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Valorization of mineral by-products through soil remineralization enhances sustainable agriculture and circular economy outcomes

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Abstract

Soil remineralization using rock powders derived from mining and industrial by-products has gained attention as a sustainable strategy to restore degraded soils, improve fertility, and reduce reliance on synthetic fertilizers. These materials, rich in nutrients and beneficial minerals, also offer potential for carbon sequestration and contribute to circular economy practices by repurpose byproducts into agricultural inputs. This review aims to critically synthesize the current state of research on rock powder applications in agriculture, with a particular focus on their agronomic potential, environmental implications, and alignment with circular economy principles. A scientific literature review of 142 articles published between 2014 and 2024 was conducted using Scopus-indexed literature. Findings reveal that Brazil, China, and Colombia lead global research efforts, with basalt, phonolite, and other silicate rocks being the most frequently studied materials. Key benefits include increased nutrient availability of potassium (K), calcium (Ca), magnesium (Mg), and phosphorus (P), improved cation exchange capacity (CEC), and enhanced microbial activity. However, limitations persist, such as slow nutrient release, high energy demands for grinding, logistical constraints, and risks of trace metal accumulation in soils. By integrating both quantitative trends and critical thematic analysis, this review provides a comprehensive overview of the opportunities and challenges associated with rock powder use. It highlights the need for region-specific strategies, long-term field trials, and regulatory frameworks to support broader adoption. The contribution of this review lies in framing soil remineralization not only as an agronomic practice but as a circular, regenerative approach to sustainable land and resource management.

Keywords Waste valorization, Mineral by-products, Soil remineralization, Sustainability, Natural resources

1 Introduction

Food security and ecosystem sustainability depend on agroecological strategies and conservation practices that restore degraded soils and maintain their quality [1–3]. Among these, soil remineralization using rock powders derived from mineral byproducts has emerged as a promising approach to regenerate nutrient-depleted soils and reduce dependency on external chemical inputs. These goals align with the United Nations' 2030 Agenda for Sustainable Development, which emphasizes food production and hunger eradication [4, 5]. This approach is also consistent with global initiatives such as the United Nations Food Systems Summit (UNFSS) and the Global Soil Partnership (GSP) of the Food and Agriculture Organization (FAO), which advocates for soil health, climate-resilient agriculture, and the sustainable use of natural resources to ensure food system transformation and long-term productivity [6, 7]. However, soil degradation and over-reliance on chemical fertilizers have driven the search for sustainable alternatives to improve soil fertility.

Among these alternatives, finely ground mineral materials from mining or industrial by-products, commonly called "rock powders" or "mineral residue-based remineralizers," have emerged as promising solutions for soil remineralization. In Brazil, a regulatory distinction exists between "agrominerals", which are recognized for their agricultural potential but not yet formally regulated [8], and "remineralizers", which are officially defined by Law No. 12,890/2013 and regulated under Normative Instruction No. 05/2016 of the Ministry of Agriculture [9], based on criteria such as reactivity, particle size, and permissible levels of potentially toxic elements. The use of such mineral amendments, including materials like limestone and phosphate rocks, has historical precedent and continues to play a relevant role in sustainable agriculture [10, 11].

Despite increasing attention to soil health and sustainable practices, there is still a limited understanding of how these remineralizers interact with various agricultural systems. Factors such as the variability of soil types, crop species, management practices, and climatic conditions pose significant challenges to generalizing the effectiveness of these amendments. Therefore, more comprehensive studies are needed to clarify their agronomic, environmental, and economic impacts in agroecosystems [10, 11].

The global dependence on potassium fertilizers, primarily produced by Russia, Canada, Germany, Belarus, and China, has been exacerbated by geopolitical conflicts, such as the Russia-Ukraine war, leading to rising costs and supply chain disruptions [12–14]. This scenario has intensified interest in alternative nutrient sources, particularly remineralizers derived from mechanically ground rocks, which can improve soil fertility without chemical processing and promote the circular economy by repurposing mining byproducts [15–17].

Several studies show that the application of rock dust and mining byproducts can improve nutrient availability (Ca, Mg, P, and K), increase CEC, regulate soil pH through mineral weathering, and stimulate beneficial soil microbiota. These effects are especially relevant in tropical regions, where severe nutrient depletion limits agricultural productivity [15–21].

For example, in sub-Saharan Africa, continuous cultivation without adequate nutrient replenishment has caused widespread soil nutrient degradation, leading to declines in maize and cassava production of up to 40% between 2012 and 2022 [22]. Similarly, studies in China have shown that P and K depletion in intensively cultivated soils reduces rice productivity and increases the risk of land abandonment due to decreased fertility [23]. This highlights the need for soil remineralization strategies that address macro- and micronutrient deficiencies to maintain agricultural productivity and food security.

The use of rock dust as an amendment also reduces dependence on synthetic fertilizers, lowers greenhouse gas emissions, and contributes to long-term soil health and resilience under diverse agroecological conditions [24, 25]. However, the magnitude of these benefits is context-dependent and influenced by factors such as the type of remineralizer, the application rate, and specific soil properties. Ongoing research continues to evaluate its performance in various agroecosystems to optimize its use for both productivity and environmental sustainability [12, 15–18, 26].

Among the most studied rocks for remineralization are basalt, diabase, dacite, dunite, syenite, phonolite, phosphorite, and biotite schist [27–29]. In Brazil, basalt rock powder has gained relevance as an environmentally and economically viable alternative to synthetic fertilizers [15–17].

Activation of low-quality phosphate rocks remains a challenge in agriculture and environmental remediation. Physical, chemical, and biological methods have been used to improve the availability of P and other nutrients such as Ca, Mg, and K, with solubilization by rhizospheric microorganisms and chemical activation with low molecular weight acids showing promising results [30–32].

Integrating mining by-products into agricultural systems, as promoted by the circular economy (CE) framework, reduces environmental impact, minimizes waste, and fosters sustainable resource management [2, 33, 34]. The use of mineral byproducts-derived rock powders exemplifies key CE principles such as industrial symbiosis, where byproducts from mining becomes a productive input in agriculture and resource efficiency by reducing reliance on high-emission synthetic fertilizers. Silicate-rich by-products not only improve soil fertility and nutrient cycling but also enhance water retention, crop resilience, and reduce nutrient leaching, thereby improving groundwater quality and mitigating the negative impacts of intensive agriculture [35–37]. Furthermore, integrating these strategies into regional supply chains contributes to decentralized, low-carbon solutions that strengthen the regenerative capacity of agroecosystems while aligning with Sustainable Development Goals (SDGs).

The use of mining-derived remineralizers requires analysis of their chemical composition and potential environmental and social impacts. Feasibility assessments should consider logistics, resource availability, and acceptance by farmers and local communities [38–40]. The integration of mineral byproducts-derived rock powders into soil management strategies exemplifies the principles of the circular economy by closing resource loops and reducing environmental burdens associated with both mining and agriculture [41]. By valorizing industrial and mining by-products as soil amendments, these approaches minimize waste generation, extend the life cycle of raw materials, and reduce the reliance on non-renewable synthetic fertilizers. In turn, these practices not only enhance soil fertility and productivity but also promote a more regenerative and resource-efficient agricultural sector that is aligned with the SDGs.

This review aims to offer a comprehensive synthesis of state-of-the-art in soil remineralization using mineral byproducts, with a particular emphasis on its alignment with circular economy principles. It combines a scientific literature review and narrative analysis of peer-reviewed publications indexed in the Scopus database from 2014 to 2024, focusing on keywords related to soil remineralization, mineral by-products, and the circular economy. The review critically examines current practices, agronomic effectiveness, environmental risks, regional applications, and research challenges. In addition to identifying trends, leading institutions, and international collaborations, it synthesizes evidence on the mechanisms and limitations of rock powder use, highlighting knowledge gaps and practical barriers to implementation. While this approach provides a broad overview of recent advances, it is subject to limitations such as publication bias, inconsistent reporting practices, and methodological heterogeneity across studies. These factors may affect the comparability of findings and the generalizability of conclusions. Future reviews should consider adopting systematic review protocols and meta-analytical approaches to enhance the robustness of evidence synthesis and inform large-scale sustainable strategies in diverse agroecological contexts.

2 Data sources and approach to scientific literature review

This review is based on an analysis of peer-reviewed literature retrieved from the Scopus database. The search was conducted in April 2024 using the following keyword combinations: ("soil remineralization" OR "rock powder" OR "mineral by-products") AND ("circular economy" OR "sustainable agriculture"). The selection was limited to articles from peer-reviewed journals published between 2014 and 2024. No language exclusion criteria were applied; however, editorials, preprints, and non-peer-reviewed sources were excluded from consideration. Likewise, articles whose primary focus was not directly related to the objective of this research were excluded. Metadata were exported from the "Analyze Results" section of Scopus in CSV format and processed in Excel for filtering, organization, visualization, and analysis of trends in the number and type of publications by year, as well as the distribution by country with the highest scientific output.

3 Global research trends in soil remineralization

This section presents a descriptive and interpretive analysis of trends in scientific production on soil remineralizers between 2014 and 2024, considering the number of publications per year, the type of studies conducted, and the countries with the largest number of contributions. The objective was to examine the evolution of academic interest in this topic.

As shown in Fig. 1a, the number of publications on soil remineralization using mineral byproducts has grown unevenly. After an initial increase between 2014 and 2017, a decline occurred until 2019, followed by a notable rise between 2019 and 2023. In 2024, only three studies were published, possibly due to delayed indexing or a stabilization in research momentum. Regarding document types, 84% of the contributions were research articles, 9% were reviews, 5% conference papers, and 2% book chapters suggesting that most outputs focus on empirical applications rather than conceptual or theoretical developments.

Figure 1b illustrates the distribution of publications by country. Brazil leads global output with 39% of total publications, followed by China, Colombia, and the United States. This geographic pattern reflects a strong research focus in tropical and subtropical regions, where soil degradation and the need for alternative soil amendments are more pressing.

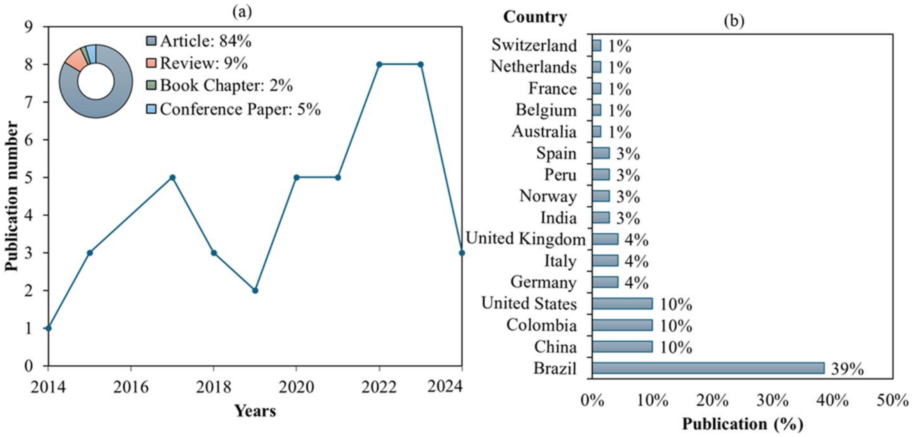

Fig. 1 Annual number of publications on soil remineralization using mineral byproducts (2014–2024). **a** Publication number for years and type publications; **b** Percentage of publications by country in soil remineralization research

The high volume of publications from Brazil reflects the country's longstanding focus on tropical soil management and the valorization of basaltic and phonolitic rock powders as low-cost alternatives to synthetic fertilizers. Brazilian research has emphasized field trials on degraded Ferralsols and the role of remineralizers in nutrient cycling, pH correction, and soil microbiome enhancement [15, 32].

In China, studies have focused on the stabilization of heavy metals and the improvement of acidic soils, particularly in mining-impacted regions [18, 42]. Colombia's emerging research contributions highlight the integration of mineral by-products from the extractive sector into sustainable agriculture initiatives [25], often linked to biochar and compost co-application [39]. The United States has approached remineralization through the lens of carbon sequestration and enhanced weathering, with an emphasis on quantifying carbon dioxide (CO_2) capture potential in temperate soils [43, 44].

These findings demonstrate that soil remineralization is gaining traction globally, particularly in regions facing acute challenges related to soil degradation, fertilizer dependency, and climate resilience [1, 25, 42]. However, the observed geographic asymmetries and the predominance of empirical studies over conceptual frameworks reveal important research gaps. There is a pressing need for more integrative approaches that connect field trials with socioeconomic assessments, circular economy principles, and long-term environmental monitoring [2, 33, 39]. Strengthening international collaboration and expanding research in underrepresented regions will be key to advancing a more equitable and comprehensive understanding of mineral byproducts-based soil management [15, 18].

4 Using rock powder for the restoration of degraded soil

Soil degradation, driven by erosion, nutrient depletion, acidification, and loss of organic matter, is a global concern affecting ecosystem functions and food security [45, 46]. This section explores how rock powders, particularly those derived from mineral byproducts, contribute to the recovery of degraded soils through mineralogical, chemical, and biological mechanisms. The aim is to highlight the processes and conditions under which rock powders support long-term soil regeneration, distinct from their use as short-term nutrient supplements.

The effectiveness of rock powders in restoring degraded soils lies in their ability to slowly release nutrients, correct pH imbalances, and improve soil structure (Fig. 2). Unlike soluble fertilizers, rock powders act as a sustained source of Ca, Mg, K, and trace elements, which gradually become available through weathering and microbial interactions [20, 21]. These minerals not only replenish nutrient stocks but also enhance CEC, promote aggregation, and stimulate rhizospheric microbial activity [16, 19]. These processes are illustrated in Fig. 4, which schematically represents the soil remineralization pathway following rock powder application.

In highly weathered tropical soils, applications of basalt, phonolite, and biotite schist have shown positive effects on plant productivity, organic matter content, and soil resilience [27, 28]. These improvements are particularly relevant in regions suffering from decades of nutrient mining and unsustainable land use practices. Additionally, remineralization can support ecological succession and vegetation recovery in marginal lands and post-mining landscapes, where conventional amendments are often ineffective or economically unfeasible [18, 25].

The restorative potential of rock powders is closely linked to site-specific factors, including parent material, application rate, climate, and cropping systems. Long-term studies are essential to quantify cumulative effects on soil quality indicators and to validate their use in land restoration programs. Moreover, combining remineralizers with organic amendments (e.g., compost or biochar) can accelerate recovery processes by improving nutrient cycling and microbial colonization [2, 24]. Integrating rock powders into ecological restoration strategies aligns with circular economic principles and offers a promising path toward sustainable soil management.

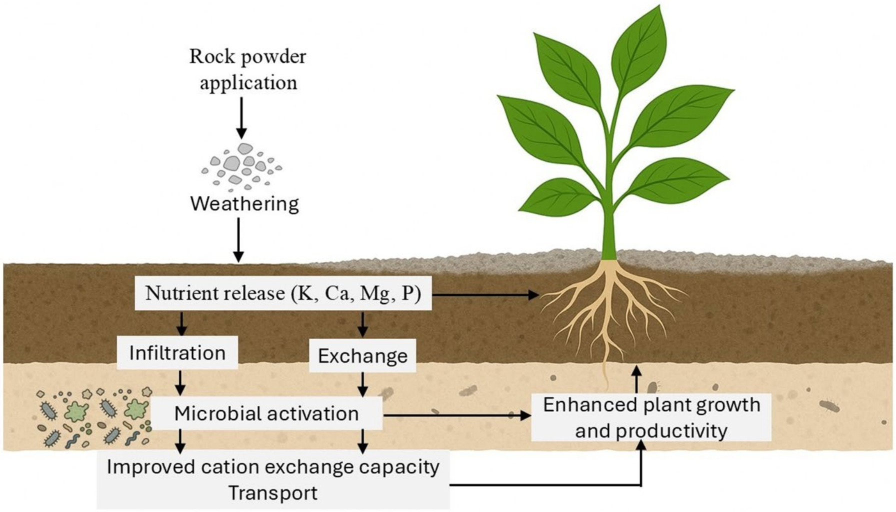

Fig. 2 Conceptual representation of the soil remineralization process after rock powder application. Weathering of applied rock powder results in the gradual release of nutrients, including K, Ca, Mg, and P. Plant roots absorb these nutrients and enhance microbial activation and CEC in the soil. The improved soil structure and nutrient availability contribute to enhanced plant growth and productivity. Conceptual model developed by the authors based on synthesis of the reviewed literature

5 Using rock powder for carbon sequestration

Restoration of degraded soils and adopting sustainable management practices in agricultural and forestry systems are key strategies for enhancing soil carbon sequestration [47, 48]. Rock weathering has been identified as a natural CO_2 sink among these strategies. This process involves chemical reactions that transform atmospheric CO_2 dissolved in rainwater into bicarbonate ions (HCO_3^-), which are subsequently stored in rivers and oceans for up to 100,000 years [49].

The application of crushed carbonate and silicate rocks, rich in Ca and Mg, has emerged as a cost-effective method to mitigate climate change impacts. This approach not only facilitates the removal of atmospheric CO_2 but also improves the regulation of river and ocean ecosystems, mitigates ocean acidification, and promotes agricultural productivity [11, 25, 47, 48]. Within this framework, enhanced rock weathering (ERW) has gained attention as an innovative technique for CO_2 capture.

ERW involves the application of highly reactive silicate rock powders to soils, enabling CO_2 sequestration through the formation of carbonate minerals (Fig. 3). During this process, silicate minerals react with CO_2 dissolved in water, forming HCO_3^- and carbonate (CO_3^{2-}) ions that are either stored in soil minerals or transported to aquatic systems, where they can remain stable for centuries. Additionally, ERW can indirectly reduce emissions of other greenhouse gases, such as nitrous oxide (N_2O), by altering soil pH and microbial processes, and in some cases, modulate methane (CH_4) emissions depending on the soil type and management practices. The estimated global sequestration potential of ERW ranges between 0.2 and 4 Gt CO_2 per year [50].

Beyond carbon sequestration, ERW offers multiple co-benefits. These include the reduction of emissions of other greenhouse gases, such as nitrous oxide, the improvement of soil fertility through the release of nutrients (such as K, P, and Ca), and the enhancement of primary productivity [3, 51–54]. The process involves the dissolution of silicate minerals in the presence of water and CO_2, generating alkaline ions and carbonates that can be stored in the soil or transported to water bodies, contributing to long-term carbon storage [55].

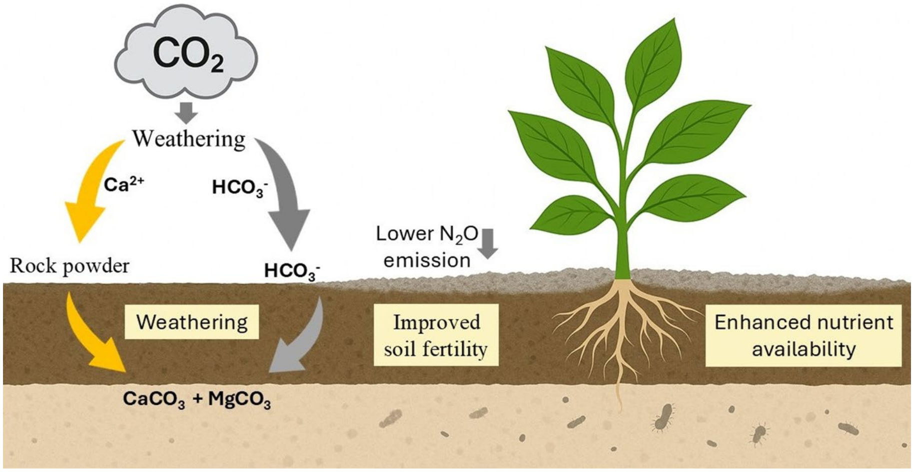

Fig. 3 The conceptual model illustrates how silicate rock dust contributes to carbon sequestration and improved soil fertility. Weathering of rock minerals in the presence of atmospheric CO_2 leads to the formation of carbonates and bicarbonates, which improves nutrient availability, stimulates microbial activity, and reduces N_2O emissions. Conceptual model developed by the authors based on the reviewed literature

The effectiveness of ERW has been demonstrated in some studies. For instance, Vienne et al. [55]. utilized basaltic rock powder and confirmed its ability to sequester CO_2 while providing agricultural benefits, such as reduced nitrogen losses and increased crop yields. The pulverization of silicate rocks increases their reactive surface area, and when applied to moist soils, it accelerates mineral dissolution and carbon sequestration. However, the total CO_2 sequestration potential of ERW depends on both the accumulation of inorganic carbon in the soil solid phase and the export of dissolved inorganic carbon through runoff. Current methodologies for estimating CO_2 sequestration often rely on changes in leached cations or exchangeable soil pools, highlighting the need for more precise quantification techniques [55].

The application of rock powders, particularly through ERW, represents a promising strategy for restoring degraded soils and enhancing carbon sequestration. Its potential to improve soil fertility, increase agricultural productivity, and mitigate climate change underscores its relevance in sustainable land management.

A particularly relevant development is the integration of ERW into emerging carbon markets, with Brazil standing out as a key example. Over the past decade, Brazil has positioned itself as a global leader in remineralization (rochagem), supported by a dedicated legal framework established in 2013 and the widespread use of rock powders in agriculture. With the recent implementation of the Brazilian Emissions Trading System (SBCE) in December 2024, ERW practices are now formally recognized in national regulations as eligible for generating verified carbon credits [56–58].

In 2025, Brazil issued its first ERW-based carbon credits, verified through robust Monitoring, Reporting, and Verification (MRV) protocols. These credits were successfully traded in international markets, highlighting the growing demand for high-quality, durable carbon removal solutions [59, 60]. Brazil's abundant reserves of reactive basalt and other silicate rocks, combined with favorable climate and agricultural conditions, provide a cost-effective and scalable platform for large-scale ERW deployment [61]. These initiatives not only contribute to atmospheric CO_2 removal but also offer co-benefits such as improved soil health, increased crop productivity, and additional income streams for farmers engaged in voluntary and compliance-based carbon markets.

Nevertheless, further research is still required to optimize ERW application methods, refine carbon accounting models, and evaluate potential environmental risks, particularly the mobilization of trace elements. Brazil's early implementation provides a valuable reference for other countries seeking to integrate soil remineralization into broader land-use strategies and climate finance frameworks.

6 Rock powder and its potential in sustainable agriculture

Soil pH is a critical abiotic factor influencing silicate rock powders' weathering rate and nutrient release. While mineral dissolution tends to increase under acidic conditions, this relationship varies depending on the mineral type. For example, olivine, augite, and plagioclase dominant in basalt can dissolve across a wide pH range, though with lower efficiency near pH 5 [55, 62]. In acidic tropical soils, basalt and other silicates release divalent cations calcium (Ca^{2+}), and magnesium (Mg^{2+}) ions that displace hydrogen (H^+) and aluminum (Al^{3+}) ions from colloids, neutralize acidity, and enhance P availability. These pH shifts improve microbial activity, nitrogen retention, and nutrient cycling [33, 43].

Silicate rock powders have gained widespread attention in agricultural applications due to their agronomic benefits. Their use has improved CEC, increased crop yields, and mitigated soil acidification. They also enhance plant resistance to pests and drought, while reducing nitrogen losses via decreased emissions of N_2O and nitrate leaching (Fig. 4). These outcomes are attributed to shifts in microbial activity, improved root-microbe interactions, and enhanced nitrogen use efficiency [55, 63]. For instance, Vienne et al. [55] reported that basalt application reduced N_2O emissions by up to 30% in acidic soils.

Rock powders are also being explored for environmental remediation strategies, such as stabilizing heavy metals and reducing nutrient runoff. They have proven effective in neutralizing soil acidification and in reducing water pollution. For instance, the application of silicate-rich materials such as basalt and wollastonite has proven effective in restoring acidic soils by releasing cations like Ca^{2+}, Mg^{2+}, and K^+, which neutralize H^+ ions in the soil [43].

In Brazil, basalt increased soil pH by 1.2 units in six months and reduced the need for chemical fertilizers [64, 65]. Similarly, Daher et al. [66] combined volcanic rock (< 20 µm) with propolis to control *Bactrocera oleae*, demonstrating potential for sustainable pest management.

Excessive P and N in water bodies cause eutrophication, a significant environmental issue affecting water quality and aquatic biodiversity. Silicate rock powders may mitigate this by adsorbing phosphate and reducing nitrate leaching. For example, Blanc-Bêtes et al. [63] found a 30% reduction in phosphate runoff after basalt application in the United Kingdom, offering a potential solution to mitigate river and lake pollution. This effect is attributed to the capacity of rock powders to retain nutrients in the soil, minimizing their transport into water bodies.

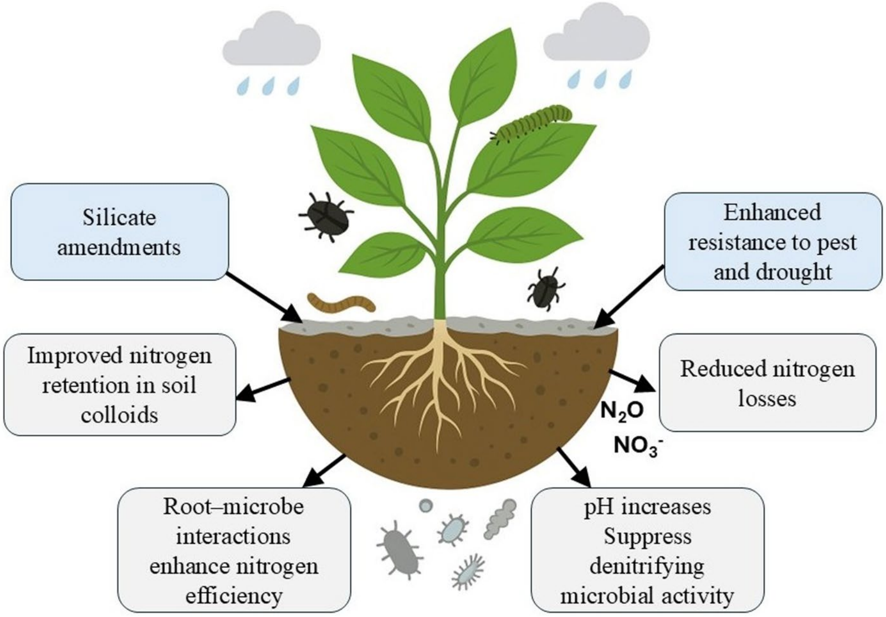

Fig. 4 Mechanisms by which silicate amendments reduce nitrogen losses and improve plant resilience. These amendments increase soil pH, improve nitrogen retention in soil colloids, and strengthen root-microbial interactions, resulting in lower N_2O emissions, increased nitrogen use efficiency, and improved resistance to pests and drought. Conceptual model developed by the authors based on the reviewed literature

The influence of pH on the dissolution of silicate minerals varies depending on the rock type. Recent studies have shown that primary minerals such as olivine, augite, and plagioclase exhibit variable dissolution rates under both acidic and alkaline conditions, with a lower efficiency observed at pH close to 5 [43, 62]. This variability must be considered when selecting specific rock types for agricultural applications.

The application of rock powders supports diverse soil improvement strategies, including acid neutralization, heavy metal stabilization, and nutrient retention. While their potential varies across environmental and agronomic settings, they offer innovative solutions aligned with sustainability and climate mitigation goals 5 [11]. Their ability to enhance soil fertility, increase crop resilience, and reduce environmental degradation reinforces their value as sustainable complements to conventional inputs. However, further research is required to refine application protocols, assess long-term risks especially those related to trace metal mobility and ensure safe use across varied agroecosystems.

While many studies report improvements in soil quality and crop yields, others have documented limited or inconsistent effects depending on site conditions and mineral characteristics. For example, Crusciol et al. [27] observed no significant increase in maize productivity following phonolite application in certain tropical regions, likely due to its low solubility and slow nutrient release. Similarly, Ramos et al. [25] noted that remineralization effects were delayed in soils with limited microbial activity or insufficient moisture. These findings emphasize the importance of site-specific assessments and reinforce the notion that rock powders should be regarded as long-term soil conditioners rather than immediate nutrient sources.

Despite these promising agronomic and environmental benefits, the efficiency of rock powders remains highly variable and context dependent. Their performance is influenced by mineralogical composition, particle size, soil pH, moisture availability, weathering rate, climate, and crop type. In some cases, crop responses have been minimal or delayed, especially under suboptimal application rates or environmental conditions. Such inconsistencies highlight the need for long-term, field-based trials across diverse agroecosystems. Moreover, the slow nutrient release profile of rock powders may not meet the rapid nutrient demands of intensive cropping systems. Finally, publication bias may obscure neutral or negative results, contributing to an overly optimistic view of their effectiveness. Therefore, while rock powders offer value as complementary soil amendments, caution is warranted before advocating for their large-scale substitution of synthetic fertilizers [25, 67].

7 Application of rock powder for remediation of soils contaminated with heavy metals

This section analyzes the mechanisms, experimental evidence, and limitations of using rock powders for the remediation of soils contaminated with heavy metals. It aims to consolidate findings on immobilization processes and critically examine their effectiveness and risks under field conditions.

Heavy metal contamination in industrial and mining-affected soils poses a major environmental challenge requiring low-cost, scalable, and environmentally sound remediation strategies. Rock powders derived from silicate-rich minerals such as basalt, wollastonite, and metabasalt can mitigate contamination through multiple chemical and biological pathways. These include adsorption of metal ions onto mineral surfaces, precipitation as hydroxides or carbonates, and CEC that displaces heavy metals from exchange sites [44, 68]. In addition, microbial activity contributes to organic-metal complexation and biotransformation into less bioavailable forms [69, 70].

These simultaneous mechanisms are depicted in Fig. 5, which illustrates how rock powder application triggers a suite of stabilization processes involving minerals and soil microbiota. The diagram illustrates how application of rock powder (basalt, wollastonite) initiates multiple parallel processes: adsorption of metal ions such as lead (Pb^{2+}), cadmium (Cd^{2+}), zinc (Zn^{2+}), copper (Cu^{2+}), nickel (Ni^{2+}), and chromium (Cr^{3+}) onto mineral surfaces; precipitation of metals as insoluble hydroxides and carbonates; CEC releasing beneficial nutrients; increased soil pH, reducing solubility and mobility; redox-driven precipitation; organic-metal complexation by microbial biofilms and exudates; and microbial transformation of metals to less toxic forms. These mechanisms together result in the formation of stable metal complexes, lower mobility and bioavailability of heavy metals, decreased plant uptake, and improved soil health [55, 69–72].

Experimental studies have demonstrated the potential of silicate amendments to reduce the mobility of toxic elements. In China, the application of wollastonite and basalt reduced Pb and Cd concentrations in soil solution by up to 40%, primarily via mineral complexation and pH-induced precipitation; this reduction in metal mobility is attributed to the ability of silicate minerals to form stable complexes with heavy metals, thereby limiting their bioavailability and leaching into groundwater [42].

However, the mineral composition of rock powders must be considered. Studies like de Souza et al. [67] found that soapstone, although improving Oxisol soil nutrients, also increased Ni and Cr uptake by plants highlighting potential toxicity risks. While soil metal levels remained within acceptable limits, these findings highlight the need for further investigation into the agricultural use of soapstone due to heavy metal mobility.

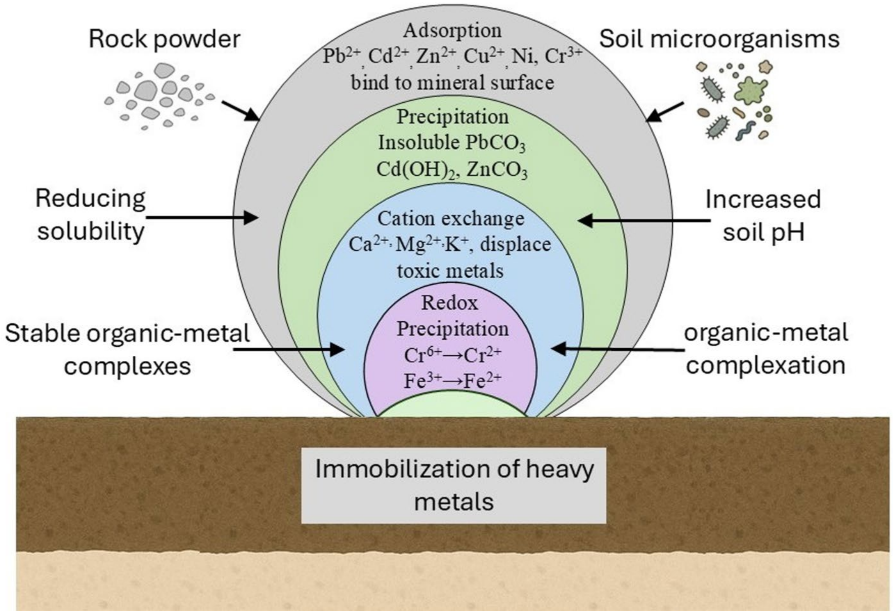

Fig. 5 Mechanisms of heavy metal immobilization in soil following rock dust application. These include adsorption on mineral surfaces, precipitation of insoluble compounds, CEC, redox reactions, pH-induced solubility reduction, and organometallic complexation. Together, these processes promote the stabilization of PTEs in the soil matrix. Conceptual model developed by the authors based on the reviewed literature

In Brazil, Perdoncini et al. [73] assessed the use of metabasalt, a by-product of amethyst mining, in swine wastewater. Doses ranging from 4 to 160 kg m^{-3} led to substantial reductions in Cu, Zn, and P in the liquid fraction, indicating the material's capacity to adsorb and immobilize both nutrients and metals over time. These findings suggest that metabasalt powder is an effective pretreatment for swine liquid waste, reducing the contaminant load in the liquid fraction and promoting the accumulation of ions in the solid fraction. This facilitates safer water disposal and underscores the potential of rock powders for environmental remediation.

Rock powders improve soil fertility and contribute to environmental remediation by enhancing pH and immobilizing contaminants. For example, metabasalt powders have demonstrated the ability to retain nutrients and reduce the mobility of potentially toxic elements (PTEs), such as Cr and Ni, in organic waste streams and acidic soils [73, 74]. Recent research demonstrates that pairing rock powders with biological amendments can enhance both soil health and greenhouse-gas dynamics. Inoculation with *Bacillus subtilis* or *Trichoderma harzianum* boosted fertility and plant growth [26], while co-application with livestock slurry led to contrasting emissions higher CH_4 but lower N_2O releases [33, 75]. The application of rock powders must consider the presence of PTE. Brazil, for example, has established limits for arsenic (As) (15 ppm), mercury (Hg) (0.1 ppm), Pb (200 ppm), and Cd (10 ppm) [9]. The ability of basaltic rock powders to increase soil pH can reduce the solubility and bioavailability of these elements, minimizing environmental risks [74].

The ability of rock powders to absorb heavy metals and reduce their mobility in contaminated soils is supported by their mineral composition and surface properties. For instance, silicate minerals such as wollastonite and basalt contain reactive sites that facilitate the immobilization of heavy metals through adsorption and precipitation mechanisms [68]. The alkaline character of certain rock powders, such as wollastonite, plays a critical role in enhancing metal immobilization by increasing soil pH. Higher pH values promote the formation of less soluble metal hydroxides, reduce the activity of free metal ions, and enhance retention in soil colloids [42, 44, 72]. This dual action chemical binding and pH-driven precipitation makes rock powders particularly suitable for acidic soils with elevated mobility of heavy metals.

Despite these benefits, the use of rock powders is not without risks. Minerals like soapstone, serpentinite, and some ultramafic rocks may contain trace levels of Ni, Cr, or cobalt (Co), which could increase in bioavailability under certain soil conditions [18, 69]. In addition, the long-term stability of immobilized metals remains poorly understood, especially under fluctuating redox or pH regimes. Field validation is limited, and most evidence derives from short-term or controlled-environmental studies. There is also a lack of standardized guidelines regarding optimal application rates, particle size, and interaction with co-contaminants or organic amendments.

Rock powders offer a promising, low-cost alternative for stabilizing heavy metals in soil, especially when integrated into circular economy frameworks that valorize mining by-products. However, their application requires careful selection of mineral types, rigorous risk assessment, and long-term monitoring to ensure environmental safety. Combining silicate amendments with organic materials such as compost or biochar may enhance performance and reduce risks, but further studies are needed to support such integrated strategies.

8 Types of rock powder and their characteristics

Rock powders have emerged as a sustainable alternative for soil remineralization, offering agronomic, environmental, and economic benefits. Derived from mafic, ultramafic, silicate, and phosphoric rocks, these materials are natural sources of nutrients, including K, Ca, Mg, and trace elements. Their application enhances soil fertility, aids in the recovery of degraded areas, facilitates pollutant adsorption and contributes to atmospheric carbon sequestration [25]. The agronomic efficiency of rock powders depends on factors such as mineralogy, rock chemistry, soil characteristics, and management practices [25, 76].

Mafic and ultramafic rocks, including basalts, lherzolites, dunites, and harzburgites, are rich in trace elements such as Ni, Cr, Cu, and Zn. These rocks are commonly found in large igneous provinces, such as the Deccan, Siberian, and Emeishan traps. Their widespread availability and low cost make them promise for agricultural use [25]. However, their application requires caution due to the possible presence of PTEs in the composition of these rocks. Regulatory limits for the presence of these elements in soils vary by country. For example, China sets thresholds of 500 ppm for Cr and 100 ppm for Ni, while Canada restricts the long-term accumulation of PTEs in soils [18].

Glauconite, a phyllosilicate rich in Fe and K, is particularly effective in tropical soils. Its honeycomb-like structure allows for water and nutrient retention, making it a potential source of K [77]. This evidence has the potential to replace synthetic fertilizers such as NPK [15–17].

Phosphate rocks, primarily composed of apatite and phosphorite, are vital sources of P. Their chemical composition includes Ca, P, Fe, Al, silicon, Mg, and K [31]. These rocks are extensively used in fertilizer production, feed additives, and detergents, accounting for 80–90% of global phosphate rock consumption [31].

Alkaline volcanic rocks, rich in sodium oxide (Na_2O) and potassium oxide (K_2O), are another significant source of K. Recent studies have demonstrated their effectiveness in plant nutrition, with mineralogical compositions including quartz, anorthite, albite, and potassium feldspar [78] (Table 1).

9 Factors influencing efficiency and broader impacts of rock powder applications

The efficiency of rock powders as remineralizers depends on several factors. Mineralogy and rock chemistry play a critical role, as less crystalline rocks with higher specific surface areas (such as fine particles) exhibit faster dissolution rates. Soil characteristics, particularly in highly weathered and acidic tropical soils, also favor mineral dissolution [33]. Plant species with long growth cycles or extensive root systems can better utilize the released nutrients. Climatic conditions, such as high temperatures and precipitation, further accelerate weathering processes [33]. The time of application is relevant, as silicate minerals require extended periods to release nutrients effectively [33]. These interactions are highly context dependent. The effectiveness of remineralizers is strongly influenced by regional variables, including soil texture (clay vs. sand), baseline pH, rainfall, and cropping systems. For instance, results observed in Brazilian Oxisols may not translate directly to loamy or calcareous soils in Europe or North America [55].

For instance, Anda et al. (2015) observed that basalt applied to tropical Oxisols increased maize yield and CEC more effectively than in sandy soils, due to better water

Table 1 Types of rocks used for soil remineralization, main mineral components, nutrients released, and primary mechanisms for nutrient release and heavy metal stabilization

Rock type	Main minerals	Key nutrients released	Soil-effect mechanisms	References
Basalt	Plagioclase, pyroxene, olivine	Ca, Mg, K, P, Fe, Mn	pH increase, CEC, adsorption, slow-release, organic-metal complexation	[15, 43]
Phonolite	Nepheline, K-feldspar	K, Na, Ca	Slow-release, CEC, mineral weathering	[12, 78]
Dacite	Quartz, feldspar, biotite	Ca, Na, K, Si	Adsorption, pH regulation, precipitation, nutrient release	[33, 76]
Wollastonite	$CaSiO_3$	Ca, Si	Adsorption, precipitation, pH increase, CEC	[42, 68]
Glauconite	Fe, K silicate	K, Fe	CEC, organic-metal complexation, pH buffering	[15, 77]
Dunite	Olivine	Mg, Fe, Si	CEC, precipitation, redox stabilization, adsorption	[27, 43]
Phosphate rock	Apatite, phosphorite	P, Ca	pH regulation, nutrient release, adsorption	[30, 31]
Carbonatite	Calcite, dolomite	Ca, Mg	pH increase, adsorption, precipitation, CEC	[33, 79]
Diabase	Plagioclase, pyroxene	Ca, Mg, Fe, K	Mineral weathering, CEC, precipitation, pH increase	[33, 76]
Syenite	K-feldspar, plagioclase, hornblende	K, Na, Ca	Slow-release, mineral weathering, CEC	[76]
Metabasalt	Plagioclase, amphibole	Ca, Mg, Fe	Adsorption, precipitation, CEC, nutrient retention	[73]
Soapstone	Talc, chlorite, magnesite	Mg, Si	Slow-release, pH buffering, precipitation	[67]
Schist	Quartz, mica, feldspar	K, Mg, Ca	Organic-metal complexation, nutrient release, pH buffering	[80]
Nepheline syenite	Nepheline, K-feldspar, albite	K, Na, Si	CEC, mineral weathering, and slow release	[81]
Volcanic rock	Various (chabasite, feldspars, etc.)	K, Ca, Mg, Si	Adsorption, pest control (with propolis), slow release	[66]

retention and microbial colonization. In contrast, Basak et al. [78] reported that in temperate Alfisols, weathering rates were slower, requiring smaller particle sizes and longer timeframes for significant nutrient release. Crop species also play a role: shallow-rooted cereals may benefit less than legumes with extensive root systems capable of mobilizing P from silicates. Similarly, basalt applied in the humid Colombian Andean foothills showed faster reactivity than in semi-arid zones where limited soil moisture slowed dissolution [25, 33].

The interaction between rock powders and soil microbiota significantly influences nutrient availability and soil health. Mineral weathering-promoting bacteria, such as *Bacillus subtilis* and *Trichoderma harzianum*, can accelerate the dissolution of minerals, increasing the availability of nutrients like K, P, and Ca [82]. In highly weathered tropical soils, rock powders have been shown to enhance microbial activity, particularly in organic matter decomposition and humic acid formation. These organic compounds interact with rock minerals, improving soil structure and promoting nutrient uptake by plants [33]. However, the impact on microbiota varies depending on the type of rock, soil conditions, and management practices. For example, in acidic soils, basaltic rock powders can increase pH, altering microbial community composition and activity [74].

The use of rock powders as soil remineralizers is not only environmentally sustainable but also economically viable. The wide availability of suitable rocks, such as basalts, shales, and phonolites, significantly reduces production costs [83]. In countries like Brazil, where K fertilizer imports exceed 96% of total usage, nutrient-rich rock powders like glauconite could reduce dependency on external inputs and lower associated costs [15–17]. However, long-term cost–benefit analyses are needed to evaluate the profitability of these practices across different agricultural contexts.

Rock powders are key to sustainable agriculture, ecological restoration and climate mitigation via carbon sequestration. Both silicate and carbonate types enhance soil structure by boosting organic-matter formation and nurturing beneficial microbial communities [47, 48]. Their fine grind accelerates weathering, releasing macro- and micronutrients at low cost and improving nutrient availability [84].

The interaction between rock powders and soil microbiota is a promising research area requiring further studies to optimize its application. Future research should focus on evaluating the long-term effects of these materials on microbial diversity and their relationship with nutrient release, as well as on developing strategies to enhance their positive impact on soil health [85].

Silicate rocks supply nutrients such as Ca, P, K, Mg, and trace elements essential for healthy plant growth. Unlike synthetic fertilizers, which primarily provide N, P, and K, rock powders also deliver micronutrients often absent in conventional fertilizers. These micronutrients are critical for increased production, phytonutrient synthesis, and optimal plant growth. Their deficiency can limit the utilization of N, P, and K, leading to nutrient imbalances and environmental contamination of groundwater, rivers, estuaries, and coastal ecosystems [47, 48].

The ERW can improve soil fertility by gradually releasing nutrients, particularly basic cations such as Ca^{2+} and Mg^{2+}found in basalt. Its application has been shown to buffer soil acidity, offering a sustainable alternative to liming with the added benefit of CO_2 sequestration [47, 48]. However, compared to conventional fertilizers, rock powders generally contain lower nutrient concentrations and exhibit slower dissolution rates, which may limit their short-term effectiveness. As such, they are better suited as complementary amendments to support long-term soil health, rather than direct replacements in high-input cropping systems [33, 75].

The effectiveness of rock powder applications is highly influenced by regional characteristics, including soil type, climate, and local agricultural practices [78]. In regions with high rainfall and acidic soils, such as the Brazilian Cerrado or the Colombian Andean foothills, basalt and phonolite powders tend to be more reactive, increasing soil pH and releasing nutrients more rapidly [10, 25]. Conversely, in arid and semi-arid zones, the lower moisture availability may limit dissolution and nutrient release, requiring tailored application rates or co-application with organic matter [33]. These examples highlight the importance of site-specific research before recommending broad-scale implementation.

10 Most studied crops and soil types

Table 2 summarizes representative case studies selected from peer-reviewed publications indexed in Scopus between 2014 and 2024, based on their representativeness, data availability, and methodological consistency across studies. The selection focused on

Table 2 Summary of case studies on crop response to rock powder application by soil type, crop, dose, and country (2014–2024)

Country	Crop	Crop	Rock powder	Dose	Soil types	Treatment time	Findings	References
Australia	Maize and basil	Maize and basil	Alkaline volcanic rock	Acid-extracted fractions	Sandy soil	45 days after sowing	Slow-release K source. Rhizosphere activity enhanced K release for plant uptake	[78]
Belgium	Potato	Potato	Basalt	50 t ha^{-1}	Loamy soil	99 days	Increased soil alkalinity and Ca/Mg content, with a 6% increase in tuber yield. Estimated CO_2 sequestration of 0.77 t ha^{-1} over 99 days	[55]
Brazil	Bean	Bean	Basalt and phosphate rock	120–350 t ha^{-1}	Red oxisol	55 days	Improved soil fertility and foliar development. Basalt and phosphate rocks were effective sources of P, Ca, and Mg	[87]
Brazil	Maize	Maize	Basalt	5 t. ha^{-1}	Clayey quartzite neosol	60 days for rock powder incubation and 40 days of greenhouse experimentation from the start of germination	Improved soil fertility (P, Fe, S, Ca, K) and plant growth parameters (height, leaf area, shoot and root dry matter)	[26]
Brazil	Maize	Maize	Carbonatite	75% single superphosphate + 25% rock powder and 50% single superphosphate + 50% rock powder	Dystrophic Red-red-yellow latosol of medium texture	N.D	In the initial development of maize, the combination of 75% single superphosphate + 25% rock powders and/or 50% of both was more efficient than conventional fertilization	[79]

Table 2 (continued)

Country	Crop	Crop	Rock powder	Dose	Soil types	Treatment time	Findings	References
Brazil	Maize	Maize	Nepheline syenite and phonolite	0–400 mg kg^{-1}	Low-K soil	Incubation 30 days before sowing, 45 days after the plants are born	Similar effects on soil attributes (pH, CEC, base saturation) and K accumulation compared to KCl. Higher doses improved dry matter yield	[81]
Brazil	Maize	Maize	Dunite	0–1542 mg kg^{-1} (clay soil), 0–933 mg kg^{-1} (sandy soil)	Rhodic hapludox	Until corn production. Time not mentioned	Increased Mg, Si, pH, and productivity. Improved grain filling and yield	[27]
Brazil	Maize and black oat	Maize and black oat	Dacite	0–7251 kg ha^{-1} (with and without dairy slurry)	Typic hapludox	70 days for Maize and black oat	Enhanced growth and nutrient uptake at 7251 kg ha^{-1} with dairy slurry. There is no significant risk of toxic element contamination	[76]
Brazil	Plum	Plum	Schist (50% shale, 50% calcareous shale)	0–3000 kg ha^{-1} $year^{-1}$	Typic Hapludox	4 years	Application of 1000 kg ha^{-1} increased cumulative production and maintained fruit quality and soil P and K levels	[80]
Brazil	Soybeans and maize	Soybeans and maize	Basalt	0, 33, 66 y 99 Mg ha^{-1}	Clayey and sandy clay loam	The seeds were planted 90 days after treatment and left until they grew	Increased dry mass of crops, elevated soil pH, and higher concentrations of Ca, Mg, and P	[16, 17]
Brazil	Tomato	Tomato	Phonolite	0–50 g (equivalent to 0–100% recommended K_2O)	Clayey oxisol	60 days incubation, 90 days culture	Phonolite served as an alternative K source, with optimal results at 12.5 g combined with organic compounds	[12]
China	Soil study	Soil study	Phosphate rock	1.25 g rock powder + 2.5 g soil	Sandy eolian soil	70 days of incubation and 6 months of cultivation	γ-polyglutamic acid increased available P by 36.15%, enhancing P activation	[85]

Table 2 (continued)

Country	Crop	Crop	Rock powder	Dose	Soil types	Treatment time	Findings	References
Switzerland	Vineyard	Vineyard	Basalt	20 t ha^{-1}	Slightly alkaline and acidic soils	1 year, 1 application only	Increased soil respiration and sodium concentration. Limited significant changes, possibly due to high dosage	[86]

diversity in soil types (e.g., Oxisols, Hapludox, Eolian soils), rock powders such as basalt, phonolite, carbonatite, and silicate rocks, and crop species to illustrate geographical and agronomic variability in application outcomes. These soil types differ in texture, mineralogy, and baseline fertility, which strongly influence the dissolution rates of silicate minerals. For instance, highly weathered Oxisols tend to show greater responsiveness to remineralizers due to their acidity and low native nutrient content, while loamy soils may buffer pH changes and delay nutrient release [33].

Studies conducted in various countries, including Switzerland, Brazil, Belgium, China, Australia, and Norway, have demonstrated that these materials, applied at doses ranging from 1 t·ha^{-1} to 350 t·ha^{-1}, significantly improve key soil parameters, such as pH, Ca, Mg, P, and K concentrations, as well as CEC [15–18, 55].

Additionally, significant increases in plant biomass, crop yield, and agronomic efficiency have been observed, particularly when rock powders are combined with microorganisms or organic amendments [13, 26, 76]. These benefits, however, are context dependent. Agronomic effectiveness varies with soil type, application dose, and microbial interactions, which modulate nutrient release rates [78, 86]. These findings collectively support using rock powders as a sustainable alternative for soil fertilization and quality improvement in diverse agricultural systems.

11 Challenges and prospects of rock powders

Although rock powders represent a promising alternative for soil remineralization, their application is not free from limitations and potential adverse effects. These limitations encompass the soil's physical, chemical, and biological aspects and practical and environmental concerns that must be considered to ensure their safe and effective use.

Repeated addition of rock powders can modify soil structure, negatively affecting its porosity and hydraulic properties. For example, pore-clogging due to fine particles can alter air–soil gas exchange processes and water dynamics, especially in the short term [50, 88]. This phenomenon has been observed in studies where the application of ground limestone affected aeration and water infiltration in agricultural soils [89, 90].

Silicate minerals used in ERW contain PTE, such as Cr, Ni, Cu, and Zn, which can be released during weathering [91]. These elements can accumulate in the soil, affecting crop health, biological activity, and nutrient cycles. Although mafic rocks, such as basalts, are considered safer due to their lower heavy metal content than ultramafic rocks, they still exhibit elevated PTE levels relative to agricultural soils [43, 92]. The accumulation of these elements can interfere with food production and safety, especially in repeated applications [74].

The large-scale application of rock powders poses logistical and economic challenges. The availability of raw materials, the costs of milling, transportation, and distribution, as well as the need for specialized equipment, can limit the viability of this practice [74]. For instance, researchers at EMBRAPA recommend that rock powder production facilities be located within a 300 km radius of farms to maintain economic feasibility, as transport costs significantly influence the final application cost [15]. Furthermore, co-location with existing mining or quarrying operations can reduce energy inputs and enhance the circular use of industrial by-products. Furthermore, the amount of material required to affect soil remineralization significantly can be considerable, increasing the costs and environmental footprint associated with its extraction and processing. Despite the initial costs, long-term benefits such as reduced fertilizer dependence, improved soil structure, and gradual nutrient release can offset economic barriers, especially when integrated with regional sustainable agriculture policies.

Adopting ERW on a large scale carries the risk of heavy metal contamination, particularly Ni, when rapidly weathering ultramafic rocks are used [93, 94]. Although basalt is proposed as a safer alternative due to its lower Ni content, its use still requires caution. In alkaline soil, the risk of Ni leaching can be reduced due to the formation of insoluble hydroxides and carbonate salts, which retain this metal in the soil [55].

However, in acidic soils, the mobility and bioavailability of PTE can increase, exacerbating toxicity risks. Initially, ultramafic rocks, such as lherzolites and dunites, were considered ideal for remineralization due to their high reactivity. However, their high Ni and Cr content led to their discard in favor of mafic rocks, such as basalts, which present lower concentrations of these elements [43, 44]. Despite this, basalt still contains significant levels of PTE, underlining the need for strict monitoring and regulation to avoid negative impacts on soil health and crops [92].

11.1 Environmental and economic limitations of rock powder use

Despite the environmental appeal of repurposed mineral byproducts, the use of rock powders in agriculture is associated with several logistical, agronomic, and environmental constraints. The grinding process required to achieve the fine particle sizes needed for agronomic effectiveness (typically < 75 μm) is energy-intensive, resulting in high operational costs and elevated carbon emissions when fossil fuels are used [75]. These emissions along with those generated during transportation and field application can partially offset the climate benefits associated with carbon sequestration through ERW. Moreover, the viability of rock powder application at scale is significantly constrained by transportation logistics; to remain economically feasible, the production and distribution of remineralizers must generally occur within a 300 km radius of target farmlands [95, 96].

Given these constraints, it is essential to evaluate whether the environmental benefits of rock powder use such as long-term carbon sequestration and reduced dependence on synthetic fertilizers effectively compensate for the energy demands and emissions associated with their production. Life Cycle Assessments (LCAs), particularly those following ISO 14044 standards, are critical tools for assessing these trade-offs. Recent studies [97, 98] have shown that grinding energy is one of the most influential factors in the environmental footprint of ERW. Future research should therefore focus on optimizing grinding technologies and promoting the use of renewable energy sources to enhance the overall sustainability of these amendments.

Another critical consideration involves the chemical composition of rock powders, particularly those derived from ultramafic or mafic sources such as serpentine or basalt. These materials may contain elevated concentrations of PTEs like Cr, Ni, and Co, which under certain conditions may accumulate in soils or be taken up by plants [18]. The mobilization of these elements is influenced by soil pH, redox potential, and microbial activity, adding complexity to their environmental management. Long-term field trials and continuous monitoring are essential to ensure that remineralization does not inadvertently lead to heavy metal contamination in agroecosystems [34].

The agronomic effectiveness of rock powders may also be limited in the short term due to the low solubility and slow-release rates of key nutrients, particularly P and K. Unlike synthetic fertilizers, which provide nutrients in readily available forms, silicate-based remineralizers require sustained microbial and chemical weathering to become plant-accessible [75]. These constraints can reduce immediate crop response and may discourage adoption by farmers who prioritize short-term productivity. Therefore, rock powders should be considered complementary soil amendments, especially suitable for long-term soil health restoration rather than direct replacements for synthetic fertilizers in intensive production systems.

While rock powders offer ecological and agronomic promise, their implementation also presents systemic challenges that must be considered through a broader sustainability lens. Beyond the well-known issues of energy consumption during grinding and transportation constraints discussed in Sect. 10 other critical factors influence their large-scale adoption. These include production and processing costs, limited awareness among farmers about their long-term benefits, and a lack of technical assistance or training programs. Additionally, restricted access to subsidies, credit, or other financial incentives represents a major barrier, particularly for smallholder farmers in developing regions.

These challenges are often exacerbated by market uncertainties and the lack of robust value chains for mineral-based inputs, which reduce the appeal of these amendments to agricultural stakeholders. Without adequate governance and market support, the adoption of mineral byproducts-based amendments may remain limited to pilot projects or isolated regional initiatives. Integrating rock powder production into localized circular economy strategies particularly in areas near mining hubs could improve feasibility, minimize environmental burdens, and foster territorial sustainability. Therefore, future policy design should incorporate not only environmental safeguards but also economic instruments that ensure equitable access and encourage widespread adoption.

11.2 Limitations of mineral byproducts as a soil amendment

The agronomic efficiency of rock powders is highly dependent on their mineralogical composition, which can vary significantly depending on the origin, weathering state, and grinding process of the source rock. This heterogeneity contributes to inconsistencies in field results across different agroecosystems. For example, basalt from one deposit may be rich in plagioclase and pyroxenes, whereas another may contain higher levels of amorphous silica or trace metals, affecting nutrient release kinetics and weathering rates. Studies by Basak et al. [78] and Crusciol et al. [27] reported improved plant growth using rock powders in tropical soils, while others found limited or no effects in temperate regions or under short-term trials. Moreover, particle size and mineral reactivity are critical factors; insufficiently ground or inert materials may persist in soils without contributing to immediate nutrient availability. This variability underscores the need for site-specific evaluation and standardization protocols prior to large-scale deployment [43].

Although the environmental safety of rock powders is often assumed, variability in their geochemical composition requires monitoring. Some rock types, particularly those of mafic or ultramafic origin, may contain trace elements such as Cr and Ni at concentrations that could pose long-term environmental risks if applied repeatedly without regulation. These elements may become more bioavailable in acidic soil, increasing their potential uptake by crops or leaching into water systems [55, 74]. Therefore, a detailed chemical characterization of materials and long-term monitoring under diverse soil conditions are necessary.

The performance of rock powders is highly context-dependent, influenced by interactions with edaphoclimatic variables such as soil pH, texture, organic matter content, microbial activity, and precipitation. For instance, favorable responses to remineralizers are often observed in nutrient-depleted tropical soils with high weathering degrees, where basic cations help reestablish fertility. In contrast, soils in arid or temperate zones may experience delayed effects due to slower mineral dissolution and lower microbial activity. Crop type, root morphology and agronomic practices (e.g., tillage, cover crops) further modulate the bioavailability of released nutrients. These environmental dependencies highlight the need for adapted application strategies based on local soil and climate conditions, validated through long-term field trials.

The interaction between rock powders and the soil microbiome remains poorly understood. Changes in microbial community structure could influence nutrient cycling, metal mobility, and overall soil functionality. Emerging studies suggest that microbial processes play a central role in regulating the dissolution of silicate minerals and mediating the formation of stable organic mineral complexes [42, 99, 100]. To address this knowledge gap, future research should incorporate metagenomic approaches to assess how microbial diversity and activity respond to different types and dosages of rock powders across soil types and climatic zones.

11.3 Legal and regulatory frameworks for the use of rock powders

The regulatory landscape for rock powder application in agriculture varies significantly across countries. In Brazil, the use of remineralizers is governed by Law No. 12.890/2013 and Normative Instruction No. 05/2016 issued by the Ministry of Agriculture, Livestock and Food Supply [9], which set clear standards for nutrient content, particle size, and permissible levels of PTEs. According to Brazilian regulations, a remineralizer must contain no more than 20% free silica. The combined content of calcium oxide (CaO), magnesium oxide (MgO), and potassium oxide (K_2O) must be equal to or greater than 9%, with a minimum of 1% K_2O. Additionally, at least one of these oxides must be present in a reactive form. The legislation also establishes maximum permissible limits for potentially toxic elements, including As, Pb, Hg, and Cd (previously mentioned in Sect. 7).

In terms of particle size distribution, the requirements vary depending on whether the material is classified as a powder or a ground (granulated) product. For powdered materials, 100% must pass through a 2 mm sieve, 70% through a 0.84 mm sieve, and at least 50% through a 0.3 mm sieve. However, this does not imply that all particles must be smaller than 2 mm in diameter; it refers to the proportion of material that can pass through sieves of specific mesh sizes. For ground materials, 100% must pass through a 4.8 mm sieve, a minimum of 80% through a 2.8 mm sieve, and a maximum of 25% through a 0.84 mm sieve [9].

While Brazil has a well-established regulatory framework, other countries are still developing legal definitions and standards. For instance, Canada does not yet provide a clear legal classification for remineralizers but does regulate the long-term accumulation of heavy metals in soils [74]. Similarly, China sets maximum thresholds for contaminants like Cr (500 ppm) and Ni (100 ppm), influencing the selection of raw materials used in agricultural applications [42].

A harmonized international framework is still lacking. Variations in permissible PTEs levels, definitions, and compositional standards across countries present a challenge to the broader adoption of rock powders. To ensure safety, consistency, and environmental integrity, it is essential to develop standardized regulatory frameworks at both national and international levels. These frameworks should include clear classification systems, testing protocols, and environmental safeguards. A coordinated approach would facilitate knowledge exchange, support global trade of remineralizers, and build trust among farmers, industry, and policymakers.

12 Prospects

Using rock powders to remineralize soils presents significant potential for sustainable agriculture, ecological restoration, and climate change mitigation. However, their widespread adoption requires addressing logistical, economic, and environmental constraints and filling knowledge gaps.

The availability of raw materials and the use of existing agricultural equipment, such as fertilizer and lime spreaders, can help overcome logistical challenges and reduce application costs [47, 48]. Sourcing powders from the by-products of the aggregates or mining industries can lower production costs and align with circular economic principles. The slow-release nature of nutrients in rock powders may reduce dependency on synthetic fertilizers and improve long-term soil health [47, 48].

Future efforts must include life cycle assessments aligned with international standards like ISO 14044 to evaluate the environmental impact of large-scale applications. Furthermore, combining rock powders with sustainable practices such as conservation agriculture or biofertilizers could enhance their agronomic benefits. For example, co-applying rock powders and compost may improve soil structure, stimulate microbial activity, and reduce PTEs mobility [75].

Priority areas for future research include examining the influence of rock powders on microbial diversity, bioturbation, and nutrient cycling, as well as comparing the environmental costs associated with their extraction, processing, and transportation relative to synthetic fertilizers. It is also required to develop strategies to enhance mineral solubility, such as the use of beneficial microbial inoculants or the co-application of organic amendments [74, 75]. Future research should assess the cumulative effects of rock powder application on soil quality, crop productivity, and the accumulation of PTEs.

Equally important is the proper characterization of the raw materials used. Lithochemical analyses are necessary to determine elemental composition and detect the presence of PTEs, while petrographic analyses help assess mineralogical composition, texture, and degree of weathering. These factors are relevant in predicting nutrient release patterns, solubility, and agronomic efficiency under different soil and climatic conditions. A standardized protocol for material evaluation would strengthen quality control and ensure safe, site-specific recommendations. Finally, it is important to advance the development of harmonized international regulations to ensure the safe and effective use of rock powders across diverse agricultural and environmental contexts.

In addition, the development of a simple decision-support framework could guide farmers, researchers, and policymakers in selecting appropriate rock powders based on key agronomic and economic factors. These include crop nutrient requirements, soil pH, mineralogical composition and solubility of the rock powder, local material availability, and application costs. Integrating these variables into a user-friendly matrix or decision tree would facilitate context-specific recommendations and support broader adoption in diverse agroecosystems.

13 Conclusions

This review provides an overview of soil remineralization using rock powders derived from mineral byproducts, analyzing its agronomic, environmental, and regulatory dimensions within the framework of the circular economy. Between 2014 and 2024, there has been growing global interest in this topic, especially in tropical and subtropical regions, where soil degradation, fertilizer dependence, and climate vulnerability constitute critical challenges.

The literature review reveals that Brazil, China, Colombia, and the United States lead global research, with basalt, phonolite, and other silicate rocks being the most studied materials. The agronomic benefits of rock powders include the gradual release of macro- and micronutrients (such as Ca, Mg, K, and P), improved CEC, pH correction in acidic soils, and stimulation of microbial activity. These effects contribute not only to soil fertility but also to ecological restoration and increased carbon sequestration, particularly through improved weathering techniques.

Environmental applications of rock powders have demonstrated potential for stabilizing heavy metals and reducing the mobility and bioavailability of toxic elements such as Cr, Ni, and Pb, especially in acidic or mining-affected soils. However, their effectiveness is context-dependent and influenced by rock type, particle size, application rate, and site-specific edaphic and climatic conditions. While basalt and metabasalt have shown consistent performance in both agronomic and remediation contexts, ultramafic rocks such as dunite and soapstone can pose risks due to elevated levels of PTE.

From an economic perspective, integrating rock powders into agricultural practices is viable when local materials are used and transport distances are minimized. However, energy-intensive milling processes and a lack of financial incentives remain key obstacles. Regulatory frameworks vary by country; Brazil is the most advanced in establishing legal standards for the use of remineralizers, while other countries still lack clear definitions and safety thresholds. To support the sustainable implementation of rock powder technologies, this review highlights five key research priorities: (1) assessing their impact on microbial diversity and nutrient cycling; (2) evaluating environmental costs compared to synthetic fertilizers; (3) developing strategies to improve mineral solubility, including microbial inoculants and organic amendments; (4) measuring long-term cumulative effects on soil and agricultural systems; and (5) promoting international regulatory harmonization.

Rock powders offer a promising avenue toward regenerative agriculture, waste valorization, and climate change mitigation. Their role should be framed not only as nutrient inputs but as long-term soil conditioners within circular economic strategies. Wider adoption requires interdisciplinary research, including site-specific policies and implementation protocols, to maximize benefits and minimize environmental and economic risks.

Author contributions

H.H.P: Conceptualization, methodology, investigation, formal analysis, visualization, writing; A.I.N.G: Investigation, writing, review & editing; A.N: Investigation, formal analysis, writing, review; D.P.O: Conceptualization, methodology, investigation; A.L.M.R: Investigation, formal analysis; C.G.R: Formal analysis, visualization, writing.

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