14]. According to incomplete statistics, abandoned mountainous mines account for more than 40% of all abandoned mines in China (Figure 1) and are mainly distributed across southwestern, northwestern, and northern China, particularly in Sichuan, Guizhou, Yunnan, Shaanxi, and Shanxi

provinces. These sites include abandoned metal mines (e.g., copper, lead–zinc, mercury, and molybdenum), non-metallic mines (e.g., limestone and basalt), and coal mines [15]. Owing to decades of intensive extraction and inadequate post-mining management, many of these sites have become environmentally degraded landscapes characterized by severe soil erosion, acid mine drainage (AMD), heavy-metal contamination, unstable slopes, and poor soil fertility [16]. Such conditions substantially increase both the technical difficulty and economic cost of ecological restoration.

Current restoration strategies have achieved considerable progress in pollution control, land reclamation, soil reconstruction, vegetation establishment, and landscape rehabilitation. Nevertheless, these approaches primarily focus on restoring ecosystem functions and environmental quality, while the potential contribution of restoration activities to carbon sequestration and greenhouse-gas mitigation has received comparatively less attention [17]. Moreover, conventional restoration often relies on extensive earthworks, imported soil amendments, and externally sourced rock materials, all of which require substantial energy inputs and may generate considerable carbon emissions throughout extraction, processing, transportation, and field application (shown as Figure 2).

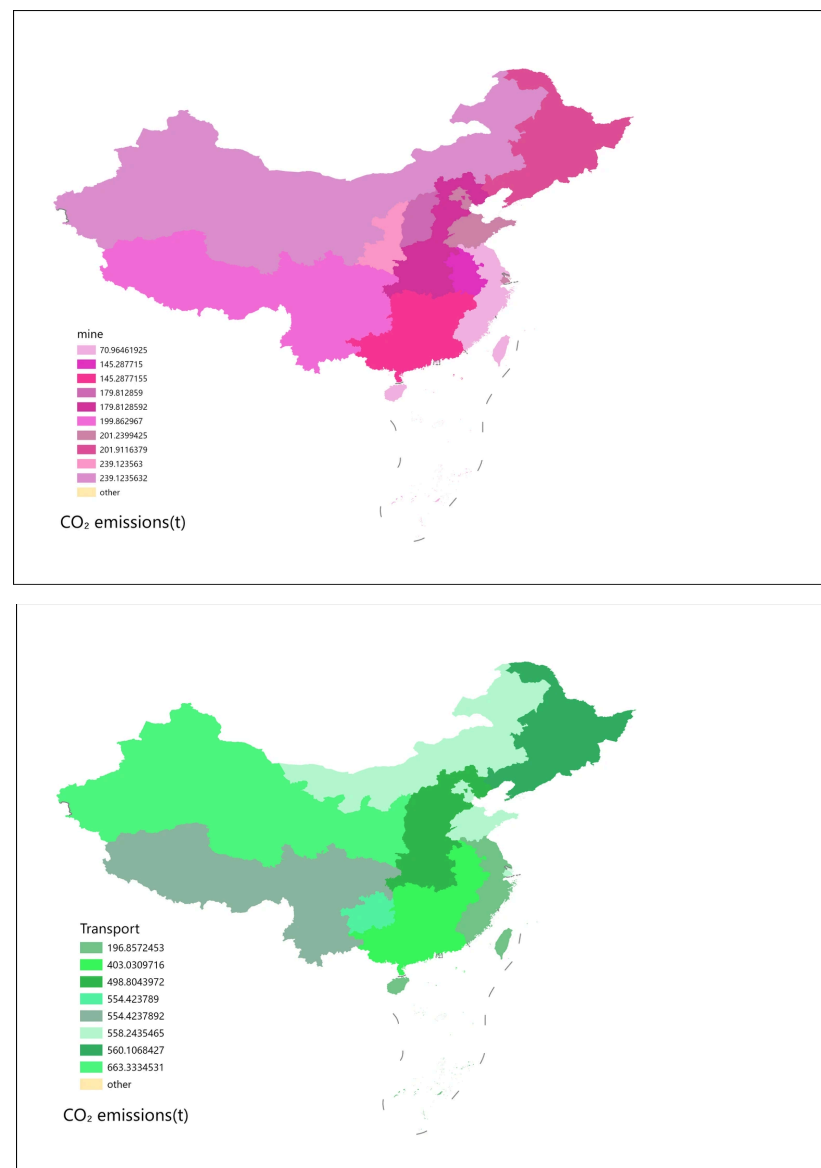


Figure 2. Cont.

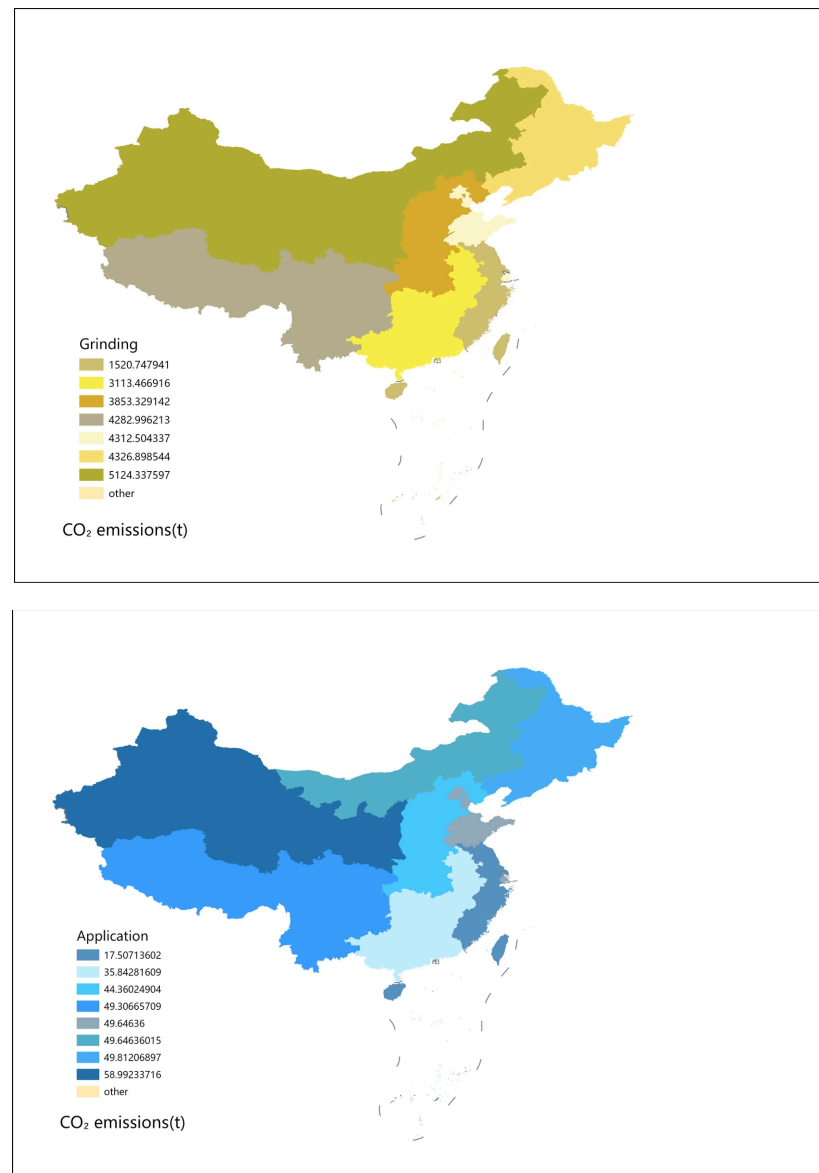


Figure 2. The proportion of CO₂ emissions in the process of basalt mining, grinding, transportation and application under different conditions, in % [18].

Enhanced Rock Weathering (ERW) has recently emerged as a promising negative-emission technology that accelerates the natural weathering of silicate minerals to capture atmospheric CO₂ while simultaneously improving soil quality [19,20]. Existing life-cycle assessments, including the example shown in Figure 2, indicate that the carbon footprint of ERW is strongly influenced by mining, grinding, transportation, and field application of rock materials. Although these estimates were developed for agricultural ERW systems, they provide an important reference for evaluating carbon emissions associated with large-scale rock-material utilization [21,22]. In the context of mountainous mine restoration, abundant waste rock, fragmented bedrock, and mine tailings are already available on site and can potentially serve as reactive weathering materials. Their direct utilization may substantially reduce or eliminate the need for additional quarrying and long-distance transportation, thereby lowering the life-cycle carbon emissions associated with ERW implementation.

Furthermore, mountainous mining environments are characterized by exposed fractured rock surfaces, pronounced diurnal temperature fluctuations, seasonal moisture avail-

ability, and active plant–microbe interactions, all of which may facilitate mineral weathering and carbonate formation [23,24]. These site-specific characteristics suggest that abandoned mountainous mines may provide favorable conditions for integrating ERW into ecological restoration. Against this background, incorporating enhanced rock weathering into mine rehabilitation represents a promising strategy to couple ecosystem recovery with long-term carbon sequestration. This review synthesizes current knowledge on the underlying mechanisms, implementation pathways, and research challenges of ERW in abandoned mountainous mines, and proposes a conceptual framework for developing low-carbon ecological restoration strategies.

2. Materials and Methods

2.1. Conceptual Framework for Integrating Enhanced Rock Weathering into Near-Natural Mine Restoration

Enhanced Rock weathering (ERW) represents a scientifically validated negative-emission technology that accelerates natural silicate mineral weathering to sequester atmospheric CO₂ through carbonate mineral formation, enabling permanent carbon storage in soils. This process involves chemical reactions between silicate minerals (e.g., feldspars, olivines) and CO₂ in aqueous environments, producing stable carbonates while simultaneously releasing essential nutrients (Ca²⁺, Mg²⁺, K⁺) that enhance soil fertility and ecosystem productivity (Figure 3) [25,26]. For abandoned mountainous mines suffering severe degradation—characterized by soil erosion, heavy metal contamination, and vegetation loss—ERW offers a dual solution: utilizing on-site waste rock for weathering eliminates the carbon emissions from importing external soil, enables in situ terrain reshaping, and achieves carbon fixation [27]. However, implementation faces critical challenges: high heavy metal concentrations inhibiting biological activity, complex geology hindering uniform weathering, and low silicate content in some substrates limiting CO₂ capture potential. Overcoming these requires an integrated approach combining geochemical pre-treatment (e.g., acid leaching for metal removal), strategic blending with high-silicate minerals, and climate-adaptive optimization [28]. This framework ensures ERW's environmental safety and scalability, positioning it as a carbon-negative cornerstone for sustainable mine rehabilitation that simultaneously addresses ecological degradation and global carbon mitigation.

Near-natural mine restoration through soil amendment has been increasingly recognized as a promising strategy for simultaneously promoting ecosystem recovery and carbon sequestration [29,30]. Rather than representing a standardized engineering methodology, the framework presented here synthesizes current knowledge on how locally available waste rock can be incorporated into ecological restoration to enhance rock weathering and long-term carbon storage.

Existing studies suggest that the effectiveness of this approach depends on the physicochemical characteristics of waste rock, including fracture density, mineral composition, weathering reactivity, and nutrient availability [31,32]. Characterization of these properties provides a basis for evaluating the suitability of different lithologies as restoration substrates and for selecting appropriate amendment strategies under site-specific conditions. Where necessary, microbial inoculants, including nitrogen-fixing bacteria and carbonate-forming microorganisms, have been reported to promote nutrient cycling, root colonization, and mineral weathering, thereby accelerating early-stage soil development.

As vegetation becomes established, interactions among plant roots, microorganisms, and fractured rock are considered key drivers of ecosystem evolution. Root penetration and microbial activity enhance biological weathering by increasing reactive mineral surface area and stimulating mineral dissolution. Carbon dioxide derived from root respiration and microbial metabolism can subsequently participate in carbonate precipitation or mineral

carbonation, contributing to long-term inorganic carbon sequestration (shown as Figure 3). Meanwhile, progressive soil formation improves water retention, nutrient availability, and substrate stability, creating increasingly favorable conditions for vegetation development.

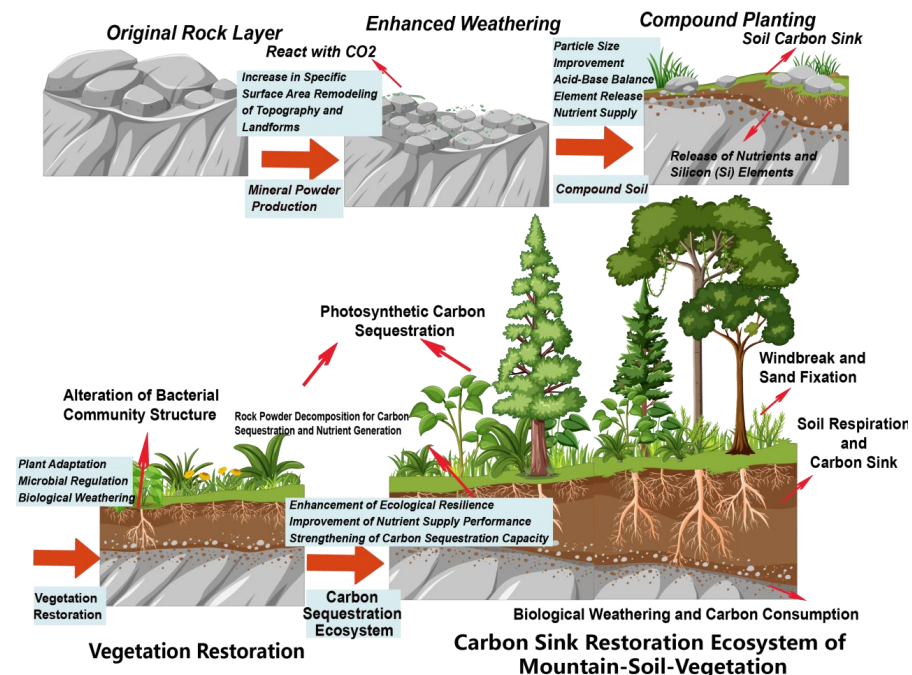


Figure 3. Conceptual diagram of the ecological restoration technology based on enhanced rock weathering.

Compared with conventional restoration approaches that frequently rely on imported soil and externally sourced amendments, the use of on-site waste rock has the potential to reduce material transportation, lower restoration-related carbon emissions, and improve resource utilization. Previous studies also indicate that restoration performance is influenced by local environmental conditions, including topography, hydrology, climatic variability, and contamination levels. Consequently, adaptive restoration measures—such as selecting metal-tolerant native plant species, optimizing water management, and integrating terrain information into restoration planning—may enhance ecosystem resilience under different site conditions [33].

Based on the available literature, these processes can be synthesized into a conceptual restoration pathway in which waste-rock weathering, soil formation, vegetation succession, microbial activity, and carbon sequestration interact through positive feedbacks. Rather than describing a universally applicable operational procedure, this framework provides an analytical perspective for understanding the coupled mechanisms linking enhanced rock weathering with ecological restoration in abandoned mountainous mines and identifies key processes that require further experimental validation and quantitative assessment.

2.2. Mechanisms of Enhanced Weathering in Mountainous Abandoned Mines

The ecological restoration of abandoned mountainous mines presents a formidable challenge, primarily centered on the establishment of resilient, self-regenerating geo-ecological systems. The fundamental prerequisite for such systemic resilience is the formation of a nutrient-rich and pedogenically active soil–rock interface [34]. Traditionally, restoration efforts have focused on immediate physical stabilization; however, the integration of ERW offers a transformative paradigm [35]. By synergizing with existing techniques—including land reclamation, geological hazard mitigation, and near-natural rehabilitation—ERW not only fortifies environmental stability but also significantly ampli-

fies terrestrial carbon sequestration. This holistic approach addresses the legacy of mining degradation by transforming inert mineral waste into a functional component of the global carbon cycle.

The conceptual framework for integrating ERW into abandoned mountainous mine restoration comprises four interconnected mechanisms that are synthesized from current knowledge rather than representing universally validated restoration outcomes (Figure 4). First, the physical restoration mechanism utilizes fragmented lithology and exposed rock surfaces to increase mineral reactive surface area, thereby potentially enhancing weathering rates while contributing to slope stabilization and the mitigation of geological hazards such as landslides and debris flows. Second, the acid–base neutralization mechanism is based on the release of alkaline cations during silicate mineral dissolution, which has been shown to alleviate soil acidity, reduce acid mine drainage (AMD), and promote the immobilization of certain heavy metals under appropriate hydrogeochemical conditions. Third, the pedogenic optimization mechanism involves the gradual development of soil structure through mineral weathering and organic matter accumulation, improving soil physicochemical properties and potentially facilitating CO₂ transport and mineral carbonation. Finally, the biological synergy mechanism highlights the interactions among plants, microorganisms, and minerals, whereby rhizosphere processes and microbial activity may accelerate weathering, improve nutrient cycling, and enhance ecosystem development. Collectively, available evidence suggests that these coupled mechanisms have the potential to promote both ecological restoration and long-term carbon sequestration in abandoned mountainous mines. However, the magnitude of these benefits is likely to depend on site-specific geological, climatic, and ecological conditions and therefore requires further quantitative field validation.

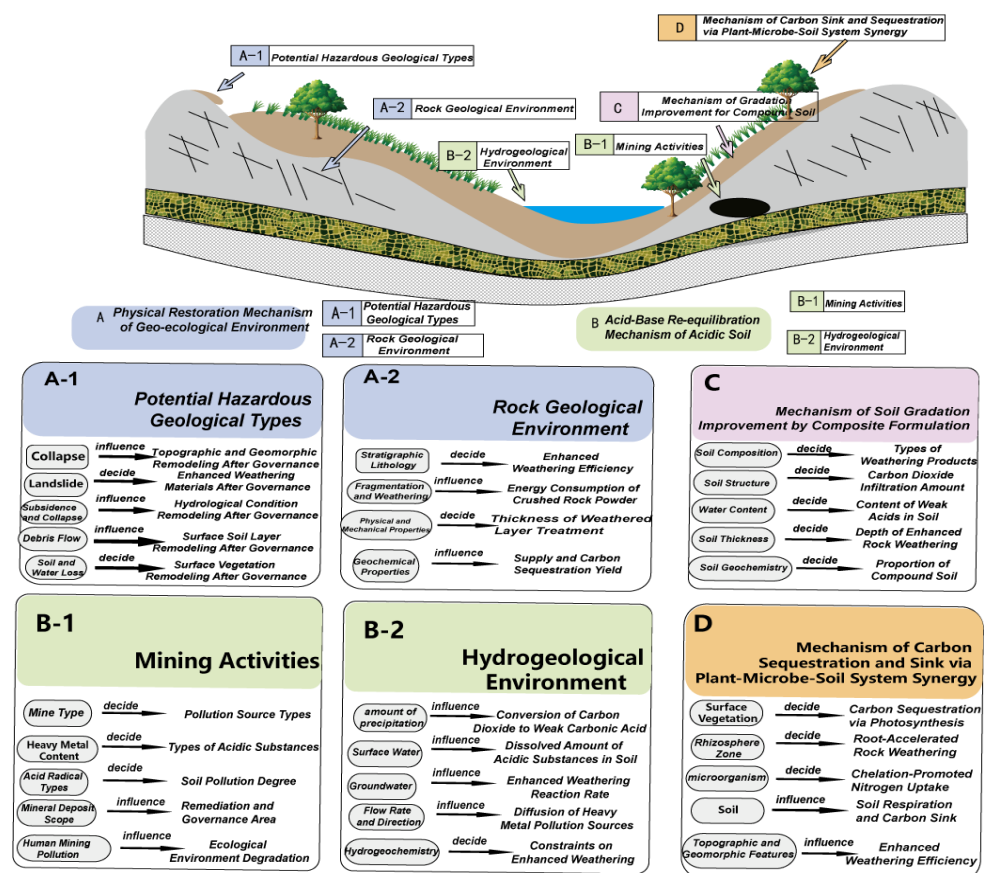


Figure 4. Schematic illustration of the ecological restoration mechanisms driven by enhanced rock weathering.

2.2.1. The Geological and Physical Restoration Mechanism

The geological structure of abandoned mines is marked by pronounced lithological heterogeneity, with different rock types subjected to irreversible anthropogenic disturbance during mining activities [36]. In particular, large-scale mechanical stripping in open-pit operations fragments ore bodies into loose surface gravels and pulverized materials, forming an artificial weathering layer that is structurally unstable and poorly cohesive. Surface rocks in mining areas are typically devoid of vegetation cover, which significantly weakens the natural self-repair capacity of the geological system and turns high-relief mining interfaces into focal zones of intense erosion. These conditions greatly increase the risk of slope instability, landslides, collapses, and debris flows, while simultaneously intensifying sediment transport and accelerating the decline of local biodiversity and ecosystem resilience.

Introducing enhanced rock weathering (ERW) into mine restoration offers a pathway to transform fragmented surface rocks from environmental liabilities into functional restoration substrates with carbon sequestration and nutrient-supply capacities [37]. Studies indicate that the reaction efficiency of ERW is controlled by the mineralogical composition and crystal structure of the rocks. Magnesium-rich olivine and calcium-rich calcite exhibit high CO₂ uptake potential, enabling rapid carbon fixation, whereas silicate minerals such as feldspar and mica release essential nutrients, including K, Ca, and Mg, through slower weathering processes that support vegetation recovery. By processing surface rock materials of different lithologies into highly reactive, carbon-sequestering rock powders, this approach provides both engineering measures for the treatment of fragmented rock masses during topographic reconstruction and a sustained source of materials for ERW. As a result, it enhances geomorphic stability while establishing a long-term rock-based carbon sink, fully unlocking the geochemical potential of mining waste and promoting the systematic ecological restoration of mined landscapes.

2.2.2. Acidic Soil Neutralization and Acid–Base Balance Mechanism

During the enhanced weathering process of surface rocks in mining areas, the dissolution behavior of different minerals and their chemical compositions strongly influence solution chemistry and pH evolution within developing soil systems. Silicate minerals such as olivine, pyroxene, wollastonite, serpentine, and anorthite commonly contain alkaline or alkaline-earth elements including Ca and Mg that may contribute to acid neutralization during weathering (the equations are presented as Equations (1)–(5)). Under favorable hydrogeochemical conditions, reactions between these minerals, CO₂, and water release alkaline cations (e.g., Ca²⁺ and Mg²⁺) together with bicarbonate, thereby increasing the buffering capacity of the restoration substrate. For example, olivine and serpentine generally exhibit relatively high weathering reactivity and may rapidly increase base saturation during the initial stages of restoration, whereas wollastonite and pyroxene can provide an additional Ca source that contributes to maintaining pH stability (Figure 5). However, weathering performance varies considerably with mineral particle size, moisture availability, temperature, and local pH conditions. In addition, minerals such as anorthite may release Al during dissolution, and some mine wastes may contain trace elements that could become mobilized under certain geochemical conditions. Consequently, the overall effects of mineral amendments depend on both mineralogical composition and site-specific environmental characteristics. In weakly to moderately acidic mine soils, appropriately selected mineral assemblages have the potential to improve pH and base saturation, although these responses require site-specific evaluation.



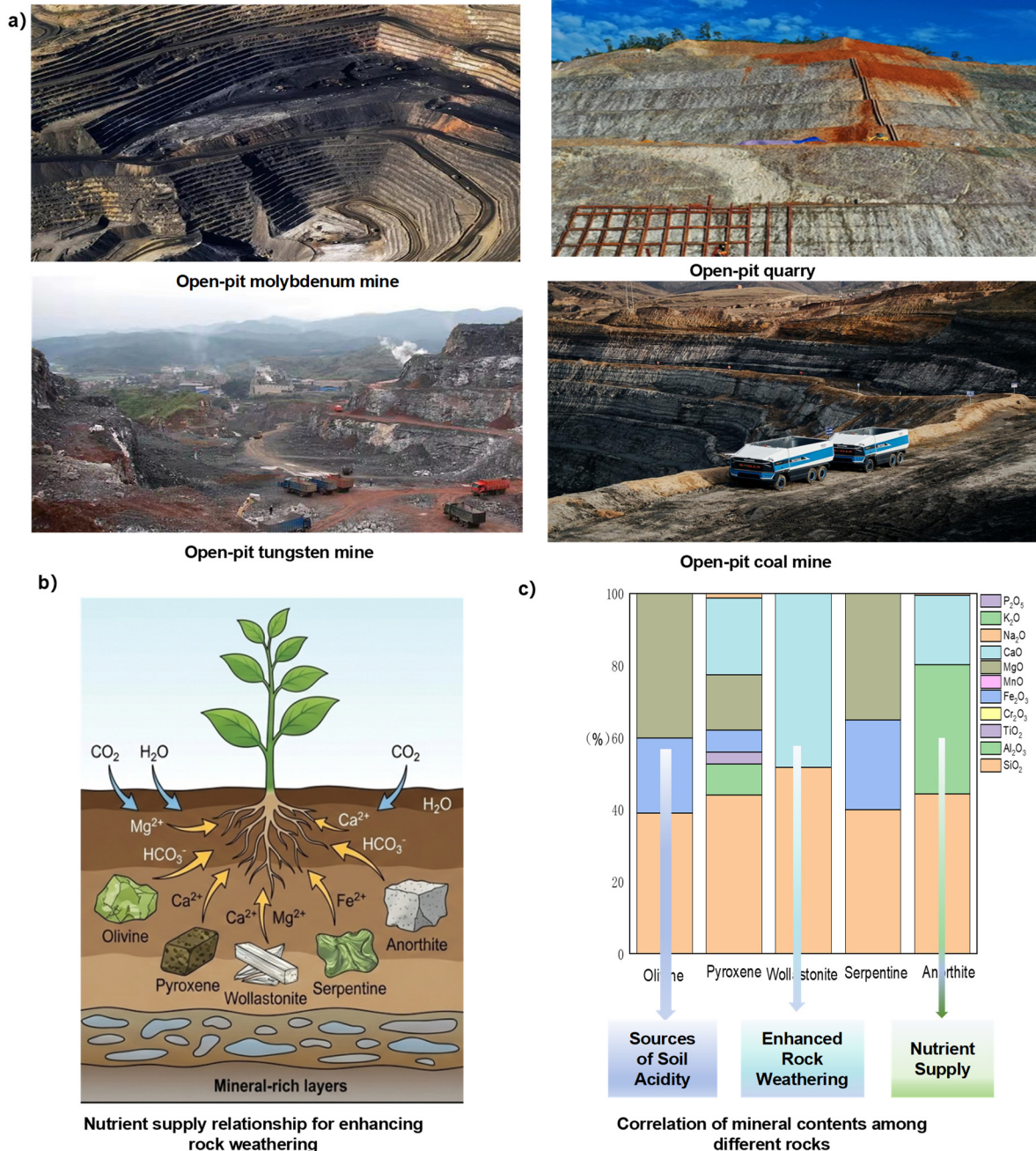
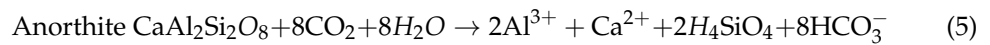
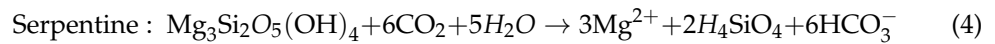
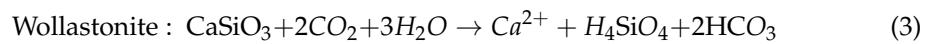
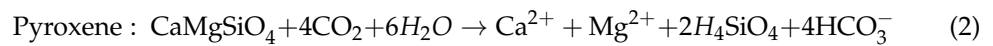


Figure 5. Chemical Composition and Related Characteristics of Surface Rocks in Major Mining Areas: (a) Different Types of Mine Slopes; (b) Acidic Soil Neutralization and Acid–Base Balance Mechanism; (c) Correlation of Mineral Contents Among Different Rocks. (Data for (c) from <https://webmineral.com> (accessed on 18 July 2026); all data based on ideal or average mineral compositions from webmineral.com. Olivine: typical forsterite–fayalite series compositions; Pyroxene: augite (common end-member, with group compositional variations); Serpentine: antigorite. Minor variations in actual samples may occur due to geological origin and trace impurities) [38].

In regulating acid–base balance, both mineral weathering kinetics and dissolution sequences are critical considerations for ERW implementation. Highly reactive Mg- and Ca-bearing silicate minerals generally dissolve more rapidly and can provide an early source of alkalinity, whereas quartz-rich materials weather slowly and contribute little to short-term pH regulation. Calcium silicates and carbonate-bearing minerals may provide more sustained buffering but can also exhibit substantial variability depending on particle size and environmental conditions. Therefore, acidic mine sites may benefit from the preferential use of reactive minerals such as olivine, serpentine, and wollastonite, while carefully controlling grain size distribution and combining minerals with different dissolution rates to avoid excessive short-term chemical fluctuations. Conversely, in alkaline environments or areas susceptible to excessive alkalization, reducing the proportion of highly reactive alkaline minerals and incorporating slower-weathering feldspar or relatively inert siliceous materials may help maintain geochemical stability. Additional management measures, including organic matter amendments and moisture regulation, can further improve restoration performance [39]. Overall, optimizing mineral selection, weathering rates, and amendment proportions should consider not only the potential benefits for acid neutralization and nutrient supply but also possible environmental risks associated with trace-element release, excessive alkalization, and heterogeneous weathering behavior under different field conditions.

2.2.3. Composite Soil Reconstruction and Improvement Mechanism

The application of finely ground rock powders within the ERW framework has been widely investigated as a strategy for improving soil fertility in degraded mining areas by accelerating mineral nutrient release. Previous studies have demonstrated that weathering of reactive silicate minerals can provide essential nutrients at rates exceeding those associated with natural soil development; however, the magnitude and persistence of nutrient release depend strongly on mineral composition, particle size distribution, climatic conditions, and soil properties. The soil chemical data summarized in Table 1, derived from previously reported experiments, illustrate the potential nutrient-enhancement effects of rock powder incorporation after 10 months of application. In both sandy and clay soils, amendments with Phonolite, Diabase, and Granite increased the concentrations of several macronutrients. For example, phosphorus (P) concentrations in clay soils increased from $23.9 \pm 1.11 \text{ mg kg}^{-1}$ in the control to $31.8 \pm 8.18 \text{ mg kg}^{-1}$ and $31.1 \pm 2.25 \text{ mg kg}^{-1}$ following Phonolite and Granite treatments, respectively. Similarly, potassium (K) and magnesium (Mg) exhibited increasing trends, particularly in sandy soils, where Granite application increased Mg concentration from 4.27 ± 0.25 to $5.04 \pm 0.23 \text{ mg kg}^{-1}$. These observations are consistent with previous studies indicating that ERW-derived mineral substrates can enhance the availability of Ca^{2+} , Mg^{2+} , and K^{+} , thereby improving cation exchange capacity (CEC) and supporting vegetation establishment in nutrient-deficient mine soils in Table 2.

Table 1. Application effectiveness of different types of ores in the ecological restoration of abandoned mines [40].

Rock Type	Carbon Sequestration Effect (CO ₂ Absorption Efficiency)	Providing Plant Nutrient Elements	Main Silicon-Containing Compounds	Silicon Content (Approx.)	Form of Silicon-Containing Compounds
Quartz	Low (slow weathering rate)	No significant contribution	Silicon dioxide (SiO ₂)	Close to 100%	Crystalline form, silicon-oxygen tetrahedral structure

Table 1. *Cont.*

Rock Type	Carbon Sequestration Effect (CO ₂ Absorption Efficiency)	Providing Plant Nutrient Elements	Main Silicon-Containing Compounds	Silicon Content (Approx.)	Form of Silicon-Containing Compounds
Feldspar	Moderate (can release K, Ca, etc.)	K, Ca, Na, etc.	Silicate	About 65–75%	Silicon-oxygen tetrahedral structure, forming complex aluminosilicates
Mica	Moderate (contains K, Na)	K, Na, Mg	Silicate	About 30–40%	Silicon-oxygen tetrahedral structure, forming phyllosilicates
Calcite	High (rich in Ca element)	Ca, Mg	Mainly calcium carbonate (CaCO ₃)	Relatively low	Non-silicate mineral
Metal Ore	Moderate (depending on mineral type)	Heavy metals such as Fe, Cu	Silicon content varies greatly	Depending on specific ore	Silicate, oxide or other forms
Olivine	High (rich in Mg element)	Ca, Mg, Fe, etc.	Silicate	About 40–50%	Silicon-oxygen tetrahedral structure, forming nesosilicates
Wollastonite	Moderate (contains silicon element)	Ca, Mg, Fe	Calcium silicate	About 50%	Silicon-oxygen tetrahedral structure, forming inosilicat

Table 2. Characterization of chemical and physical properties of soils collected prior to the experiment [40].

Chemical and Physical Properties	Sandy Soil	Clay Soil
pH (CaCl ₂)	5.09	5.87
SOM (g dm ⁻³)	11.0	33.9
P (mg dm ⁻³)	16.4	49.3
S (mg dm ⁻³)	9.80	12.6
K (mmol _c dm ⁻³)	2.40	5.45
Ca (mmol _c dm ⁻³)	19.7	73.7
Mg (mmol _c dm ⁻³)	8.50	40.3
Al (mmol _c dm ⁻³)	<0.1	<0.1
H + Al (mmol _c dm ⁻³)	23.2	24.7
SB (mmol _c dm ⁻³)	30.6	119
CEC (mmol _c dm ⁻³)	53.8	144
V (%)	57.0	83.0
m (%)	0.00	0.00
B (mg dm ⁻³)	0.30	0.60
Cu (mg dm ⁻³)	1.20	4.80
Fe (mg dm ⁻³)	30.6	25.4
Mn (mg dm ⁻³)	16.5	35.9
Zn (mg dm ⁻³)	2.70	6.30
Sandy (g kg ⁻¹)	820	334
Silt (g kg ⁻¹)	30	256
Clay (g kg ⁻¹)	150	410

To quantitatively evaluate the effectiveness of ERW implementation in mining areas, an integrated assessment framework is required to compare predicted weathering performance with field observations. In this context, statistical evaluation metrics provide essential tools for determining the reliability of ERW prediction models and restoration assessments. The coefficient of determination (R^2) (Equation (6)) is introduced to quantify the agreement between predicted and observed values of key ERW indicators, such as mineral dissolution

rates, released nutrient concentrations, CO₂ removal capacity, or soil quality improvement parameters. A higher R² value indicates stronger consistency between model simulations and field measurements, reflecting improved predictive capability.

$$R^2 = \frac{\sum_{i=1}^n (x(i) - \bar{x})(y(i) - \bar{y})}{\sqrt{\sum_{i=1}^n (x(i) - \bar{x})^2} \sqrt{\sum_{i=1}^n (y(i) - \bar{y})^2}} \quad (6)$$

However, R² alone cannot describe prediction errors; therefore, the root mean square error (RMSE) (Equation (7)) is applied to quantify the absolute deviation between predicted and observed ERW performance indicators. Lower RMSE values indicate improved model accuracy and reduced uncertainty in estimating weathering efficiency, nutrient release, or carbon sequestration potential.

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (x(i) - y(i))^2}{n}} \quad (7)$$

To further compare ERW performance among different mine sites, mineral types, or restoration scenarios with different measurement scales, the relative root mean square error (rRMSE) (Equation (8)) is introduced. By normalizing RMSE against observed values, rRMSE enables comparative evaluation of model performance across different datasets and provides a standardized criterion for selecting suitable mineral materials and restoration strategies.

$$rRMSE = \frac{RMSE}{\bar{x}} \quad (8)$$

where x(i) and y(i) are the observed and predicted values, respectively; and denote the average observed and predicted values, respectively; and n is the number of samples.

Despite the mineral advantages of rock powders, a holistic approach to soil reconstruction must also address the limited supply of organic components and the physical constraints associated with fine-grained materials. While ERW provides inorganic nutrients, it may not independently supply sufficient soil organic matter (SOM) to sustain microbial activity and long-term nutrient cycling. Therefore, synergistic incorporation of organic fertilizers or bio-based amendments may be necessary to establish a functional soil–plant–microbe system. Furthermore, reconstructed soil structure requires careful grain-size optimization. Excessive accumulation of fine particles may promote dense carbonate crust formation or low-permeability layers, restricting gas exchange and water infiltration. Because ERW efficiency depends on the coupled availability of reactive mineral surfaces, CO₂, and moisture, inappropriate particle-size distributions may reduce weathering rates despite increasing mineral surface area (Figure 6). Therefore, balancing fine reactive minerals with coarse structural aggregates is essential to maintain suitable porosity, permeability, and gas diffusion conditions, thereby improving the stability and long-term carbon sequestration potential of ERW-based restoration systems.

Three mechanisms govern ERW-enhanced soil formation [41]: ① Grain-size gradation control—Excessively fine-grained soils form dense carbonate crusts that hinder gas exchange and water infiltration, while overly coarse soils reduce structural stability and promote erosion. Optimized gradation balances porosity, permeability, and stability. ② Nutrient mapping mechanism—The nutrient composition of blended rock powders can be tailored to match plant requirements. The accelerated weathering of such mineral mixtures releases nutrients up to 100 times faster than natural weathering, forming fertile soils conducive to vegetation growth. ③ Carbonation-compaction mechanism—Fine particles (e.g., quartz, feldspar) fill soil pores, improving aggregation and water retention. Layered combinations

of easily weathered and resistant rock types maintain long-term structural stability and uniform carbon sequestration efficiency (Figure 7).

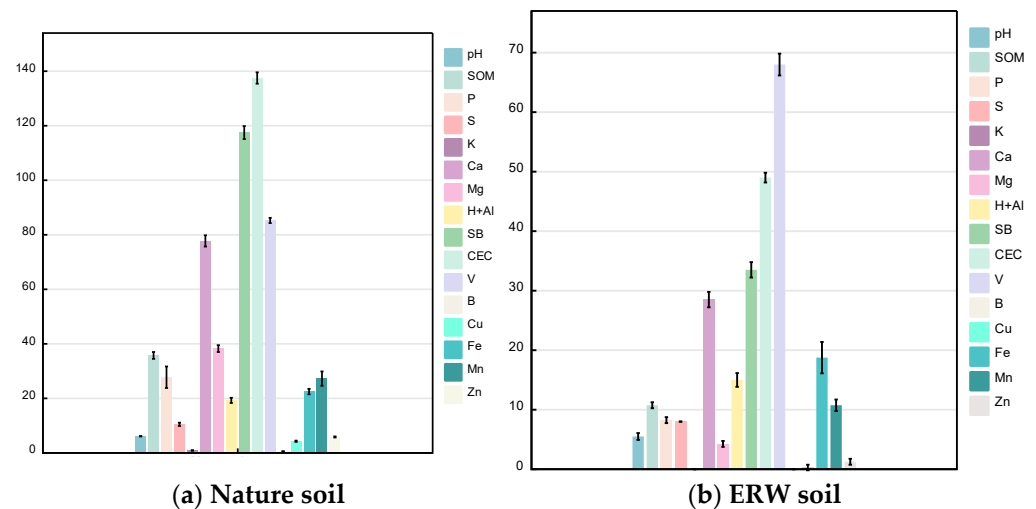


Figure 6. Soil chemical properties after 10 months of rock powders for each soil type [41].

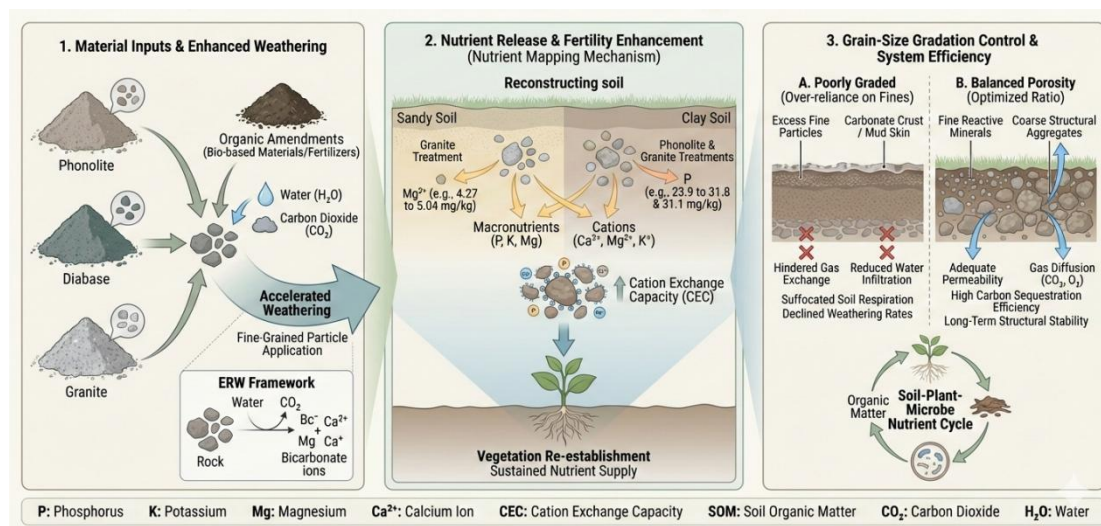


Figure 7. Composite Soil Reconstruction and Improvement Mechanism Plant–Microbe–Soil Synergistic Carbon Sequestration Mechanism.

The restoration of degraded mine ecosystems transcends mere revegetation; its ultimate objective is to cultivate a self-sustaining plant–microbe–soil continuum capable of long-term carbon sequestration. In this framework, Enhanced Rock Weathering (ERW) serves as a catalytic engine, driving the carbon cycle through integrated biophysical and biochemical pathways. Firstly, the structural heterogeneity of fractured bedrock and the application of rock powders compensate for the scarcity of topsoil, expanding the rhizosphere's physical footprint [42]. Our data reveals that root-driven mineral dissolution is significantly amplified by the secretion of organic acids and enzymes, which not only facilitates nutrient mobilization but also accelerates the conversion of atmospheric CO₂ into stable pedogenic carbonates. Secondly, the microbial community serves as a biological accelerator for mineral weathering [43]. As shown in the taxonomic profiles (Figure 1), the shift in dominant phyla such as Actinobacteriota and Ascomycota under rock powder treatment indicates a specialized microbial assembly adapted to mineral-rich environments. These microbes enhance weathering rates by several orders of magnitude compared to

abiotic processes through the production of chelating agents and organic acids, which effectively modulate soil pH and sequester heavy metals. Finally, the Pearson correlation analysis (Figure 8) underscores a robust synergy: improvements in soil physicochemical properties (e.g., CEC, SB, and pH) are positively coupled with plant biomass (PB) and nutrient uptake (KU). This creates a “positive feedback loop” where enhanced plant photosynthesis supplies carbon-rich exudates to microbes, which in turn accelerate rock weathering, thereby replenishing the soil nutrient pool and reinforcing the system’s overall carbon-sink capacity.

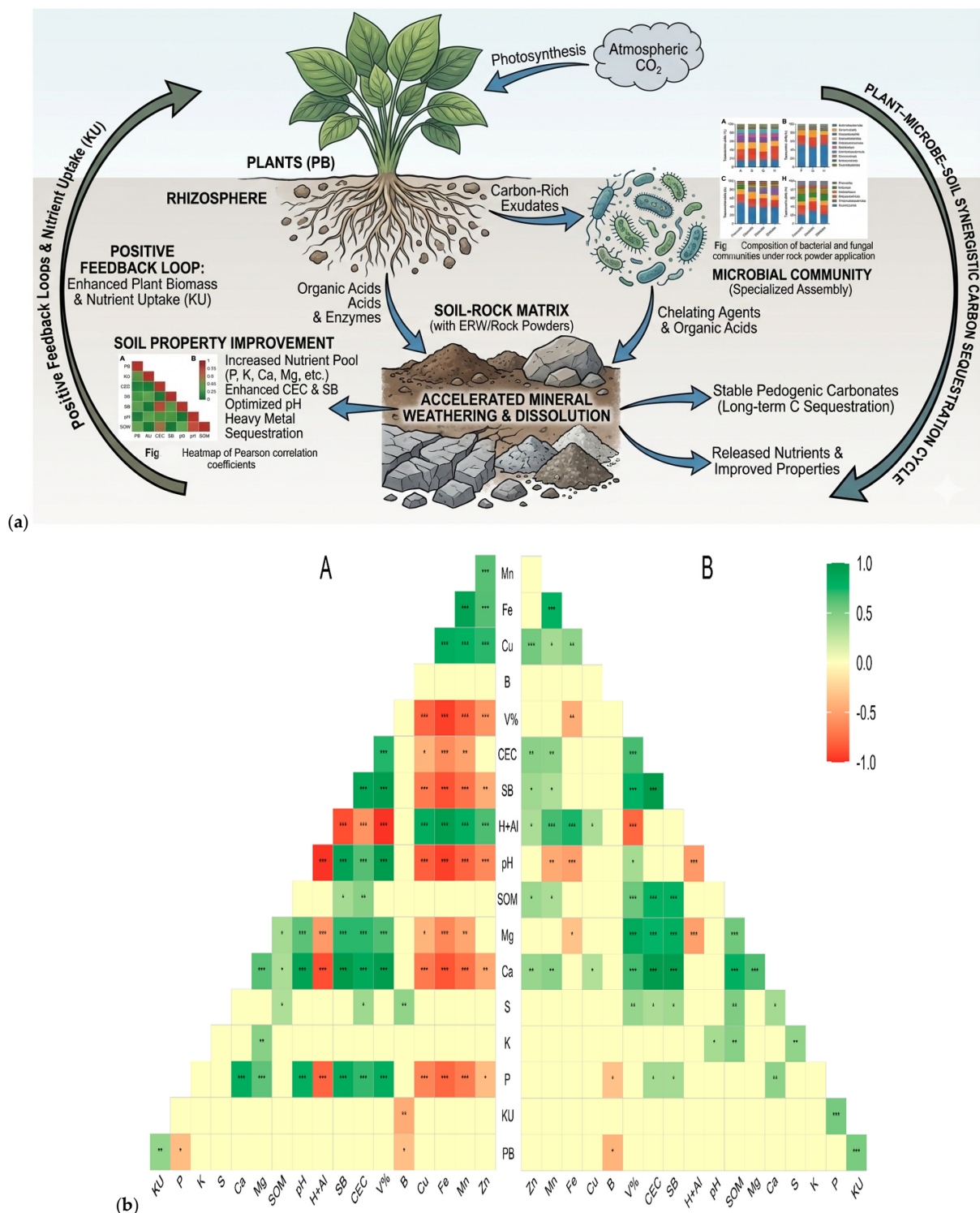


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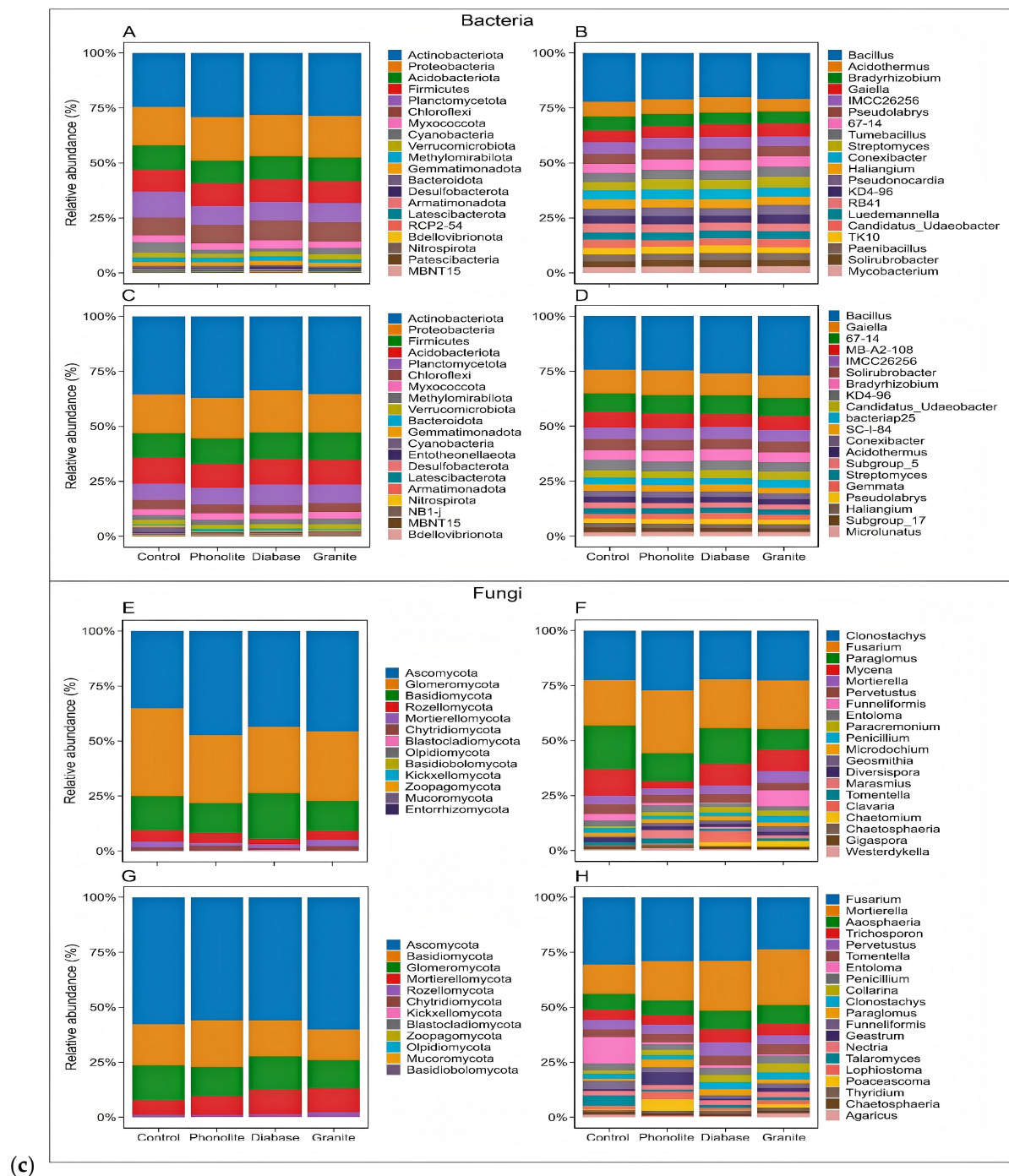


Figure 8. Plant–Microbe–Soil Synergistic Carbon Sequestration Mechanism (a) Schematic diagram of the principle; (b) Heatmap of Pearson correlation coefficients (A represents the mapping relationship between soil after enhanced weathering and plant nutrient elements, B represents the mapping relationship between natural soil and plant nutrient elements); (c) Proportion of bacterial growth for different fungal classes in soil after applying enhanced weathering [44]. The detailed experimental parameters, additional test results and raw data are presented in Supplementary Materials.

3. Results and Discussion

3.1. Enhanced Rock Weathering as a Core Driver of Mine Ecological Restoration

ERW acts as a system-level mechanism that reconnects disrupted geological, pedological, and biological processes in abandoned mine landscapes (Figure 9). Open-pit mining and surface excavation fragment bedrock into unconsolidated materials, interrupting natu-

ral weathering pathways and weakening carbon and nutrient cycling. ERW reintroduces an accelerated yet regulated weathering continuum, linking mineral dissolution, CO₂ sequestration, and ecosystem recovery within a coupled geo-eco framework.

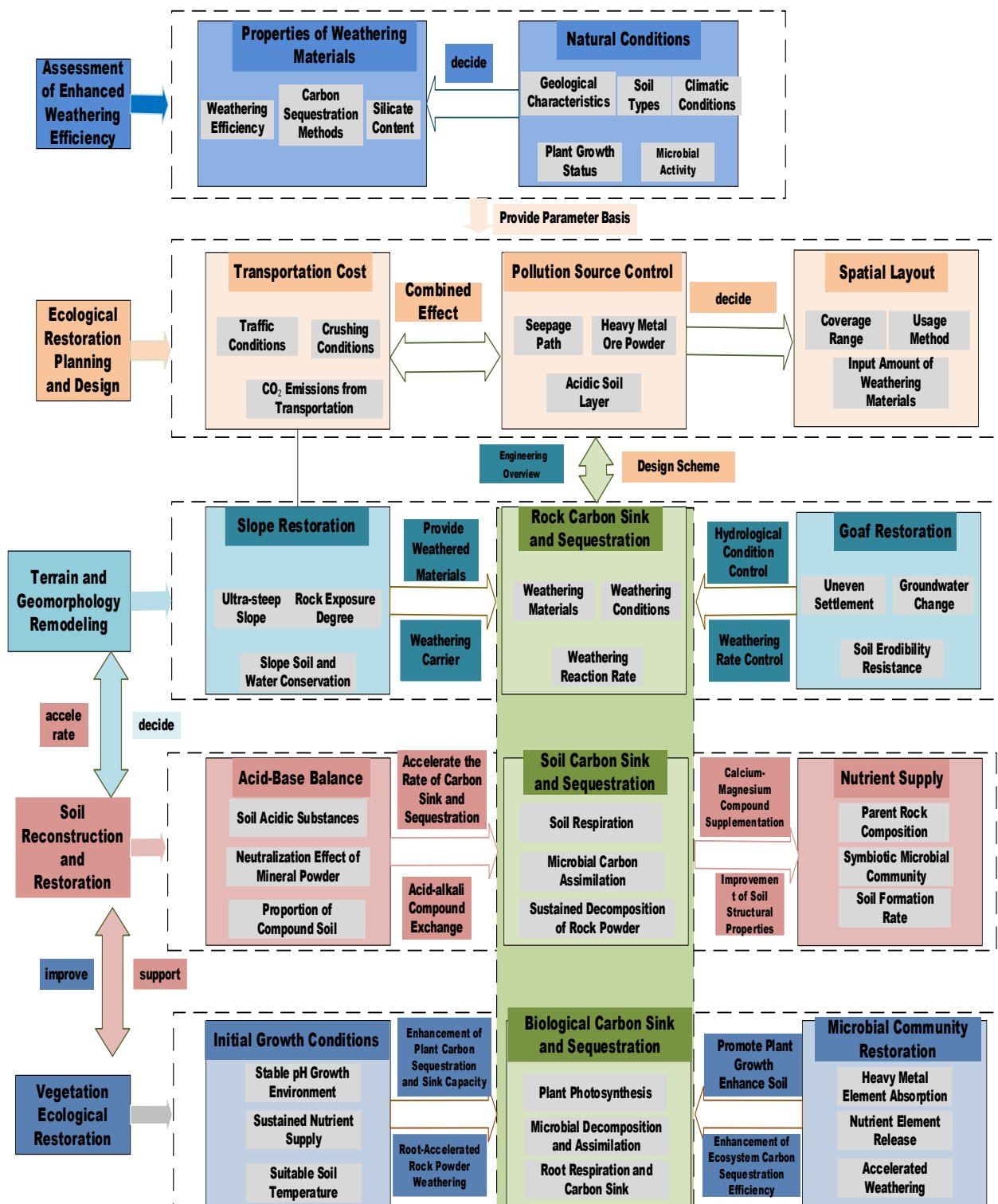


Figure 9. Technical framework for mountainous mine restoration based on enhanced weathering processes.

The effectiveness of ERW is inherently site-specific and emerges from interactions among mineralogy, climate, soil chemistry, and biological activity. Reactive silicate minerals such as basalt and olivine exhibit high CO₂ uptake potential, yet their performance varies

with soil pH, moisture regime, and particle size. Experimental evidence demonstrates that moderate mineral additions can substantially improve soil chemical conditions. For example, lime amendments increased soil pH from 3.55 to 6.06 within three months, whereas low and high olivine applications (0.008 and 0.04 g g^{-1} soil) raised pH to 4.68 and 5.18, respectively (Figure 9). Notably, higher olivine dosages showed lower dissolution efficiency (7.1%) compared with lower dosages (26.7%), highlighting the necessity of optimizing mineral loading rather than maximizing application rates. These quantitative results confirm that ERW efficiency is governed by threshold behavior rather than linear responses.

3.2. ERW-Oriented Planning: Linking Materials, Transport, and Soil Design

Incorporating ERW into restoration planning shifts mine rehabilitation from fragmented engineering interventions toward integrated system design. Material sourcing, mineral composition, and spatial deployment jointly determine net carbon benefits and ecological outcomes. Although transportation emissions generally represent a minor fraction of total ERW carbon sequestration, empirical assessments indicate that transport distances exceeding approximately $990 \pm 116 \text{ km}$ can offset weathering-derived CO_2 uptake. This threshold underscores the importance of prioritizing locally sourced waste rock and tailings, which simultaneously reduces emissions and ensures geochemical compatibility with site conditions.

Mineral blending strategies must balance weathering reactivity and soil buffering capacity. Excessively reactive inputs may destabilize soil chemistry, while insufficient dosages limit ecological effectiveness (Figure 9). Composite soil formulations, tailored to local climate and vegetation requirements, enable ERW substrates to function as long-term nutrient reservoirs rather than short-lived amendments. Spatial planning of application intensity and coverage further ensures that soil improvement, vegetation establishment, and biodiversity recovery proceed coherently at the landscape scale.

3.3. Geomorphological Reshaping Technologies in Mine Areas

Geomorphological reshaping provides the engineering foundation upon which ERW can be implemented, but it should be distinguished from the weathering-driven carbon sequestration process itself. Conventional measures such as slope regrading, subsidence correction, and terrain smoothing improve landform stability and generate fragmented rock materials that may subsequently serve as suitable substrates for ERW. The effectiveness of these materials for carbon sequestration, however, depends on their mineralogical composition, weathering reactivity, and local environmental conditions rather than on geomorphological modification alone (Figure 9).

On steep slopes, the incorporation of weatherable minerals with appropriate water-retention capacity can improve soil moisture availability and reduce erosion under intense rainfall, thereby creating more favorable conditions for vegetation establishment and mineral weathering. Likewise, in uneven or subsidence-prone areas, optimizing the proportion of hydrophilic mineral materials may enhance soil cohesion and hydrological regulation, supporting the long-term stability of reconstructed soils. Nevertheless, the extent to which these engineering measures contribute to carbon sequestration is influenced by multiple factors, including climate, hydrology, vegetation development, and post-restoration management. Therefore, geomorphological engineering should be regarded as an enabling strategy that creates suitable physical conditions for ERW, while the magnitude of subsequent carbon sequestration depends on the coupled interactions among mineral weathering, ecological processes, and site-specific environmental conditions.

3.4. Soil Reconstruction and Restoration Technologies

Soil reconstruction represents a critical transitional stage linking physical stabilization and biological recovery. ERW accelerates soil development by regulating acid–base balance, enhancing mineral dissolution, and sustaining nutrient supply. Particle size optimization plays a key role in maintaining soil porosity and gas exchange, thereby supporting microbial activity and continuous mineral carbonation (Figure 9).

At the soil scale, inorganic carbon sequestration via mineral weathering operates alongside organic carbon accumulation driven by plant inputs [12]. These complementary carbon pools differ in turnover time but jointly enhance long-term carbon stability. Nutrient release mapping of weathering minerals (e.g., Ca, Mg, K, and Si) enables soil–plant matching strategies that improve nutrient-use efficiency and reduce dependence on external fertilizers, particularly in severely degraded mine substrates.

3.5. Vegetation Restoration Technologies in Mine Areas

Vegetation restoration represents the ultimate expression of ERW effectiveness. Although soil carbon pools provide long-term storage, photosynthetic carbon fixation by plants constitutes the dominant carbon input in restored mine ecosystems. ERW supports sustained plant growth by buffering soil acidity and maintaining nutrient availability throughout successional stages (Figure 9).

Root systems form a vertical coupling mechanism between geological and biological processes. Deep roots enhance bedrock fracturing and water infiltration, intermediate roots stimulate mineral–microbe interactions, and surface biomass drives photosynthetic CO₂ uptake and organic matter return. Through these multi-layered interactions, ERW integrates rock weathering carbon sinks, soil carbon stabilization, and biological sequestration into a synergistic, self-sustaining ecosystem.

3.6. Key Technical Challenges

The restoration of mountainous abandoned mines faces multiple challenges due to complex terrain, heterogeneous mineral composition, and harsh climatic conditions (Table 3).

Table 3. Basic ecological restoration characteristics of typical mountainous mines.

Mine Type	Mineral Composition of Surface Rocks	Weathering Characteristics	Remediation Measures	Minimum Remediation Threshold
Quarry	Quartz, feldspar, mica, calcite	Intense weathering, loose surface, prone to soil erosion	1. Soil improvement (adding organic matter) 2. Soil and water conservation (constructing drainage systems, slope protection) 3. Vegetation restoration (planting drought-tolerant plants)	Soil has certain fertility, with significant soil and water conservation effect
Copper Mine	Copper ores (chalcopyrite, malachite, chrysocolla, etc.), quartz, feldspar	Moderate weathering, more exposed ores, possibly accompanied by metal pollution	1. Heavy metal pollution control (chemical precipitation, phytoremediation) 2. Soil improvement 3. Vegetation restoration	Ore pollution is high, requiring special remediation measures to restore ecological balance

Table 3. Cont.

Mine Type	Mineral Composition of Surface Rocks	Weathering Characteristics	Remediation Measures	Minimum Remediation Threshold
Mercury Mine	Cinnabar, metacinnabar, quartz	Fast weathering rate, mercury released from minerals causing soil pollution	1. Mercury pollution control (solidification treatment, chemical adsorption) 2. Ecological restoration (planting pollution-tolerant plants)	In case of severe mercury pollution, deep remediation is needed with a high remediation threshold
Gold Mine	Gold ores (pyrite, chalcopyrite, etc.), quartz, calcite	Slow weathering, main pollutants are heavy metals and arsenic	1. Arsenic pollution treatment 2. Soil improvement 3. Vegetation restoration (planting native plants)	Gold mining areas are severely polluted by arsenic, with slow vegetation restoration effect
Silver Mine	Silver ores (silver sulfide, silver chloride), quartz	Slow weathering, mainly affecting soil fertility	1. Heavy metal pollution control 2. Soil improvement 3. Vegetation restoration (planting pollution-tolerant plants)	Gradual removal of silver pollution in soil is needed, with a low remediation threshold
Molybdenum Mine	Molybdenum ores (molybdenite, uranomolybdenite), quartz, feldspar	Slow weathering, main pollutants are molybdenum and other trace elements	1. Molybdenum pollution control 2. Soil improvement 3. Vegetation restoration (planting native plants)	Pollution in molybdenum mining areas is relatively light, with a low remediation threshold

Explanation: The mineral composition of surface rocks varies among different mines and significantly influences both weathering rates and the complexity of ecological restoration. Mines rich in metallic minerals tend to release heavy metals during weathering, thereby increasing the risk of soil and groundwater contamination. Moreover, the degree of rock weathering determines the physical stability of the substrate and overlying soils. Sites exhibiting rapid weathering rates often face higher risks of erosion and pollutant mobilization, posing additional challenges to long-term environmental rehabilitation. The detailed experimental parameters, additional test results and raw data are presented in Supplementary Materials.

Geological and climatic constraints—Difficult terrain and poor accessibility increase operational costs and reduce material transport efficiency. Variable temperature and humidity conditions affect weathering rates—cold or arid climates may significantly slow ERW reactions. Thus, adaptive technical schemes tailored to local climatic and geological conditions are essential.

Contaminant release from parent rocks—ERW may inadvertently mobilize toxic elements such as heavy metals from mine tailings, leading to water and soil contamination. Since mountainous regions often serve as critical water sources, preventing secondary pollution during ERW application is vital to safeguard downstream ecosystems and human health.

Heterogeneous silicate content—Many abandoned mines contain low-silicate, high-carbonate ores, which are less effective for CO₂ sequestration. Rational design of mineral mixtures and complementary ecological measures—such as vegetation recovery and water-soil conservation—can enhance the overall carbon capture and soil improvement efficiency.

4. Conclusions

ERW represents a promising pathway for integrating geological engineering with ecological restoration in abandoned mountainous mines. By utilizing weatherable rock materials generated during mine rehabilitation, ERW has the potential to simultaneously support landform stabilization, soil reconstruction, nutrient replenishment, and atmo-

spheric CO₂ removal. Based on the literature synthesized in this review, a conceptual three-dimensional carbon sink framework involving bedrock, reconstructed soils, and vegetation is proposed to illustrate how geological, pedological, and biological processes may interact to promote long-term ecosystem recovery and carbon sequestration. This framework should be regarded as a conceptual model that requires further validation under different geological, climatic, and management conditions.

China possesses abundant basalt resources that provide favorable material conditions for the future application of ERW. Theoretical estimates based on the resource potential of the Emeishan Large Igneous Province suggest that these materials could contribute substantially to long-term CO₂ removal if suitable geological, environmental, and engineering conditions are met. However, such estimates represent theoretical resource potential rather than practically achievable carbon removal. The actual contribution of ERW will depend on multiple factors, including rock availability, mineralogical composition, particle size, transportation distance, energy consumption during processing, weathering kinetics, ecological responses, and long-term monitoring of carbon storage. Comprehensive life-cycle assessment, techno-economic evaluation, and field-scale verification are therefore essential before regional carbon mitigation potential can be reliably quantified.

Beyond carbon sequestration, ERW may provide multiple co-benefits that are highly relevant to ecological restoration, including improvement of soil fertility, enhancement of nutrient cycling, mitigation of acid mine drainage, stabilization of degraded slopes, and immobilization of certain contaminants under appropriate environmental conditions. These additional ecosystem services suggest that ERW could complement existing near-natural restoration strategies by improving both ecological resilience and resource-use efficiency. Nevertheless, the magnitude and persistence of these benefits are expected to vary among mine types and environmental settings, emphasizing the importance of site-specific design and adaptive management.

Overall, current evidence suggests that ERW has considerable potential to become an important component of low-carbon mine restoration and Nature-based Solutions (NbS). Rather than representing a universally applicable solution, ERW should be viewed as one element within an integrated restoration framework that combines geomorphological engineering, soil reconstruction, vegetation recovery, hydrological regulation, and ecological succession. Future research should prioritize long-term field experiments, quantitative carbon accounting, life-cycle assessment, and multi-scale process modeling to better constrain weathering rates, carbon sequestration efficiency, environmental risks, and engineering feasibility. Such efforts will provide a more robust scientific basis for evaluating the role of ERW in sustainable mine restoration and climate-change mitigation.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/environments13080428/s1>, Figure S1: Distribution map of minerals such as nitrogen, phosphorus, potassium, magnesium, and other elements in China. Data source; Figure S2: Distribution of volcanic rocks in China; Figure S3: Composition of bacterial and fungal communities under rock powder application after 10 months. (A, B) Bacterial phyla and genera in sandy soil; Figure S4. Heatmap of Pearson correlation coefficients between plant performance indicators, soil nutrients, and physicochemical properties in (A) sandy and (B) clay soils. Plant parameters; Table S1: Engineering costs for mining, grinding, transportation, and application in different regions of China; Table S2: Characterization of chemical and physical properties of soils collected prior to the experiment; Table S3. Typical Components Table.

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Data Availability Statement: The data presented in this study include experimental results generated by the authors and datasets collected from previously published studies, as referenced throughout the manuscript. The authors have verified and integrated these data for the analysis and discussion presented in this review. The original experimental data generated by the authors are available from the corresponding author upon reasonable request.

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