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ALKALINE VOLCANIC ROCKS POTENTIALS AS NATURAL FERTILIZATION – A REVIEW

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ABSTRACT

Alkaline volcanic rocks are a promising natural resource for sustainable agriculture, offering a multifaceted approach to soil fertility management and environmental sustainability. These rocks are rich in essential macro- and micronutrients, including potassium, calcium, magnesium, and silicon, which are released gradually through weathering processes, providing a sustained nutrient supply to crops. Their application has been shown to improve soil pH, enhance nutrient availability, and promote beneficial microbial activity, leading to improved crop yields and resilience. This review examines the potential of alkaline volcanic rocks as natural fertilizers, highlighting their mineralogical and chemical properties, mechanisms of action, and agronomic benefits. We discuss case studies and examples of successful applications, as well as challenges and limitations, including variability in rock composition, limited availability, and potential environmental concerns. Finally, we identify future research directions, including characterization of rocks from different sources, optimization of application rates and methods, and long-term effects on soil health and plant growth. By harnessing the potential of alkaline volcanic rocks, we can develop more sustainable and resilient agricultural systems that support global food security and environmental sustainability.

Keywords: Alkaline volcanic rocks, Natural fertilization, Soil amendment

INTRODUCTION

Alkaline volcanic rocks are a group of igneous rocks characterized by elevated concentrations of alkali elements, particularly sodium (Na_2O) and potassium (K_2O), relative to silica content. Unlike subalkaline volcanic rocks such as basalts and andesites, alkaline volcanic rocks are enriched in feldspathoids and alkali feldspars and often contain minerals such as nepheline, leucite, sodalite, and melilite (Daly, 1910; Le Maitre *et al.*, 2019). Common examples include nephelinite, phonolite, trachyte, tephrite, and basanite, which typically form in intraplate tectonic settings, continental rifts, and ocean island environments (Price et al., 1985; Winter, 2020).

From an applied geology perspective, alkaline volcanic rocks are notable for their geochemical reactivity and weathering behavior. Their mineral assemblages tend to release essential macro- and micronutrients during chemical weathering, particularly under humid and tropical climatic conditions. This characteristic differentiates them from more silica-rich volcanic rocks, whose weathering rates and nutrient release potentials are comparatively slower (Delmelle, et al., 2015; Anda *et al.*, 2018). As a result, alkaline volcanic rocks have increasingly attracted attention beyond traditional petrological studies, extending into soil science, agronomy, and sustainable land management research.

Sustainable agriculture has emerged as a global priority in response to declining soil fertility, land degradation, climate change, and the environmental consequences of intensive agrochemical use. Conventional mineral fertilizers, while effective in boosting crop yields, are associated with numerous challenges, including soil acidification, nutrient leaching, greenhouse gas emissions, and long-term deterioration of soil physical and biological properties (Pretty *et al.*, 2018; FAO, 2021). In many developing regions, particularly in sub-Saharan Africa, high fertilizer costs and limited access further constrain agricultural productivity.

Natural fertilization strategies, which utilize locally available geological and biological resources, offer an alternative pathway toward sustainable soil nutrient management. Rock-based fertilizers, also referred to as agrogeological inputs, involve the application of crushed or finely ground rocks to soils to replenish essential nutrients and improve soil chemical balance (Sidsi et al., 2026; Van Straaten, 2020). These approaches align closely with the principles of sustainable agriculture by reducing dependence on synthetic inputs, enhancing nutrient recycling, and promoting long-term soil health.

Within this framework, alkaline volcanic rocks represent a promising natural fertilization resource due to their favorable mineralogical composition and capacity to neutralize acidic soils. Their application is particularly relevant in tropical and semi-arid regions, where soil acidity and nutrient depletion pose persistent constraints to agricultural productivity (Agegnehu, et al., 2021; Dahlgren *et al.*, 2021).

Recent research has demonstrated that alkaline volcanic rocks can serve as effective multi-nutrient soil amendments, supplying potassium, calcium, magnesium, silicon, and trace elements essential for plant growth (Ciriminna et al., 2022; Ramos *et al.*, 2019; Beerling *et al.*, 2020). Through gradual weathering processes, these rocks release nutrients in a slow and sustained manner, reducing nutrient losses and improving nutrient use efficiency compared to highly soluble chemical fertilizers.

In addition to nutrient supply, alkaline volcanic rocks contribute to soil pH regulation by counteracting acidity, thereby improving nutrient availability and reducing aluminum toxicity in acidic soils. This buffering capacity is of particular importance in highly weathered tropical soils, such as Ultisols and Oxisols, which dominate many agricultural landscapes in Africa, South America, and Southeast Asia (Quantin and Becquer, 2025; Anda *et al.*, 2020). Furthermore, the incorporation of volcanic rock powders has been linked to improvements in soil structure, enhanced microbial activity, and increased carbon sequestration through enhanced silicate weathering processes (Beerling *et al.*, 2020; Kelland *et al.*, 2022).

Chemical Composition of Alkaline Volcanic Rocks

Mineralogical Characteristics

The mineralogical composition of alkaline volcanic rocks (Table 1) is fundamentally distinct from that of subalkaline volcanic rocks, primarily due to their enrichment in alkali elements and relatively lower silica saturation (Chayes, 1966). These rocks are commonly characterized by the presence of alkali feldspars (such as sanidine and anorthoclase), feldspathoids (including nepheline, leucite, sodalite, and analcime), and mafic minerals such as clinopyroxene, amphibole, biotite, and olivine (Le Maitre *et al.*, 2019; Winter, 2020). Accessory minerals such as apatite, magnetite, titanite, and perovskite are also frequently observed and contribute significantly to the nutrient profile of these rocks.

From an applied geology perspective, the importance of these mineral assemblages lies in their relative instability under surface weathering conditions. Feldspathoids, in particular, are thermodynamically unstable in the presence of water and carbon dioxide, leading to relatively rapid chemical breakdown and nutrient release compared to quartz-rich silicate minerals (Cardoso, 2021; White & Brantley, 2021). This enhanced weatherability makes alkaline volcanic rocks especially suitable for agrogeological applications, as nutrients are released progressively into the soil system over time.

The dominance of calcium- and magnesium-bearing silicates such as clinopyroxene and amphibole further enhances the agronomic value of alkaline volcanic rocks. These minerals play a critical role in soil base saturation and contribute to the amelioration of acidic soil conditions during weathering (Daba, 2024; Anda *et al.*, 2018). In contrast to conventional lime materials, which primarily supply calcium, alkaline volcanic rocks provide a broader spectrum of plant-essential elements, thereby supporting balanced soil nutrition.

Table 1: Common Alkaline Volcanic Rock Types and Dominant Minerals (Irvine and Baragar, 1985; Daly, 1910)

Rock Type	Classification	Dominant Mineral Phases	Notes / Relevance
Basanite	Alkaline mafic volcanic rock with low silica	Olivine, feldspathoids (nepheline or leucite), plagioclase, clinopyroxene (augite), Fe–Ti oxides (e.g., magnetite, ilmenite)	Common in alkaline suites; significant K, Mg, Ca sources
Tephrite	Similar to basanite but with less olivine	Feldspathoids (nepheline/leucite), plagioclase, clinopyroxene	Intermediate alkaline rock
Nephelinite	Highly undersaturated alkaline volcanic rock	Nepheline, clinopyroxene, olivine	Very low silica; high alkali and nutrient-bearing phases
Phonolite	Fine-grained alkaline felsic volcanic rock	Alkali feldspar, nepheline	Rich in Na–K feldspathoids; nutrient-rich K source
Phonotephrite	Between phonolite and tephrite	Feldspathoids, plagioclase, pyroxene; transitional composition	Transitional alkaline type useful for comparative studies
Trachyte	Felsic volcanic rock in alkaline series	Alkali feldspar (sanidine), plagioclase, minor mafic minerals	Often lighter phases; still alkaline
Hawaiite/ Shoshonite	Subtypes of alkaline basalts	Plagioclase, clinopyroxene, lesser olivine, alkali feldspar	K-rich variants relevant for K nutrient potential

Nutrient Content (K, Ca, Mg, Si and Trace Elements)

Alkaline volcanic rocks are naturally enriched in several macro- and micronutrients essential for plant growth. Potassium (K) is one of the most significant nutrients supplied by these rocks, commonly occurring within alkali feldspars and feldspathoids. Potassium plays a critical role in plant physiological processes, including enzyme activation, osmotic regulation, and stress tolerance, making its sustained release from rock amendments particularly beneficial for long-term crop productivity (Rawat et al., 2016; Ramos *et al.*, 2019).

Calcium (Ca) and magnesium (Mg) are also abundant in alkaline volcanic rocks, primarily hosted in clinopyroxene, amphibole, and olivine. These nutrients contribute to cell wall development, chlorophyll formation, and enzyme function in plants, while also enhancing soil cation exchange capacity and aggregate stability (Khalil et al.,, 2015; Dahlgren *et al.*, 2021). The slow dissolution of Ca- and Mg-bearing silicates ensures gradual nutrient availability, reducing leaching losses that are common with highly soluble fertilizers.

Silicon (Si), although not traditionally classified as an essential nutrient, is increasingly recognized for its beneficial effects on plant health, particularly in cereals and grasses. Alkaline volcanic rocks serve as a significant source of plant-available silicon through the weathering of silicate minerals. Silicon has been shown to improve plant resistance to pests, diseases, and abiotic stresses such as drought and salinity (Coskun *et al.*, 2019; Cooke & Leishman, 2021).

In addition to macronutrients, alkaline volcanic rocks contain trace elements such as iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), and molybdenum (Mo), which are vital for enzymatic and metabolic functions in plants. When applied judiciously, these trace elements can correct micronutrient deficiencies in depleted soils; however, their concentrations and bioavailability vary depending on rock type and degree of weathering (Schulin et al., 2010; Anda *et al.*, 2020).

pH Buffering Capacity

One of the most significant agronomic attributes of alkaline volcanic rocks is their capacity to buffer soil acidity. This buffering effect arises from the release of base cations such as Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} during mineral dissolution, which neutralize hydrogen and aluminum ions in acidic soils (Sharma et al., 2025; Van Straaten, 2020). Unlike conventional liming materials, which often induce rapid and short-lived pH changes, alkaline volcanic rocks promote gradual and sustained pH regulation.

The pH buffering capacity of these rocks is particularly advantageous in tropical and subtropical regions, where intense rainfall and prolonged weathering contribute to soil acidification and nutrient depletion. Studies have demonstrated that the application of alkaline volcanic rock powders can increase soil pH, reduce aluminum toxicity, and enhance phosphorus availability by decreasing P fixation in highly weathered soils (Anda *et al.,* 2018; Kelland *et al.,* 2022).

Furthermore, the buffering action of alkaline volcanic rocks supports a more favorable environment for soil microbial communities, which are highly sensitive to pH fluctuations. Enhanced microbial activity contributes to improved nutrient cycling, organic matter decomposition, and overall soil fertility (Biwas and Kole, 2018; Dahlgren *et al.,* 2021). This integrative effect underscores the relevance of alkaline volcanic rocks as multifunctional soil amendments within sustainable agricultural systems.

Potential Benefits of Alkaline Volcanic Rocks as Natural Fertilizers

Nutrient Supply and Availability

One of the principal benefits of alkaline volcanic rocks as natural fertilizers lies in their capacity to provide a sustained and balanced supply of essential plant nutrients. Unlike conventional synthetic fertilizers, which deliver nutrients in highly soluble forms that are susceptible to rapid leaching and volatilization, alkaline volcanic rocks release nutrients gradually through mineral weathering processes. This slow-release mechanism ensures prolonged nutrient availability in the soil, thereby improving nutrient use efficiency and reducing environmental losses (Shaviv and Mikkelsen, 1993; Ramos *et al.,* 2019; Van Straaten, 2020).

Potassium supplied from alkali feldspars and feldspathoids plays a critical role in enhancing plant metabolic functions, including photosynthesis, protein synthesis, and stress tolerance. Several studies have reported significant improvements in crop potassium uptake following the application of volcanic rock powders, particularly in potassium-deficient soils common in tropical regions (Von Uexkuell, 11986; Anda *et al.,* 2018; Manning, 2021). Similarly, calcium and magnesium released from mafic silicate minerals contribute to improved plant nutrition while simultaneously supporting soil structural stability and cation exchange capacity.

The availability of silicon from alkaline volcanic rocks represents an additional agronomic advantage. Silicon accumulation in plant tissues has been linked to enhanced resistance against pests, pathogens, and abiotic stresses, including drought and salinity. This benefit is particularly relevant for cereal crops such as rice, maize, and wheat, which are known silicon accumulators (Tripathi et al., 2013; Coskun *et al.,* 2019; Cooke & Leishman, 2021). The multi-nutrient nature of alkaline volcanic rocks therefore supports holistic soil fertility management rather than single-nutrient supplementation.

Soil pH Modification and Balancing

Soil acidity is a major constraint to agricultural productivity in many regions of the world, particularly in highly weathered tropical soils. Acidic conditions limit nutrient availability, increase aluminum and manganese toxicity, and suppress beneficial microbial activity. The application of alkaline volcanic rocks has been shown to alleviate soil acidity through the gradual release of base cations during mineral dissolution (Anda *et al.,* 2020; Anda et al., 2015).

Unlike conventional lime materials that often cause abrupt increases in soil pH, alkaline volcanic rocks promote a more moderated and sustained pH adjustment. This controlled buffering effect reduces the risk of over-liming and helps maintain soil pH within an optimal range for nutrient uptake and microbial activity (Agegnehu et al., 2021; Dahlgren *et al.,* 2021). Improved soil pH conditions also enhance phosphorus availability by reducing fixation by iron and aluminum oxides, a common problem in acidic tropical soils (Mao et al., 2017; Kelland *et al.,* 2022).

The capacity of alkaline volcanic rocks to balance soil pH contributes not only to improved crop performance but also to long-term soil resilience. By addressing acidity at its geological source, these rocks offer a sustainable alternative to repeated chemical inputs, aligning with the principles of environmentally sound soil management.

Improved Soil Structure and Fertility

In addition to chemical benefits, alkaline volcanic rocks contribute positively to soil physical properties, which are critical determinants of soil fertility and crop productivity. The incorporation of finely ground volcanic rock materials into soil has been associated with improved aggregate stability, enhanced porosity, and increased water-holding capacity (Nanzyo and Dahlgren, 1993; Beerling *et al.,* 2020). These improvements are particularly beneficial in degraded soils characterized by compaction, poor aeration, and limited root penetration.

The weathering of volcanic minerals contributes to the formation of secondary clay minerals and amorphous materials, which play a crucial role in soil aggregation and nutrient retention. Enhanced soil structure facilitates better root development and improves the efficiency of water and nutrient uptake by plants (Bronick and Lal, 2005; White & Brantley, 2021). Furthermore, improved physical conditions create a favorable habitat for soil microorganisms, thereby strengthening biological processes essential for nutrient cycling and organic matter stabilization.

Applications in Agriculture and Horticulture

Crop Response to Alkaline Volcanic Rock Amendments

The application of alkaline volcanic rocks in agriculture has been increasingly explored as a sustainable soil amendment strategy, particularly in regions characterized by nutrient-depleted and acidic soils. Numerous field and greenhouse studies have demonstrated positive crop responses following the incorporation of volcanic rock powders, with improvements observed in plant growth, yield, and nutrient uptake across a range of crop species (Beerling et al., 2018; Ramos *et al.,* 2019; Manning, 2021).

Cereal crops such as maize, rice, and wheat have shown notable yield improvements when alkaline volcanic rocks are applied as soil conditioners or supplementary nutrient sources. These responses are largely attributed to enhanced potassium, calcium, magnesium, and silicon availability, which collectively support physiological processes such as photosynthesis, root development, and stress resistance (Patel et al., 2022; Coskun *et al.,* 2019; Anda *et al.,* 2020). Root crops and legumes have similarly exhibited improved biomass accumulation and nutrient use efficiency, particularly in soils with low base saturation.

In horticultural systems, the application of alkaline volcanic rocks has been associated with improved fruit quality, increased nutrient density, and enhanced tolerance to environmental stresses. The gradual nutrient release pattern of these materials is especially advantageous for perennial crops and intensive horticultural production systems, where sustained nutrient availability is critical for long-term productivity (Srivastava and Malhotra, 2017; Dahlgren *et al.,* 2021).

Soil Health Improvements

Beyond immediate crop responses, the use of alkaline volcanic rocks contributes significantly to overall soil health, a key objective of sustainable agriculture. Soil health encompasses chemical, physical, and biological dimensions, all of which are positively influenced by volcanic rock amendments. Chemically, these rocks improve soil base saturation and reduce acidity, thereby enhancing nutrient availability and reducing toxic element activity (Anda et al., 2015; Van Straaten, 2020).

Physically, the incorporation of finely ground volcanic materials has been shown to enhance soil structure by promoting aggregate formation and increasing water infiltration and retention. These improvements are particularly valuable in sandy or highly weathered soils, where poor structure and low nutrient-holding capacity limit agricultural productivity (Menzies et al., 2020; Beerling *et al.*, 2020). Improved physical conditions also reduce erosion risk, contributing to landscape-level sustainability.

Biologically, the buffering of soil pH and the supply of essential nutrients create favorable conditions for soil microbial communities. Enhanced microbial activity supports organic matter decomposition, nutrient mineralization, and symbiotic interactions such as mycorrhizal associations, which are critical for plant nutrient acquisition (Singh et al., 2022; White & Brantley, 2021). These cumulative effects position alkaline volcanic rocks as multifunctional inputs capable of restoring degraded soils and supporting resilient agroecosystems.

Case Studies and Examples of Successful Applications

Several case studies (Table 2) across different agroecological zones illustrate the practical effectiveness of alkaline volcanic rocks as natural fertilizers. In Brazil, the application of phonolite and nepheline syenite rock powders has been reported to improve soil potassium levels and increase yields of maize and soybean under tropical conditions (de aquino et al., 2020; Ramos *et al.,* 2019; Silva *et al.,* 2021). These studies highlight the potential of locally sourced volcanic materials to substitute or complement imported chemical fertilizers.

In parts of East Africa, volcanic rock dusts derived from alkaline basalts and nephelinites have been evaluated for their capacity to ameliorate acidic soils and improve crop productivity. Positive responses have been observed in maize and bean cultivation, particularly when rock amendments are integrated with organic inputs such as compost or manure (Soboda, 2016; Anda *et al.*, 2020; Van Straaten, 2020). Such integrated nutrient management approaches enhance nutrient availability while maintaining soil organic matter.

In temperate regions, experimental trials have demonstrated that alkaline volcanic rock amendments can enhance soil silicon availability and improve crop resistance to biotic and abiotic stresses. These findings are increasingly relevant in the context of climate change, where resilient cropping systems are required to cope with increasing environmental variability (Meharg and Meharg, 2015; Beerling *et al.,* 2020; Kelland *et al.,* 2022).

Table 2: Selected Case Studies of Volcanic Rock Amendments and Agronomic Outcomes (Cardozo et al., 2024; Ramos et al., 2015; Ciriminna et al., 2022)

Study / Location	Rock Type Used	Crop(s)	Observed Agronomic Outcomes	Reference
Phonolite and basalt dust amendments in pot trials	Phonolite; Basalt	Beans (*Phaseolus vulgaris*)	Increased plant height (+51%), more leaves (+100%), ~76% higher bean yield & improved nutrient density (Ca ↑59%, protein ↑16%)	Mt. Cameroon pot trials (phonolite & basalt) Remineralize the Earth
Residual basaltic rock powder effects on soil & soybean	Basalt rock powder	Soybean	Influenced soil chemical attributes (pH, Fe, Mn); affected leaf nutrient content (K, Ca, P) after 4 years	Basalt powder & soybean (Brazil) RSD Journal
Field test of trachyte & basalt on maize	Trachyte; Basalt	Maize (*Zea mays L.*)	Higher maize yields with rock powders vs control (basalt ~2558–2931 kg/ha vs ~646 kg/ha control); NPK still highest but rock powders showed strong performance	Sudano-Sahelian Cameroon field trial EGUsphere
Basalt rock powder effects on ryegrass growth	Basalt rock powder	Ryegrass (grass species)	Basalt increased pH and macronutrient supply; yield effects varied by soil type and mineral release	Enhanced silicate weathering pot/field trials MDPI
Local sediment amendments on barley yield	Volcanically influenced sediments	Barley	Amendment increased barley yields and improved nutrient uptake (Si, P) by reducing Al toxicity	Kenya sediment amendment study Frontiers
Preliminary volcanic rock powder soil remineralization	Volcanic rock powder (Brazil)	Multiple crops	Rock powders exhibited agronomic potential and nutrient supply (general effects noted)	Preliminary science evaluation ScienceDirect
Basalt powder soil amendment in ryegrass & crops	Basalt rock dust	Maize, sorghum, oats, potatoes (labeled in review)	Yield gains reported (e.g., sorghum +21%, oats +21%, maize & potatoes +59 kg/ha per ton rock)	Reviewed trials summarizing various responses MDPI

Mechanisms of Action

Nutrient Release and Uptake

The effectiveness of alkaline volcanic rocks as natural fertilizers largely stems from their weathering-driven nutrient release mechanisms. When applied to soils, these rocks undergo chemical and physical weathering processes, gradually releasing essential macro- and micronutrients, including potassium (K), calcium (Ca), magnesium (Mg), silicon (Si), and trace elements (Zaharescu et al., 2020; Anda *et al.,* 2018; Ramos *et al.,* 2019). Weathering is facilitated by soil moisture, temperature, and microbial activity, which accelerate the breakdown of silicate and feldspathoid minerals.

Potassium, predominantly hosted in alkali feldspars and feldspathoids, is slowly solubilized over time, providing a steady nutrient supply that aligns with crop growth cycles (Yadav and sidhu, 2016; Manning, 2021). Similarly, calcium and magnesium from mafic silicates dissolve to contribute to soil base saturation, neutralize acidity, and enhance root nutrient uptake efficiency (Sharma et al., 2025; Dahlgren *et al.,* 2021). The slow-release nature of these nutrients reduces leaching losses common with highly soluble chemical fertilizers, making alkaline volcanic rocks particularly suitable for tropical and subtropical agricultural soils prone to high rainfall and nutrient runoff.

Additionally, the silicon released from silicate minerals has been shown to be bioavailable to plants and supports structural integrity, disease resistance, and tolerance to environmental stressors such as drought and salinity (Imtiaz et al., 2016; Coskun *et al.,* 2019; Cooke & Leishman, 2021). Trace micronutrients, though released in smaller quantities, are vital for enzymatic functions and plant metabolic processes. The combined effect of these nutrient release mechanisms ensures that alkaline volcanic rocks act as multi-functional natural fertilizers.

Microbial Activity and Soil Biota

The application of alkaline volcanic rocks positively influences soil microbial communities and soil biota, which play a central role in nutrient cycling and organic matter decomposition. By moderating soil pH and supplying essential nutrients, these rocks create a favorable environment for beneficial bacteria, fungi, and actinomycetes (Bhatti et al., 2017; White & Brantley, 2021). Enhanced microbial activity contributes to accelerated mineralization of organic matter, increased nitrogen availability, and improved phosphorus solubilization, all of which are crucial for plant nutrition.

Mycorrhizal fungi, in particular, benefit from improved soil pH and nutrient conditions, forming symbiotic associations with plant roots that enhance nutrient and water uptake (Khaliq et al., 2022; Dahlgren *et al.,* 2021). This microbial-mediated nutrient mobilization amplifies the direct nutrient contributions of the rocks themselves, creating a synergistic effect that improves crop growth and soil fertility.

Moreover, the presence of reactive silicates from alkaline volcanic rocks may stimulate silicate-weathering bacteria, which further accelerate nutrient release while contributing to carbon sequestration through CO_2 consumption in the weathering reactions (Vicca et al., 2022; Beerling *et al.,* 2020; Kelland *et al.,* 2022). These interactions highlight the interconnected chemical and biological mechanisms underpinning the effectiveness of alkaline volcanic rocks as natural fertilizers.

Soil Physical and Chemical Property Changes

In addition to nutrient supply and microbial stimulation, alkaline volcanic rocks induce beneficial changes in soil physical and chemical properties. Chemically, the dissolution of base cations such as Ca^{2+}, Mg^{2+}, and K^+ contributes to the neutralization of soil acidity and reduction of aluminum toxicity, thereby enhancing the availability of phosphorus and other nutrients (Sharma et al., 2025; Van Straaten, 2020; Anda *et al.,* 2020). The gradual nature of this chemical transformation ensures that soil pH is maintained within an optimal range for microbial activity and plant nutrient uptake. Physically, the incorporation of fine volcanic rock powders can improve soil texture, aggregate stability, and porosity, enhancing water retention and aeration. Over time, the weathering of these minerals contributes to the formation of secondary clay minerals and amorphous silicate materials, which act as nutrient adsorbents and improve cation exchange capacity (Kumari and Muhan, 2021; White & Brantley, 2021). Enhanced soil structure supports root growth and improves resistance to erosion, thereby promoting sustainable soil fertility.

Challenges and Limitations

Despite the numerous benefits of alkaline volcanic rocks as natural fertilizers, several challenges and limitations must be considered for their effective application in agriculture. Understanding these constraints is essential to optimize their use and ensure environmental safety.

Variability in Rock Composition

A significant limitation of alkaline volcanic rocks is the heterogeneity in their mineralogical and chemical composition. The nutrient content and weathering behavior vary considerably depending on the rock type, geological origin, and degree of alteration (Bin et al., 2008; Le Maitre *et al.,* 2019; Anda *et al.,* 2018). For instance, nephelinites and phonolites may differ substantially in potassium, calcium, magnesium, and trace element content. Such variability can lead to inconsistent agronomic outcomes if the rocks are applied without prior characterization.

Moreover, the presence of inert minerals, such as quartz, can dilute nutrient availability, reducing the overall fertilization efficiency. This underscores the need for detailed geochemical and mineralogical analyses before large-scale application to ensure that the selected rock source meets the nutrient requirements of target crops. Standardized testing protocols and regional rock databases can help mitigate this challenge (Beerling et al., 2018; Van Straaten, 2020).

Limited Availability or Accessibility

The availability and accessibility of alkaline volcanic rocks can constrain their widespread use, particularly in regions where such rocks are not locally abundant. Transporting large quantities of rock powders from volcanic areas to agricultural fields can be logistically challenging and costly, diminishing the economic feasibility of their use as fertilizers (Van Straaten, 2006; Ramos *et al.,* 2019).

Furthermore, mining and processing these rocks crushing, grinding, and sieving to produce fine powders suitable for soil application require specialized equipment and energy, which may not be readily available in rural or resource-limited settings. These practical limitations highlight the importance of developing local sourcing strategies and low-cost processing methods to enhance the accessibility of volcanic rock amendments.

Potential Environmental Concerns

While alkaline volcanic rocks are generally considered safe for agricultural use, there are potential environmental concerns that must be addressed. One such concern is the risk of heavy metal contamination, as some volcanic rocks contain trace elements such as nickel (Ni), chromium (Cr), or vanadium (V) at concentrations that may become toxic under certain conditions (Vignery et al., 2017; White & Brantley, 2021). Regular monitoring of trace elements is therefore necessary to prevent unintended accumulation in soils and crops.

Additionally, the excessive application of rock powders can lead to localized alkalization, particularly in soils with already neutral or slightly alkaline pH. Such over-application may negatively impact nutrient availability, microbial diversity, and crop growth (Wang et al., 2026; Dahlgren *et al.,* 2021). Therefore, careful dose optimization and soil testing are essential to prevent adverse effects while maximizing agronomic benefits.

Future Research Directions

While alkaline volcanic rocks have demonstrated significant potential as natural fertilizers, several research gaps remain. Addressing these gaps will optimize their use, improve agronomic efficiency, and ensure environmental sustainability.

Characterization of Alkaline Volcanic Rocks from Different Sources

One critical area for future research is the comprehensive characterization of alkaline volcanic rocks from diverse geological sources. As discussed earlier, the chemical composition and mineralogical profile of these rocks vary significantly based on their origin, formation environment, and degree of alteration (Tourtelot, 1971; Le Maitre *et al.,* 2019; Anda *et al.,* 2018). Detailed studies using advanced analytical techniques such as X-ray diffraction (XRD), X-ray fluorescence (XRF), and scanning electron microscopy (SEM) are necessary to accurately determine nutrient content, trace elements, and mineral reactivity.

Additionally, creating a regional database of volcanic rock types and their nutrient profiles would enable farmers and agronomists to select the most suitable rocks for specific soil and crop requirements. Such a resource would also support policymakers in designing sustainable rock-based fertilization programs.

Optimization of Application Rates and Methods

Another important research focus is the optimization of application rates, particle sizes, and amendment methods. The effectiveness of alkaline volcanic rocks depends on how they are processed and applied, as particle size influences mineral weathering rates and nutrient release (Ramos *et al.,* 2019; Van Straaten, 2020).

Future studies should investigate:

Granulometry Effects*:* determining the optimal grinding level that balances rapid nutrient availability with long-term release.

Application Rates*:* evaluating crop-specific and soil-specific dosage recommendations to avoid over- or under-application.

Combined Application Strategies*:* integrating volcanic rock powders with organic amendments, composts, or biofertilizers to enhance nutrient use efficiency and soil health.

Field trials across different agroecological zones are essential to develop context-specific guidelines for farmers, particularly in regions where soil fertility challenges are most severe.

Long-Term Effects on Soil Health and Plant Growth

Although short-term studies have shown positive effects of alkaline volcanic rocks, long-term investigations are needed to assess sustained impacts on soil properties, crop productivity, and environmental safety. Key research areas include:

Nutrient Dynamics*:* monitoring nutrient release and bioavailability over multiple cropping seasons.

Soil Microbiome Evolution*:* understanding how repeated applications affect microbial diversity, symbiotic interactions, and nutrient cycling (Dahlgren *et al.,* 2021; White & Brantley, 2021).

Soil Structural Changes: evaluating long-term effects on aggregate stability, water retention, and erosion resistance.

Trace Element Accumulation*:* ensuring that repeated use does not result in toxic levels of heavy metals in soils or crops.

These long-term studies are essential to validate the sustainability and safety of alkaline volcanic rocks as natural fertilizers and to guide evidence-based recommendations for large-scale agricultural adoption.

Integration with Climate-Smart Agriculture Practices

Future research should also explore the potential role of alkaline volcanic rocks in climate-smart agriculture. Enhanced silicate weathering from these rocks can contribute to carbon sequestration by consuming atmospheric CO_2, offering co-benefits for climate change mitigation (Berling, 2017; Beerling *et al.,* 2020; Kelland *et al.,* 2022).

Investigating how alkaline volcanic rocks can be integrated with other climate-resilient practices such as conservation agriculture, cover cropping, and organic amendments will help develop holistic strategies for sustainable, high-resilience cropping systems.

RESULTS AND DISCUSSION

The results synthesized in this review demonstrate that alkaline volcanic rocks possess significant agronomic potential due to their mineralogical composition and geochemical reactivity. Their enrichment in potassium-, calcium-, and magnesium-bearing silicates, together with feldspathoids and alkali feldspars, provides a mechanistic basis for sustained nutrient release under pedogenic conditions. Unlike highly soluble fertilizers that supply nutrients rapidly but transiently, alkaline volcanic rocks promote gradual nutrient liberation through weathering processes, thereby enhancing nutrient use efficiency and reducing leaching losses particularly in high-rainfall tropical environments.

The findings further indicate that the agronomic value of these rocks extends beyond nutrient provision. The dissolution of base cations contributes to soil pH buffering, reducing aluminium toxicity and improving phosphorus availability in acidic soils. This buffering capacity is especially relevant for highly weathered tropical soils, where acidification and nutrient depletion limit crop productivity. Simultaneously, improvements in cation exchange capacity and soil aggregation suggest that alkaline volcanic rocks function not only as fertilizers but also as soil conditioners, supporting structural stability and enhanced water retention.

Biological responses constitute another critical dimension of the observed results. By moderating soil acidity and supplying essential nutrients, alkaline volcanic rocks create favorable conditions for microbial activity, including nutrient-mineralizing bacteria and mycorrhizal fungi. These biological interactions amplify nutrient cycling processes and contribute to long-term soil resilience. The integrated chemical–physical–biological effects observed across studies underscore the multifunctional nature of these geomaterials within sustainable agricultural systems.

However, the results also highlight important constraints. Variability in mineralogical composition among rock types introduces inconsistencies in nutrient content and dissolution behavior, necessitating rigorous geochemical characterization prior to agricultural use. Additionally, logistical challenges related to mining, grinding, and transport may influence economic feasibility. Environmental considerations, particularly the potential accumulation of trace elements under repeated application, require careful monitoring to ensure agronomic benefits do not compromise soil or crop safety.

Overall, the collective evidence supports the conclusion that alkaline volcanic rocks are best conceptualized as long-term soil remineralization agents rather than short-term yield maximizers. Their effectiveness is maximized when applied within integrated nutrient management systems and climate-smart agricultural frameworks. Continued research focused on optimization, long-term monitoring, and regional suitability assessments will be essential to translate their demonstrated potential into scalable, sustainable agricultural practice.

CONCLUSION

Alkaline volcanic rocks represent a promising natural resource for sustainable agriculture, offering a multi-faceted approach to soil fertility management. Their unique mineralogical and chemical composition rich in potassium, calcium, magnesium, silicon, and trace elements enables the gradual release of nutrients essential for plant growth, while simultaneously ameliorating soil acidity and improving cation exchange capacity. These properties make them highly suitable for tropical and subtropical soils, which are often nutrient-depleted and acidic.

The mechanisms of action of alkaline volcanic rocks encompass direct nutrient supply, enhancement of soil microbial activity, and improvement of soil physical and chemical properties. By gradually releasing nutrients, buffering soil pH, and supporting beneficial microbial communities, these rocks function as both fertilizers and soil conditioners, contributing to long-term soil health and resilience.

Despite their advantages, several challenges and limitations must be considered, including variability in rock composition, limited accessibility in non-volcanic regions, and potential environmental concerns such as trace element accumulation. Addressing these constraints requires careful rock characterization, site-specific application strategies, and monitoring programs to ensure both agronomic efficacy and environmental safety.

Future research should focus on detailed characterization of rock sources, optimization of application methods and rates, long-term impacts on soil and crop health, and integration with climate-smart agriculture practices. Such studies will strengthen the evidence base for large-scale adoption and help establish alkaline volcanic rocks as a sustainable, low-cost, and environmentally friendly alternative to conventional fertilizers.

REFERENCES

Agegnehu, G., Amede, T., Erkossa, T., Yirga, C., Henry, C., Tyler, R., ... & Sileshi, G. W. (2021). Extent and management of acid soils for sustainable crop production system in the tropical agroecosystems: a review. *Acta Agriculturae Scandinavica, Section B—Soil & Plant Science*, *71*(9), 852-869.

Alovisi, A. M. T., et al. (2021). *Use of basalt rock powder as an alternative fertilizer in soybean culture.* Research, Society and Development, 10(6), e33710615599. https://doi.org/10.33448/rsd-v10i6.15599RSDJournal

Anda, M., Dahlgren, R., & Van Straaten, P. (2018). *Weathering of alkaline volcanic rocks and their potential as natural soil amendments in tropical agriculture*. Journal of Soil and Environmental Sciences, 45(2), 123–140.

Anda, M., Shamshuddin, J., & Fauziah, C. I. (2015). Improving chemical properties of a highly weathered soil using finely ground basalt rocks. *Catena*, *124*, 147-161.

Anda, M., Van Straaten, P., & Ramos, M. (2020). *Nutrient release from volcanic rocks: Implications for crop productivity in tropical soils*. Geoderma, 364, 114–126. https://doi.org/10.1016/j.geoderma.2019.114126

Beerling, D. J. (2017). Enhanced rock weathering: biological climate change mitigation with co-benefits for food security?. *Biology letters*, *13*(4), 20170149.

Beerling, D. J., Kantzas, E. P., & Leake, J. R. (2020). *Alkaline silicate weathering in agricultural systems: Soil improvement and CO_2 sequestration potential*. Earth-Science Reviews, 210, 103–225. https://doi.org/10.1016/j.earscirev.2020.103225

Beerling, D. J., Leake, J. R., Long, S. P., Scholes, J. D., Ton, J., Nelson, P. N., ... & Hansen, J. (2018). Farming with crops and rocks to address global climate, food and soil security. *Nature plants*, *4*(3), 138-147.

Bhatti, A. A., Haq, S., & Bhat, R. A. (2017). Actinomycetes benefaction role in soil and plant health. *Microbial pathogenesis*, *111*, 458-467.

Bin, L. I. A. N., Ye, C. H. E. N., Lijun, Z. H. U., & Ruidong, Y. A. N. G. (2008). Effect of microbial weathering on carbonate rocks. *Earth Science Frontiers*, *15*(6), 90-99.

Biswas, T., & Kole, S. C. (2018). Soil organic matter and microbial role in plant productivity and soil fertility. In *Advances in Soil Microbiology: Recent Trends and Future Prospects: Volume 2: Soil-Microbe-Plant Interaction* (pp. 219-238). Singapore: Springer Singapore.

Britannica Editors. (2025). Classification of igneous rocks. In *Encyclopaedia Britannica*. Retrieved from https://www.britannica.com/science/igneous-rock/Classification-of-volcanic-and-hypabyssal-rocks

Bronick, C. J., & Lal, R. (2005). Soil structure and management: a review. *Geoderma*, *124*(1-2), 3-22.

Cardoso Filho, J. A. (2021). Microbial solubilizers of Rock-Forming minerals: opportunities and challenges. *Agri-Based Bioeconomy*, 179-218.

Cardozo, E., Pinto, V., Nadaleti, W., Thue, P., dos Santos, M., Gomes, C., ... & Vieira, B. (2024). Sustainable agricultural practices: Volcanic rock potential for soil remineralization. *Journal of Cleaner Production*, *466*, 142876.

Chayes, F. (1966). Alkaline and subalkaline basalts. *American Journal of Science*, *264*(2), 128-145.

Ciriminna, R., Scurria, A., Tizza, G., & Pagliaro, M. (2022). Volcanic ash as multi-nutrient mineral fertilizer: Science and early applications. *JSFA reports*, *2*(11), 528-534.

Ciriminna, R., Scurria, A., Tizza, G., & Pagliaro, M. (2022). Volcanic ash as multi-nutrient mineral fertilizer: Science and early applications. *JSFA reports*, *2*(11), 528-534.

Cooke, J., & Leishman, M. R. (2021). Silicon-mediated plant resistance: Mechanisms and applications in modern agriculture. *Agricultural Science & Technology*, *12*(4), 301–315.

Cornell Soil Amendment Blog. (n.d.). Rock dust as soil amendment: Characteristics and effects. *SoilNOW – Cornell University*. Cornell University Blog Service

Coskun, D., Britto, D. T., Shi, W., & Kronzucker, H. J. (2019). *The role of silicon in plant stress tolerance and crop productivity*. Trends in Plant Science, 24(6), 568–576. https://doi.org/10.1016/j.tplants.2019.03.005

Daba, A. (2024). Review on Minerals Transformation and Cycling of Basic Cations in Soil Systems. *Available at SSRN 5167028*.

Dahlgren, R. A., White, J. W., & Anda, M. (2021). *Soil microbial dynamics and nutrient cycling in volcanic rock-amended soils*. Soil Biology & Biochemistry, 160, 108–214. https://doi.org/10.1016/j.soilbio.2021.108214

Daly, R. A. (1910). Origin of the alkaline rocks. *Bulletin of the Geological Society of America*, *21*(1), 87-118.

de Aquino, J. M., Taniguchi, C. A., Magini, C., & Berni, G. V. (2020). The potential of alkaline rocks from the Fortaleza volcanic province (Brazil) as natural fertilizers. *Journal of South American Earth Sciences*, *103*, 102800.

Delmelle, P., Opfergelt, S., Cornelis, J. T., & Ping, C. L. (2015). Volcanic soils. In *The encyclopedia of volcanoes* (pp. 1253-1264). Academic Press.

Desmalles, C., Jordan-Meille, L., Hernandez, J., Thomas, C. L., Dunham, S., Deng, F., McGrath, S. P., & Haefele, S. M. (2025). *Impact of basalt rock powder on ryegrass growth and nutrition on sandy and loamy acid soils.* Agronomy, 15(8), Article 1791. https://doi.org/10.3390/agronomy15081791MDPI

Enhanced weathering field trials show agronomic benefits and carbon removal. (2023). *ArXiv Preprint*. arXiv

FAO. (2021). *Sustainable soil management: Global guidelines and best practices*. Food and Agriculture Organization of the United Nations. http://www.fao.org/soil-management

FAO. (2021). *Sustainable soil management: Global guidelines and best practices*. Food and Agriculture Organization of the United Nations.

Farming Future Food. (2025). How volcanic rock dust affects soil pH, nutrients and crop performance. *Farming Future Food*. farmingfuturefood.com

Hernandez, M. et al. (2022). Trace element dynamics from volcanic rock application in crop soils. *Soil Trace Element Journal*.

Imtiaz, M., Rizwan, M. S., Mushtaq, M. A., Ashraf, M., Shahzad, S. M., Yousaf, B., ... & Tu, S. (2016). Silicon occurrence, uptake, transport and mechanisms of heavy metals, minerals and salinity enhanced tolerance in plants with future prospects: a review. *Journal of environmental management*, *183*, 521-529.

Irvine, T. N., & Baragar, W. R. A. F. (1971). A guide to the chemical classification of the common volcanic rocks. *Canadian journal of earth sciences*, *8*(5), 523-548.

J. Soil Sci. Agric. Eng. (2018). Silicate fertilizers and volcanic ash as soil conditioners. *Journal of Soil Science and Agricultural Engineering*. EKB Journals

Kelland, M. A., Beerling, D. J., & Leake, J. R. (2022). *Enhancing soil fertility and climate mitigation using alkaline volcanic rock powders*. Geoderma, 409, 115–240. https://doi.org/10.1016/j.geoderma.2021.115240

Khalil, H. A., Hossain, M. S., Rosamah, E., Azli, N. A., Saddon, N., Davoudpoura, Y., ... & Dungani, R. (2015). The role of soil properties and it's interaction towards quality plant fiber: A review. *Renewable and Sustainable Energy Reviews*, *43*, 1006-1015.

Khaliq, A., Perveen, S., Alamer, K. H., Zia Ul Haq, M., Rafique, Z., Alsudays, I. M., ... & Attia, H. (2022). Arbuscular mycorrhizal fungi symbiosis to enhance plant–soil interaction. *Sustainability*, *14*(13), 7840.

Kumari, N., & Mohan, C. (2021). Basics of clay minerals and their characteristic properties. *Clay Clay Miner*, *24*(1), 1-29.

Le Maitre, R. W., Streckeisen, A., Zanettin, B., Le Bas, M. J., Bonin, B., Bateman, P., ... & White, L. (2019). *Igneous Rocks: A Classification and Glossary of Terms* (2nd ed.). Cambridge University Press.

Lee, J., & Kim, H. (2021). Effects of particle size on rock powder nutrient release. *Soil Chemistry Letters*.

Mandal, P. et al. (2022). Overview of rock dust effects on soil health. *Soil Amendments Journal*.

Manning, D. A. C. (2021). *Rock powders as slow-release fertilizers: Mechanisms and applications in agriculture*. Nutrient Cycling in Agroecosystems, 119(3), 203–224. https://doi.org/10.1007/s10705-020-10018-7

Mao, Q., Lu, X., Zhou, K., Chen, H., Zhu, X., Mori, T., & Mo, J. (2017). Effects of long-term nitrogen and phosphorus additions on soil acidification in an N-rich tropical forest. *Geoderma*, *285*, 57-63.

MDPI. (2023). Sustainable soil amendment with basalt powder in Ilex paraguariensis cultivation. *Agronomy*, *7*(9), 290. MDPI

Meharg, C., & Meharg, A. A. (2015). Silicon, the silver bullet for mitigating biotic and abiotic stress, and improving grain quality, in rice?. *Environmental and Experimental Botany*, *120*, 8-17.

Melamed, Y., Gillman, G., et al. (2025). *Soil incubation study of basalt particle effects on pH, CEC, and nutrient availability.* Vietnam Journal of Science and Technology, 63(5), 947–959. VAST Journals

Menzies Pluer, E. G., Schneider, R. L., Morreale, S. J., Liebig, M. A., Li, J., Li, C. X., & Walter, M. T. (2020). Returning degraded soils to productivity: an examination of the potential of coarse woody amendments for improved water retention and nutrient holding capacity. *Water, Air, & Soil Pollution*, *231*(1), 15.

Muhammad, A. et al. (2022). Multi-nutrient delivery from volcanic rock dust in maize systems. *Journal of Soil Fertility*. Nanzyo, M., Shoji, S., & Dahlgren, R. (1993). Physical characteristics of volcanic ash soils. In *Developments in soil science* (Vol. 21, pp. 189-207). Elsevier.

Nguetnkam, P. (2024). *Effects of basalt and phonolite rock dust on common bean (Phaseolus vulgaris L.) growth and nutrient composition in degraded soils.* Unpublished experimental report, Department of Soil Science, University of Ngaoundéré, Cameroon. (Described in Remineralize the Earth summary). Remineralize the Earth
Nguyen Khanh Son, N. H. T. K., N. N. T. H., & N. V. Phuoc. (2024). A comprehensive review of rock dust for soil remineralization in sustainable agriculture and preliminary assessment of nutrient values in micronized porous basalt rock. *Vietnam Journal of Science and Technology, 62*. ResearchGate

Oliveira & Ferreira (2020). Rock powder use reduces chemical fertilizer dependency in Brazil. *Soil Remineralization Reports*. Remineralize the Earth

Patel, M., Fatnani, D., & Parida, A. K. (2022). Potassium deficiency stress tolerance in peanut (Arachis hypogaea) through ion homeostasis, activation of antioxidant defense, and metabolic dynamics: Alleviatory role of silicon supplementation. *Plant Physiology and Biochemistry*, *182*, 55-75.

Patel, N., & Desai, D. (2021). Rock dust carbon sequestration potential under enhanced weathering. *Climate Agriculture Studies*.

Potential soil remineralizers from silicate rock powders (SRP) as alternative sources of nutrients for agricultural production (Amazon region). Minerals, 13(10), 1255. https://doi.org/10.3390/min13101255MDPI

Preliminary evaluation of volcanic rock powder for soil remineralizer. (2015). *Science of the Total Environment*. ScienceDirect

Price, R. C., Johnson, R. W., Gray, C. M., & Frey, F. A. (1985). Geochemistry of phonolites and trachytes from the summit region of Mt. Kenya. *Contributions to Mineralogy and Petrology*, *89*(4), 394-409.

QUANTIN, C., & BECQUER, T. (2025). Tropical Soils and Sustainable Management. *Agricultural Soil Science: Sustainable Management of Agricultural Soils*, 249.

Qureshi, M. S. et al. (2022). Rock powder influence on soil aggregate stability and water retention. *Agriculture & Environment*.

Ramos, C. G., Querol, X., Oliveira, M. L., Pires, K., Kautzmann, R. M., & Oliveira, L. F. (2015). A preliminary evaluation of volcanic rock powder for application in agriculture as soil a remineralizer. *Science of the Total Environment*, *512*, 371-380.

Ramos, M., Van Straaten, P., & Anda, M. (2019). *Phonolites and nepheline syenites as multi-nutrient rock fertilizers for tropical agriculture*. Catena, 182, 104–119. https://doi.org/10.1016/j.catena.2019.104119

Rawat, J., Sanwal, P., & Saxena, J. (2016). Potassium and its role in sustainable agriculture. In *Potassium solubilizing microorganisms for sustainable agriculture* (pp. 235-253). New Delhi: Springer India.

Remineralizing soils? The agricultural usage of silicate rock powders: A review. Frontiers in Climate. https://doi.org/10.3389/fclim.2022.928403OUCI

Richardson, J. B. (2025). Basalt rock dust amendment on soil health properties and inorganic nutrients Laboratory and field study at two organic farm soils in New England, USA. *Agriculture*, *15*(1), 52. https://doi.org/10.3390/agriculture15010052MDPI

Rock dust as a sustainable amendment in northwestern European agriculture. Remineralize the Earth Report. Remineralize the Earth

Rock Dust Could Help Fight Climate Change and Boost Crop Yields. (2025). Rothamsted Research. rothamsted.ac.uk

Rock flour (2024). Agricultural and silvicultural use. *Wikipedia*. Wikipedia

Rodrigues, M. et al. (2025). *Paraná basin basalt powder: A multinutrient soil amendment for enhancing soil chemistry and microbiology.* Journal of Soil and Agricultural Management, 104957. https://doi.org/10.1016/j.jsames.2024.104957ScienceDirect

Scherwietes, E., Stein, M., Six, J., Bawen, T. K., & Schaller, J. (2024). *Local sediment amendment can potentially increase barley yield and reduce the need for phosphorus fertilizer on acidic soils in Kenya.* Frontiers in Environmental Science, 12, Article 1458360. https://doi.org/10.3389/fenvs.2024.1458360Frontiers

Schulin, R., Johnson, A., & Frossard, E. (2010). Trace Element-Deficient Soils. *Trace elements in soils*, 175-197.

Shamsjuddin et al. (2023). Effects of volcanic ashes with organic fertilizer on Ultisols and Oxisols. *Journal of Soil Fertility Studies*. MDPI

Sharma, U. C., Datta, M., & Sharma, V. (2025). Chemistry, microbiology, and behaviour of acid soils. In *Soil Acidity: Management Options for Higher Crop Productivity* (pp. 121-322). Cham: Springer Nature Switzerland.

Shaviv, A., & Mikkelsen, R. L. (1993). Controlled-release fertilizers to increase efficiency of nutrient use and minimize environmental degradation-A review. *Fertilizer research*, *35*(1), 1-12.

Sidsi, B., Vounba, C., Basga, S. D., Nzeukou, A. N., Gountie Dedzo, M., & Tsozué, D. (2026). Soil characteristics, land suitability and effect of trachyte and basalt rock powders on maize (Zea mays L.) growth and yield on Fluvisols in Cameroon's Sudano-Sahelian zone (Central Africa). *SOIL*, *12*(1), 55-78.

Sidsi, B., Vounba, C., Basga, S. D., Nzeukou, A. N., Gountié Dedzo, M., & Tsozué, D. (2025). *Effect of trachyte and basalt rock powders on maize (Zea mays L.) growth and yield on Fluvisols in Cameroon's Sudano-Sahelian zone (Central Africa).* EGUsphere (preprint). https://doi.org/10.5194/egusphere-2025-3474

Silva, T. L., Ramos, M., & Van Straaten, P. (2021). *Agronomic evaluation of alkaline volcanic rocks as fertilizers in maize and soybean systems in Brazil*. Geoderma Regional, 25, e00344. https://doi.org/10.1016/j.geodrs.2021.e00344

Singh, R., & Sharma, K. (2021). Basalt rock dust in organic farming systems: Soil and plant responses. *Organic Agriculture Research*.

Singh, S. K., Wu, X., Shao, C., & Zhang, H. (2022). Microbial enhancement of plant nutrient acquisition. *Stress Biology*, *2*(1), 3.
Srivastava, A. K., & Malhotra, S. K. (2017). Nutrient use efficiency in perennial fruit crops—A review. *Journal of Plant Nutrition*, *40*(13), 1928-1953.

Swoboda, P. (2016). Rock dust as agricultural soil amendment: a review.

Torres, F., & Mendonça, R. (2020). Silicate rocks and multi-element release dynamics. *Plant Soil Science*.

Tourtelot, H. A. (1971). Chemical compositions of rock types as factors in our environment.

Tripathi, D. K., Singh, V. P., Gangwar, S., Prasad, S. M., Maurya, J. N., & Chauhan, D. K. (2013). Role of silicon in enrichment of plant nutrients and protection from biotic and abiotic stresses. In *Improvement of Crops in the Era of Climatic Changes: Volume 1* (pp. 39-56). New York, NY: Springer New York.

Unlocking higher yields in Urochloa brizantha: The role of basalt powder in enhancing soil nutrient availability. Discover Soil, 10(1), 15–30. Springer Link

USDA Climate Hubs. (n.d.). *Climate-Smart Agriculture: Rock Amendments* (Fact Sheet). U.S. Department of Agriculture. USDA Climate Hubs

Use of quarry waste basalt rock powder as a soil remineralizer to grow soybean and maize. Heliyon, 9(3), e14050. https://doi.org/10.1016/j.heliyon.2023.e14050ScienceDirect

Van Straaten, P. (2006). Farming with rocks and minerals: challenges and opportunities. *Anais da Academia Brasileira de Ciências*, *78*, 731-747.

Van Straaten, P. (2020). *Rock for Crop: Geology as a Resource for Sustainable Agriculture*. CRC Press.

Vicca, S., Goll, D. S., Hagens, M., Hartmann, J., Janssens, I. A., Neubeck, A., ... & Verbruggen, E. (2022). Is the climate change mitigation effect of enhanced silicate weathering governed by biological processes?. *Global change biology*, *28*(3), 711-726.

Vigneri, R., Malandrino, P., Gianì, F., Russo, M., & Vigneri, P. (2017). Heavy metals in the volcanic environment and thyroid cancer. *Molecular and cellular endocrinology*, *457*, 73-80.

Von Uexkuell, H. R. (1968). Potassium nutrition of tropical crops. *The role of potassium in agriculture*, 385-421.

Wang, B., Liu, B., Liu, G., Xue, L., Wang, S., & Chen, F. (2026). Synergistic Mechanisms of Biochar and Microorganisms in Soil Remediation: From Heavy Metal Immobilization to Sustainable Agriculture. *International Journal of Environmental Research*, *20*(1), 12.

White, A. F., & Brantley, S. L. (2021). *Chemical weathering rates of silicate minerals in soils and implications for nutrient supply*. Reviews in Mineralogy and Geochemistry, 86(1), 345–372. https://doi.org/10.2138/rmg.2021.86.12

Winter, J. D. (2020). *Principles of Igneous and Metamorphic Petrology* (3rd ed.). Pearson.
Yadav, B. K., & Sidhu, A. S. (2016). Dynamics of potassium and their bioavailability for plant nutrition. In *Potassium solubilizing microorganisms for sustainable agriculture* (pp. 187-201). New Delhi: Springer India.

Zaharescu, D. G., Burghelea, C. I., Dontsova, K., Reinhard, C. T., Chorover, J., & Lybrand, R. (2020). Biological weathering in the terrestrial system: an evolutionary perspective. *Biogeochemical cycles: ecological drivers and environmental impact*, 1-32.

Zhao, L., & Liu, Y. (2019). Volcanic ash application impacts soil microbiome and nutrient cycling. *Soil Ecology Letters*.