An assessment of the agronomic benefits of silicate rock powders in Brazil in the context of a novel classification

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Abstract

The sustainable intensification of tropical agriculture requires innovative approaches to restore soil health, reduce dependency on imported fertilizers, and increase crop productivity. Brazil has emerged as a global leader in the use of silicate agrominerals (ASi), silicate rich rock powders that supply plant nutrients and improve soil properties. These materials could advance low-cost soil sustaining crop production, particularly in the deeply weathered and nutrient-depleted soils of the tropics. This article synthesizes 56 Brazilian crop trials using a novel classification system for ASi based on lithochemistry and practical agricultural considerations. It evaluates the effects of ASi on soil health parameters, plant growth, and nutrient uptake across a range of crops and tropical soil types. The results demonstrate that ASi can significantly improve soil pH, cation exchange capacity, and base saturation, while enhancing yield and nutrient availability. Furthermore, evidence is emerging for ASi to indirectly increase soil phosphorus availability. We recommend minimum requirements for standardized methodologies and suggest real-world research designs to support broader ASi adoption. Brazil's pioneering role offers valuable insights for scaling the usage of silicate agrominerals across tropical agricultural systems worldwide, contributing to sustainable food production and climate resilience.

1 Introduction

Global agriculture stands at the intersection of three urgent and interlinked challenges: ensuring food security, restoring soil health, and combating climate change (Smith et al. 2014; Meybeck 2018). These issues are interconnected—degraded soils lead to reduced agricultural productivity and resilience, which in turn exacerbates food insecurity and diminishes the land's ability to function as a carbon sink (Denny et al. 2023). The tropics are projected to carry the greatest burden of future food production, driven by rapid population growth and expanding agricultural frontiers (Meybeck 2018). At the same time, tropical countries such as Brazil are characterized by highly weathered and nutrient-depleted soils. Oxisols and Ultisols, the predominant soil types, are naturally acidic, low in cation exchange capacity (CEC), and deficient in essential macro- and micronutrients (Sanchez 2019).

One major barrier for sustainable agricultural intensification in the tropics is nutrient replacement (Manning and Theodoro 2020). In many tropical countries, nutrients removed through agricultural activities are not adequately replenished due to a lack of access to conventional fertilizers—most of which are imported, expensive, and partly unsuited to the chemical and physical characteristics of tropical soils (Sanchez 2019). Soluble fertilizers like KCl are prone to leaching, and micronutrient deficiencies often go uncorrected in standard NPK regimes, resulting in long-term fertility decline (Cakmak 2002).

This creates both a profound challenge and a unique opportunity. As emphasized by Denny et al. (2023), Brazil's tropical climate and geographic diversity offer substantial potential for implementing sustainable, low-emission agricultural practices that can simultaneously enhance productivity and contribute to national climate goals. Improving tropical soil health through regenerative practices could both close yield gaps and contribute to climate mitigation via soil carbon sequestration.

Given these challenges, silicate agrominerals (Van Straaten 2004)—geological materials that supply plant nutrients and improve soil properties, also known as remineralizers (REM) or silicate rock powders— have garnered increasing attention as a sustainable alternative for soil fertility enhancement in tropical agroecosystems. Silicate agrominerals (ASi) could fill the unresolved and escalating gap for affordable and accessible macro- and micronutrient soil amendments, which neither conventional fertilizers nor limestone can currently sufficiently address (Swoboda et al. 2022; Manning and Theodoro 2020). Agrominerals can furthermore enhance plant resilience to biotic and abiotic stresses due to the beneficial effects of bioavailable silicon (Meena et al. 2014), and they may indirectly increase soil phosphorus bioavailability by altering sorption dynamics and mobilizing otherwise inaccessible P pools (Schaller et al. 2024).

More recently, the enhanced rock weathering (ERW) aspect has gained increased attention, as it has the potential to sequester significant amounts of atmospheric CO_2 (Hartmann et al. 2013; Beerling et al. 2020). Climatic and soil conditions in tropical regions are more favorable for rock weathering compared to temperate regions (White 2003; White and Brantley 2018), with Brazil accounting for nearly a quarter (24.41%) of the global silicate rock carbon sink (Zhang et al. 2021). Nevertheless, bicarbonate formation is maximized under neutral to mildly alkaline conditions (Clarkson et al. 2024), highlighting the importance of identifying agricultural settings where agronomic benefits and bicarbonate formation are optimized. .

Important synergies can also occur regarding the stabilization of soil organic matter through Fe/Al oxides formed during weathering of rocks like basalt (Buss et al. 2024), which might be particularly relevant for highly weathered tropical soils that are often low in residual reactive mineral phases (Doetterl et al. 2025). Recent studies suggest analyzing the effects of rock amendments on both organic and inorganic carbon pools (Steinwidder et al. 2025), with some showing positive effects on net carbon stocks (Sohng et al. 2025). Direct comparison with liming also indicates significantly reduced soil CO_2 efflux for silicate rock amendments (Dietzen et al. 2018). Novel findings also suggest potential influences towards soil physical properties, with effects largely depending on application amount and the respective soil texture and particle size (Costanzo et al. 2025).

Additionally, the use of ASi can create several direct and indirect jobs related to production chains in the same regions where agriculture is developed (Manning and Theodoro 2020). Overall, silicate agrominerals could have the potential to advance low-cost soil sustaining crop production that contributes to various sustainable development goals (Swoboda et al. 2022).

Among the tropical countries, Brazil stands out as a pioneer of rock powder research and implementation. Pioneering advances occurred in research (Leonardos et al. 2000), legal implementations (Manning and Theodoro 2020), and novel classifications of silicate agrominerals used in agriculture (Martins et al. 2024). Novel classifications are highly relevant, as there are currently several—often interchangeably used— terms to describe the application of crushed rocks for agricultural purposes, which complicates structured and clear proceedings of the field and ASi end usage. Therefore, the following section provides a short overview regarding the nomenclature and thereafter introduces a recently proposed ASi classification.

1.1 Nomenclature of rocks used in agriculture

Crushed rocks have been used since more than a century (Van Straaten 2006), and their usage has been named in different ways over the last centuries (Leonardos et al. 2000). Silicate rock powder (SRP) is a generic term for finely ground rocks containing primarily silicate minerals (Swoboda et al. 2022). Other terms include rock dust, rock fertilizer, petrofertilizer, and stone meal (or rock meal, (Theodoro and Leonardos 2006)), which was coined as "rochagem" in Portuguese by (Leonardos et al. 1976). The term 'remineralizer' gained popularity through the 1994 establishment of the "Remineralize the Earth" (Campe 2025) and the regulatory category "remineralizador", which was officially adopted in the Brazilian legislation (Brazil 2016). To be classified as a remineralizer, the material has to fulfil strict guidelines regarding chemical and physical characteristics (see section 1.2). The term agromineral, coined by Van Straaten (2004), refers to processed and unprocessed geological materials that contain one or more essential plant nutrients and are used to enhance soil fertility. By definition, agrominerals can encompass various ground rocks used to replenish the mineral content of agricultural soils, and their scope of usage has expanded in recent years (Zhang et al. 2017).

Agrominerals can be classified according to their principal anions, such as chloride, sulfate, carbonate, phosphate, and silicate (Table 1). The primary associated cations include calcium (Ca), magnesium (Mg), and potassium (K), whereas several other plant nutrients can be associated with each class (Harley and Gilkes 2000). Salts associated with chlorides and sulfates are highly soluble in water, while carbonates, phosphates, and borates exhibit low solubility (Heřmanská et al. 2022; Oelkers and Addassi 2025). Silicates, although having very low water solubility, are the most abundant, covering 84.2% of the Earth's land surface (Goldscheider et al. 2020). In second place are carbonates, which cover 15.2% of the Earth's land surface. Conversely, salts (chlorides and sulfates) and phosphates are very rare, covering less than 0.01% of the Earth's land surface. Overall, the most relevant agrominerals in the context of this review are the ASi. It is important to note that although some silicate minerals contain ammonium (NH_4^+) in substitution for K, silicate rocks should not be regarded as a source of N for agricultural purposes.

Table 1. Types of agrominerals classified according to the principal anion and cation association, with examples of existing products for agricultural use; [1]Goldscheider et al. (2020); [2]Heřmanská et al. 2022; Oelkers and Addassi 2025. A detailed description of the terms outlined here can be found in the glossary provided in the SI2.

Main anion		Rock source	Main cations	Crust abundance[1]		Water solubility (relative[2])	Agricultural products examples
				area %	mass %		
Chloride	**Cl^-**	Evaporitic deposits (sedimentary)	K	0.00	<1	Very high	Sylvite (potash)
Sulphate	**SO_4^{2-}**	Evaporitic deposits (sedimentary)	Ca, Mg, K	0.00	<1	Very high	Gypsum; Polyhalite
Carbonate	**CO_3^{2-}**	Limestone (sedimentary) Carbonatite (igneous) Marble (metamorphic)	Ca, Mg, (K)	15.0	2	Moderate to low	Lime
Phosphate	**PO_4^{3-}**	Phosphorite (sedimentary) Phoscorite (igneous)	Ca	0.00	<1	Low	Phosphate rock
Borate	**BO_3^{3-}**	Borate (sedimentary)	Ca	0.00	<1	Low	Ulexite
Silicate	**SiO_4^{4-}**	Sedimentary Igneous Metamorphic	Ca, Mg, K	85.0	93.0	Very low	Glauconite, Basalt, Mica schist

However, a subsequent classification of silicate agrominerals constitutes a major hurdle for science and practitioners due to their complex chemical and mineralogical composition. The primary mineralogical basis for classifying silicate minerals is the degree of polymerization of the SiO_4 tetrahedra, whereas the chemical composition and crystallographic properties refine this classification into mineral families and species (Deer et al. 2013). This classification is, however, not practical, as advanced mineralogical knowledge constitutes an entry barrier for farmers and agronomists. Practically speaking, what is needed is a classification that provides both an overview of the rocks' lithochemistry as well as their agronomic suitability.

1.2 Novel Classification of Silicate Agrominerals

A new lithochemical classification of ASi has been proposed by (Martins et al. 2024) in the agricultural journal Novo Solo, as it emerged from a joint effort between scientists and farmers to facilitate the work with crushed silicate rocks. This classification has been further developed and an updated version with a refined division is presented here. According to this classification, an ASi is composed of more than 50% silicates, whereas a subsequent classification is based on the bases percent in the form of oxides: CaO, MgO, and K_2O. The sum of these oxides is referred to as sum of $bases_{rocks}$ (SB_r), to distinguish it from the sum of base terminology in soil science (SB_s), which also includes sodium (Na) (Azevedo and Manning 2023). To qualify as a remineralizer, the SB_r must exceed 9%, which is the minimum criterion in the Brazilian regulation (further elaborated below). The resulting classification consists of eight ASi sub-classes (Figure 1).

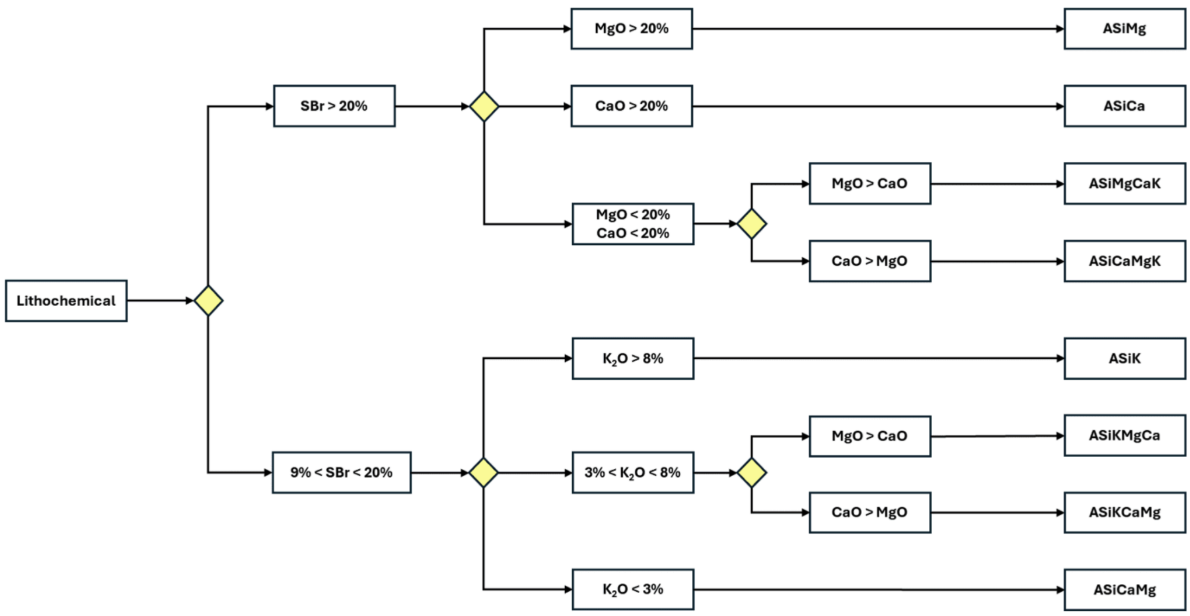

Figure 1. Lithochemical classification of silicate agrominerals considering the sum of bases in the form of oxides (SB_r = CaO + MgO + K_2O) and the base contents. SB_r - sum of $bases_{rocks}$ as oxides (MgO + CaO + K_2O; (Azevedo and Manning 2023).

ASi are initially categorized into two groups based on their sum of bases (SB_r) content: those with SB_r between 9% and 20%, and those exceeding 20%. The upper limit of 20% SB_r is related to the typical maximum concentrations found in potassium-rich rocks and basic rocks. The other group, with SB_r above 20%, is related to ultramafic and ultramafic alkaline rocks, as well as silicate rocks with carbonate contributions, such as marls, certain marbles, and calc-silicate rocks.
When the SB_r in the form of oxides is equal or exceeds 20%, ASi are divided into the following classes:

Magnesium silicate agrominerals (ASiMg) - containing more than 20% MgO. These are derived from typical ultramafic rocks (e.g., dunites, pyroxenites, serpentinites) and industrial processes, such as nickel ore slags.

Calcium silicate agrominerals (ASiCa) – containing more than 20% CaO, like certain calc-silicate rocks (e.g. certain marl, calcium paragranulites), and industrial processes, such as steel slags.

Calcium-magnesium-potassium silicate agrominerals (ASiCaMgK) – containing less than 20% MgO, less than 20% CaO, and CaO>MgO, rich in calcium and derived from igneous rocks like anorthosites and calc-silicate metamorphic rocks (e.g., calc-schists), as well as from steel slags.

Magnesium-calcium-potassium silicate agrominerals (ASiMgCaK) - containing less than 20% MgO, less than 20% CaO, and CaO<MgO, primarily derived from alkaline ultramafic rocks (e.g., kamafugites, ugandites, kimberlites, olivine melilitites) and certain magnesium-rich metamorphic rocks.

When the SB_r in the form of oxides is between 9% and 20%, ASi are divided into the following classes:

Potassium silicate agrominerals (ASiK) - with more than 8% K_2O derived from alkaline rocks like high K syenites and phonolites, and also sedimentary and metamorphic rocks rich in glauconite, e.g., glauconitic siltstones and sandstones.

Potassium-magnesium-calcium silicate agrominerals (ASiKMgCa) – between 3 and 8% K_2O, MgO>CaO, derived from rocks rich in biotite or phlogopite (certain gneisses, schists, silicate portions of carbonatite bodies, and hydrothermal origin rocks).

Potassium-calcium-magnesium silicate agrominerals (ASiKCaMg) - between 3 and 8% K_2O, CaO>MgO, derived from determined alkaline rocks with intermediate K levels, like some syenites and phonolites, and granitic rocks (e.g., granodiorite, dacite, rhyolite).

Calcium-magnesium silicate agrominerals (ASiCaMg) - with less than 3% K_2O. These come from basic rocks (e.g., basalts, diabases, gabbros, andesites, amphibolites, basic granulites).

Importantly, as outlined above, this classification is aligned to the recently enacted agricultural legislation for Brazilian fertilizers (Brazil 2013). In Brazil, soil remineralizers are products regulated under the Federal Law 12.890 and Regulation 5 (Brazil 2016) by the Ministry of Agriculture, Livestock, and Food Supply (MAPA). Specifically, remineralizers are comminuted rock products that must be derived from ASi, contain SB_r higher than 9% in the form of oxides, and the amount of K_2O must be higher than 1%. Also, they must not contain more than 25% free SiO_2 (in other words as quartz or another silica polymorph), and the levels of heavy metals are not allowed to exceed: arsenic (As): 15 ppm; cadmium (Cd):10 ppm; mercury (Hg): 0.1 ppm; and lead (Pb): 200 ppm. REMs are considered a new category of mineral inputs in Brazilian legislation (Brazil 2024). Following this logic, all REMs are ASi, but not all ASi are REM.

A major purpose of the Federal Law of 2013 was to overcome the lack of regulatory status that hindered the commercialization and broader use of rock powders. The subsequent normative instructions further specified the requirements for classification, packaging, labeling, and sale of remineralizers. This legal recognition boosted interest from both smallholder and large-scale farmers, as rock powders were seen as cheaper, locally available, and effective, especially in regions or systems where conventional inputs were economically or legally not permitted (e.g., organic systems) (Brazil 2016; Manning and Theodoro 2020). Although the legislative enactment and the classification are recent developments, the Rochagem movement has been steadily progressing for several decades, and continues to review the use of ASi in order to inform and update regulation as necessary.

1.3 Soil Remineralization in Brazil

The Rochagem movement in Brazil has been instrumental in using crushed rocks as soil remineralizers, as reviewed in detail by (Manning and Theodoro 2020). Starting with pioneering research in the 1950s (Guimaraes 1955; Ilchenko 1955), it gained momentum in the 1970s, with proposals by Leonardos and Fyfe for using volcanic rocks to recover fertility in Brazilian soils (Leonardos et al. 1976). Despite the dominance of the Green Revolution model, which emphasized agrochemicals and high-input farming, the need to support smallholders and degraded tropical soils created space for alternative approaches. By the early 2000s, the effectiveness of ultra-potassic kamafugites in improving yields of maize, sugar cane, and cassava, especially for smallholder farmers, had been shown through Brazil's Agrarian Reform program. Simultaneously, the Brazilian Agricultural Research Corporation (EMBRAPA), Brazil's national agricultural research organization, began investigating the use of powdered rocks due to rising fertilizer costs and the country's heavy dependence on imports for its fertilizer supply. This convergence of research and economic concern led to the 2004 "Rocks for Crops" international conference in Brasília, which laid the groundwork for the Interinstitutional Working Group (GTI)—a coalition of government ministries, universities, and industry partners (Manning and Theodoro 2020). Subsequent national congresses in 2009, 2013, 2016, and 2025 produced over 200 scientific contributions and emphasized the need to establish technical parameters for regulating remineralizers (ABREFEN 2025).

Research presented at these events reported that agrominerals can provide multiple agronomic and environmental benefits. They can be up to 80% cheaper than conventional fertilizers and potentially supply nutrients for up to five years (Manning and Theodoro 2020). Additional advantages can include increased biomass, and reduced risk of water eutrophication due to gradual solubility. They are also well suited for organic agriculture, which is growing rapidly in Brazil (Theodoro and Leonardos 2006; Manning and Theodoro 2020).
The movement also benefited from Brazil's robust mining sector, which consists of over 3,300 active mines, most of which are small-scale and distributed throughout the country. These mines produce materials such as basalt, shale, and granite, many of which meet the regulatory standards set out in the Federal law of 2013 (Manning and Theodoro 2020).
Since the enactment of the laws, and following the 5th Rochagem Conference (ABREFEN 2025), a growing number of Brazilian farmers have adopted SRPs, particularly basalts, phonolites, and ultramafic rocks, as alternatives or supplements to conventional fertilizers. Additionally, Brazil has become a central node in the scientific exploration of SRPs, with an increasing volume of field trials and implementation of case studies.

Despite this growing body of research, no comprehensive synthesis currently exists that consolidates ASi findings within the tropical context, and particularly within Brazil. The research landscape remains fragmented, lacking consistent methodologies and a shared scientific framework. Furthermore, trial designs vary widely in terms of rock type, particle size, soil conditions, application rates, and duration, complicating efforts to compare outcomes or derive generalizable insights.

The aim of this paper is therefore to synthesize the existing body of Brazilian ASi studies according to the novel classification presented by (Martins et al. 2024), focusing on soil fertility parameters and effects on plants. The results are then discussed from an agro-economical perspective, and recommendations for future agromineral research are presented.
By consolidating Brazil's unique experience with rock powders in agriculture, this paper aims to provide a foundation for scaling this approach across tropical agricultural systems worldwide—where the intersection of soil degradation, food insecurity, and climate urgency demands integrated and locally viable solutions.

2 Effects of the use of silicate agrominerals in the tropics

This section summarizes the effects of different Brazilian ASi studies on soils and plants. The analysis extends the factorial scope and analytical detail from (Swoboda et al. 2022). In total, 56 peer-reviewed studies written in English were analyzed according to effects on yield, biomass (above and below ground), plant nutrient uptake, and several soil parameters. Results were differentiated into the categories: significantly positive, non-significant positive, non-significant, significantly negative, and non-significant negative. These categories were chosen due to the different ways the studies were set up, and to extend those used by Swoboda et al. (2022), which differentiate between significantly positive, insignificant, and significantly negative, and so misrepresent the nuances of several positive trends as merely insignificant. This decision was also taken as the majority of trials traditionally follow a randomized complete block design (RCBD) with a few replicates, which often has limited statistical power due to the heterogeneity of environmental factors involved, and results which can thus be prone to a statistical misinterpretation (Piepho et al. 2011). Furthermore, various other details were extracted for each study, which can be accessed in the Supplement Table S1.

A soil or plant effect is counted as one when the treatment shows a statistically significant ($p<0.05$ or $p<0.01$) or non-significant increase or decrease compared to the negative control (no fertilization), respectively. Baseline soil amendments were applied in some studies prior to the treatments, and mostly involved limestone as pH correction and soluble fertilizers like NPK to raise nutrient levels. Several studies analyzed more than one rock powder and/or soil and/or plant. If this was the case, each rock, soil, and/or plant type was considered individually. For soils, the respective nutrient supply was evaluated by considering alterations in exchangeable nutrient concentrations, whereas for plants the nutrient content was analyzed.

If there are several dosages, and all dosages had a significantly positive effect, all of them are counted as one "significant positive". If there are several dosages, and all dosages had a significantly negative effect, this is counted as "significant negative". The same applies for non-significant positive or negative. When dosages had mixed results, this was counted as non-significant and outlined in the comment section of the Supplement Table S1.

The main trends for soils and plants are outlined for different ASi classes. For some ASi classes, few or only one study existed, therefore some classes were grouped together in one section according to lithochemical similarities. The following sections cover a summary of all silicate agromineral classes (2.1), silicate agrominerals with sum of bases >20% (2.2), potassium silicate agrominerals (2.3), and silicate agrominerals with <8% K_2O (2.4).

2.1 Summary of effects for all silicate agrominerals

The overall effects of all ASi analyzed were predominantly positive (Fig. 2). Consistent increases in yield, aboveground and belowground biomass, and plant nutrient levels were reported. Importantly, there was no trial reporting statistically significant decreases in yield or aboveground biomass. Only one study (Rodrigues et al. 2024c) reported a statistically non-significant negative yield compared to the unfertilized control, although the control outperformed conventional fertilization in this experiment, necessitating careful interpretation of this study. All four non-significant negative results for aboveground biomass are derived from the rock powders tested in (Reis et al. 2024), for which the KCl treatment unexpectedly also decreased biomass. For soils, the majority of studies reported consistently positive results, with the major effects being ameliorations of pH, CEC, and the increase of both macro- and micronutrients.

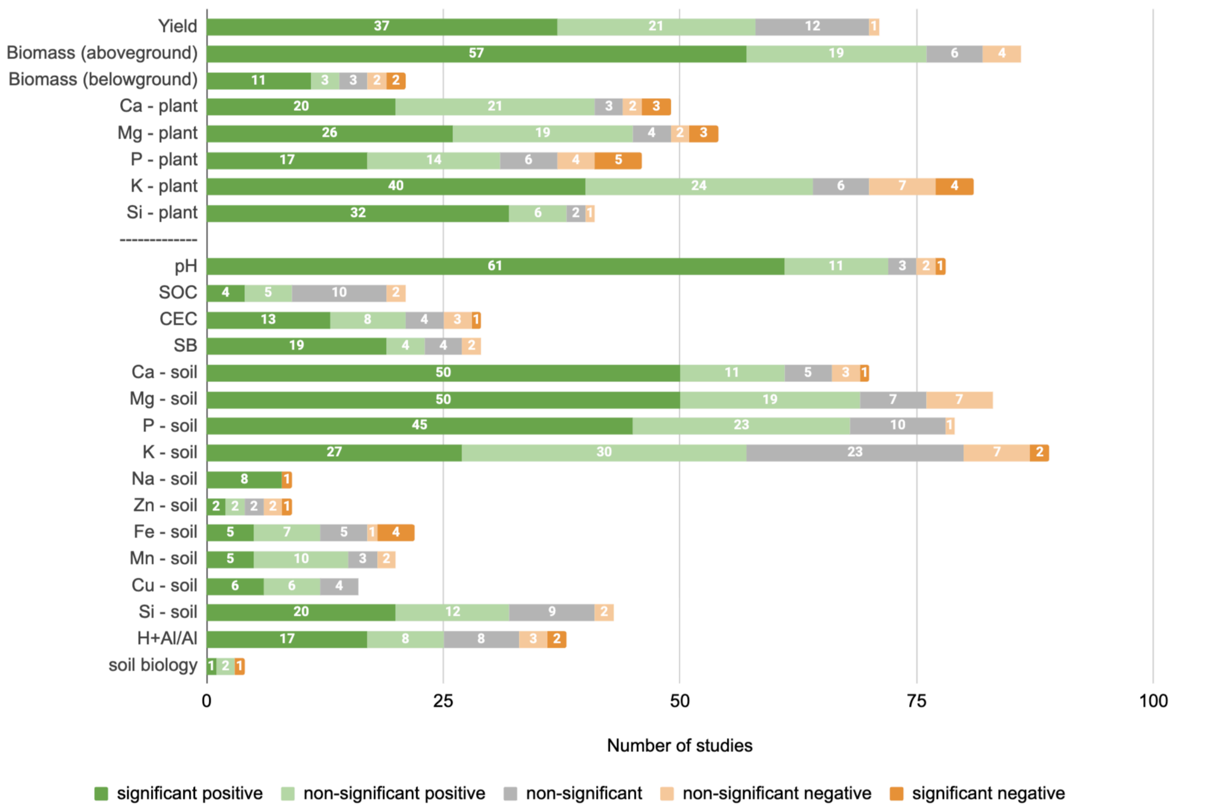

Figure 2. Summarized agronomic effects of 56 silicate agromineral experiments in Brazil. The count for significant positive (dark green), non-significant positive (light green), non-significant (gray), non-significant negative (light orange), significant negative (orange), and refers to comparisons to the negative control treatment. Various studies evaluated several rock, soil, and/or plant species, therefore the count exceeds 56 for some parameters.

Importantly, non-significant or negative findings of certain nutrients have to be interpreted in the context of the rock´s mineralogy, particle size, and application dose, as certain rocks do not supply all nutrients (Table 2). Accordingly, high application amounts can lead to yield increases despite simultaneous decrease of one or more nutrients in the soil and/or plant, which can be caused by higher absolute nutrient uptake despite lower concentrations or competitive nutrient uptake.

Table 2. Summary of major parameters of each ASi class. [1]sum of $bases_{rocks}$; [2]Neutralizing potential as $CaCO_3$ equivalence (Silveira et al. 2014) derived by the formula: $CaCO_3$ = %CaO*1.79 + %MgO*2.48, [3]ASi but unclassified since the sum of $bases_{rocks}$ is below 9%; [4]minimum to maximum yield or biomass increase compared to the control reported in the analyzed experiments for each ASi class.

ASi class	**range SB_r[1] (%)**	**range NP[2] (%)**	**ASi count**	**Range yield increase[4]**	**Rock sources from the experiments**
ASiCaMg	9.9 – 19.5	16.6 – 40.7	23	3.9 – 466.7%	kamafugite saprolite, basalt, dacite, gabbro, andesite, gneiss
ASiK	8 – 27.8	0 – 30.1	20	0 – 500%	biotite syenite, phonolite, glauconitic siltstone, syenite
ASiKCaMg	9.2 – 14.2	12 – 22.1	6	9.1 – 180.9%	siltstone, tephrite, gneiss, dacite, mica schist
ASiMgCaK	23.4 – 35	40.7 – 69.7	7	-24.7 – 1697%	olivine melilitite, kamafugite
ASiMg	23.8 – 40	50 – 99.2	7	5.3 – 100%	dunite, steatite, vermiculite
ASiCaMgK	28 – 33.1	55.1 – 58	3	16 – 31.4%	rhythmite
ASiKMgCa	9.8	15.1	1	5 – 10%	mica schist
ASiCa	44	85.7	1	18.4 – 69.6%	calcium silicate
Unclassified ASi (<9% SB_r)[3]	4 – 10	0 – 14.2	10	7.9 – 100%	phonolite, biotite schist, bentonite, nepheline syenite, granite, bituminous shale

The highest number of trials was conducted with calcium-magnesium silicate agrominerals (ASiCaMg) like basalts, followed by potassium silicate agrominerals (ASiK, Table 2). The ASi with over 20%SB_r (ASiCa, ASiMg, ASiCaMgK, and ASiMgCaK) are characterized by neutralizing potentials that range between 40.7% and almost 100% that of limestone. The third biggest class was 'unclassified ASi', as their SB_r was below 9%, and they thus did not qualify as remineralizers. However, also these unclassified ASi increased yield to differing degrees.

The analyzed soil types have mostly been various forms of Oxisols/Ferralsols/Latossolos (USDA/WRB/SiBCS soil taxonomies, respectively) and Ultisols/Acrisols/Argissolos, and other soils that were described with varying degrees of detail in one of the three soil taxonomies (Santos et al. 2025). For consistency, the soil types—where applicable—will be presented in the order USDA/WRB, whereas the Brazilian soil types and equivalents will be outlined in the glossary, which is in the SI.

2.2 Silicate agrominerals with sum of bases >20%

2.2.1 ASi (>20% SB_r) effects on soil

This ASi class showed almost exclusively positive and significantly positive effects on soil chemical properties (Figure 3). The most consistent and significant improvement observed across this study group was amelioration of soil pH, which correlated with the concomitant increase in Ca and Mg. Except for two cases (Assunção et al. 2023; Castro and Crusciol 2013), Mg and Ca levels increased for all plants and soils tested. Interestingly, although most of the ASi (>20%SB_r) contained little to no P, its bioavailability was increased in all but one experiment with vermiculite (Marchi et al. 2024), which however still reported significant yield increases. One potential reason for this non-significant effect on P could have been the low SiO_2 (38.2%) content of the vermiculite, which potentially limits indirect P liberation through Si.

K showed positive to mixed results, which could partly be explained by little to no K content in these rocks, the K-hosting minerals exhibiting low dissolution rates, and potential nutrient imbalances resulting from overfertilization with other base cations. When the K-bearing mineral in the rocks is reactive, e.g. as phlogopite in olivine melilite (Almeida et al. 2022; Cunha et al. 2022), a predominantly positive effect on the release and absorption of K is observed. An explanation for non-significant or reduced soil K values despite yield gains is an increased extraction of soil K through increased plant growth without equivalent substitution (Almeida et al. 2022; Castro and Crusciol 2013). The general improvement of base cations is also reflected in the consistently positive effect on the sum of bases. Cation exchange capacity (CEC) also exhibited frequent and, in many cases, statistically significant improvements. Soil organic carbon was analysed in a few studies and had contrasting results.

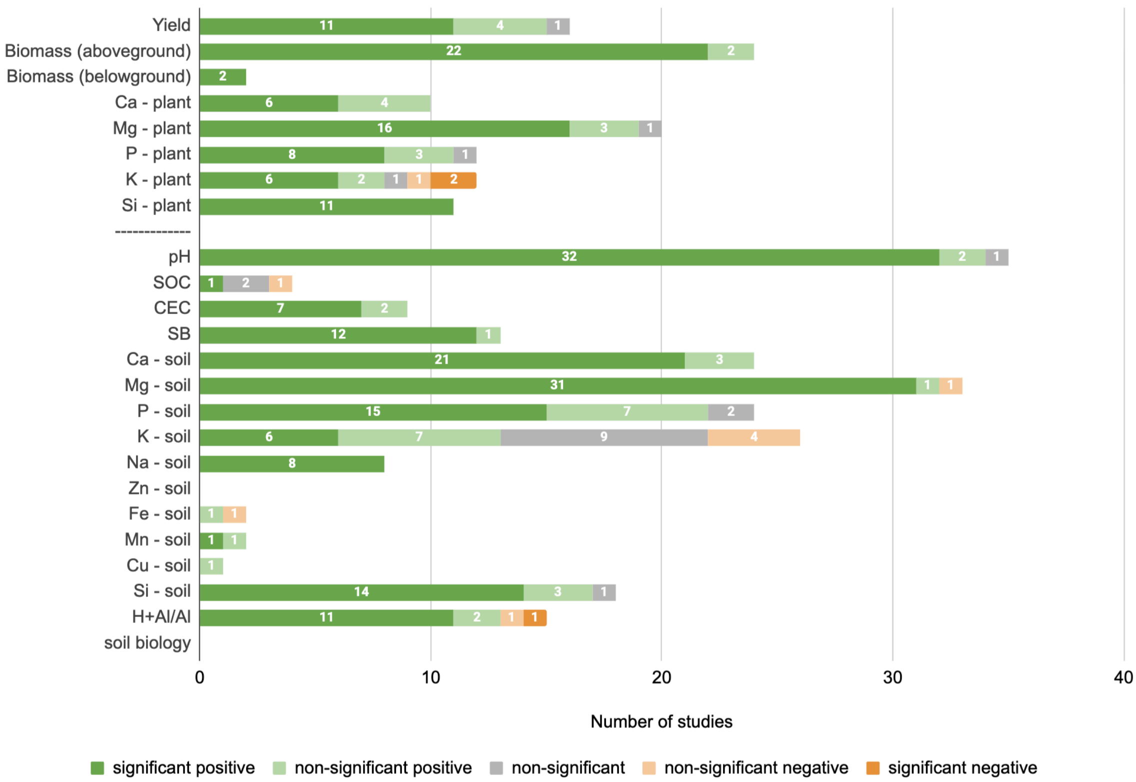

Figure 3. Summarized agronomic effects of 14 studies with silicate agrominerals (ASi) containing more than 20% sum of bases (SB_r) in Brazil. The count for significant positive (dark green), non-significant positive (light green), non-significant (gray), non-significant negative (light orange), significant negative (orange), and refers to comparisons to the negative control treatment.

Silicon (Si) demonstrated consistently positive responses. Additionally, indicators of soil acidity stress, such as $H+Al^{3+}/Al^{3+}$, tended to decrease under remineralization treatments, supporting the hypothesis that these amendments help buffer aluminum toxicity (Swoboda et al. 2022). Micronutrient responses were generally less pronounced, also because few experiments evaluated their content.

2.2.2 ASi (>20% SB_r) effects on plants

Legumes

Experiments with ASi >20%SB_r resulted in exclusively positive or significantly positive results regarding yield and biomass of soybean (*Glycine max (L.*). Most of the trials were pot studies that received a baseline fertilization typically consisting of different ratios of NPK (Cunha et al. 2022; Moretti et al. 2019) or a pH correction (Almeida et al. 2022). Comparisons with limestone are inconclusive, also because there is no reliable methodology for determining soil-specific rock comparison application rates. For example, Cunha et al. (2022) and Almeida et al. (2022) report better effects with limestone than with ASi, whereas superior results were found for a calcium silicate compared to limestone for a field trial with soy and bean (*Phaseolus vulgaris L.*) (Castro and Crusciol 2013). Most soybean yield gains correlated with increases in plant Ca and Mg concentrations, whereas Castro and Crusciol (2013) reported significantly reduced plant levels of K despite yield gains, which could be explained by a reduced K absorption efficiency through Mg competing with K for uptake sites.

Maize

Pot and field trials with maize and Mg-rich and Ca-rich ASi resulted in significant yield and biomass gains. Thermomagnesium resulted in significant increases of yield and biomass of 6-10% when maize was grown on a sandy and clayey soil compared to the control (Bossolani et al. 2021). Both soils from (Bossolani et al. (2021) were fertilized before the treatments to reach 60% base saturation, and received NPK as a baseline treatment. Dunite, another Mg-rich ASi, led to equal gains in maize biomass and yield when applied to a sandy and clayey soil in a pot trial, which received a complete macro- and micronutrient baseline fertilization (Crusciol et al. 2019). About 40% more maize yield was reported by with a Ca-rich silicate (likely a wollastonite rich rock) in a field trial with an acid clayey Rhodic Hapludox/Rhodic Ferralsol compared to control (Castro and Crusciol 2013). The field received a baseline NPK fertilization, and the ASi achieved slightly higher results than the limestone treatment (Castro and Crusciol 2013). Steatite, a rock rich in Mg and the mineral talc, increased maize biomass growth compared to the control in pot trials with Oxisol/Ferralsol, whereas the rock powder performed particularly well when combined with a vermicompost treatment (de Souza et al. 2013).

Other grasses

The grass species analyzed involved sorghum, Urochloa grass, Brachiaria, and sugarcane. Sorghum (*Sorghum bicolor*) total dry mass was significantly increased for olivine melilitite, with better effects for the Humic Dystrudept/Dystric Cambisol than the Typic Hapludult/Haplic Acrisol soil (Almeida et al. 2022). Significant increases for Urochloa grass were reported by Marchi et al. (2024) with vermiculite treatments. The treatments lead to 100% higher yields for the short pot trial of 50 days, whereas a baseline fertilization with P led to an additional significant increase in total dry mass, which was equally the case for other rock powders tested in this trial, outlining the importance of a soil optimized fertilizer mixture. Rodrigues et al. (2021a) report significant increases for *Urochloa ruziziensis* with rhythmite (limestone interlayers with bituminous shale) in pot trials that received a baseline NPK fertilization. Overall, yield gains were higher for the Oxisol/Ferralsol than for the Entisol/Arenosol and correlated with increased levels of Ca, Mg, and P in the plant tissues. In a similar pot trial with rhythmite applied to an Oxisol/Ferralsol and Ultisol/Acrisol that received a baseline NPK fertilization, Rodrigues et al. (2021b) found that sugarcane growth was increased and base cation nutrient levels were raised, although the results were statistically non-significant.

2.3 Potassium silicate agrominerals (ASiK)

2.3.1 ASiK effects on soil

The major effect of potassium silicate agrominerals (ASiK) on soils was its supply of K and Si. Bioavailable K was mostly measured via Mehlich-1 and showed predominately positive results. The agronomic efficiency compared to KCl is often time dependent, so that it is typically lower in short term trials, but increases with trial time due the long-term fertilization effect from ASi compared to a short fertilization effect of KCl (Arrieta et al. 2020; Nogueira et al. 2021). Effects on pH are reported, but are less analyzed for most trials, as the major purpose for ASiK trials is its suitability as an alternative K fertilizer, agreeing with the generally low pH correction capacity outlined in table 2. Other macronutrients like Ca and Mg were mostly non-significantly influenced, whereas Fe levels were partly decreased (Marchi et al. 2024). Effects on cation exchange capacity and soil organic carbon were equally non-significantly influenced by most ASiK tested.

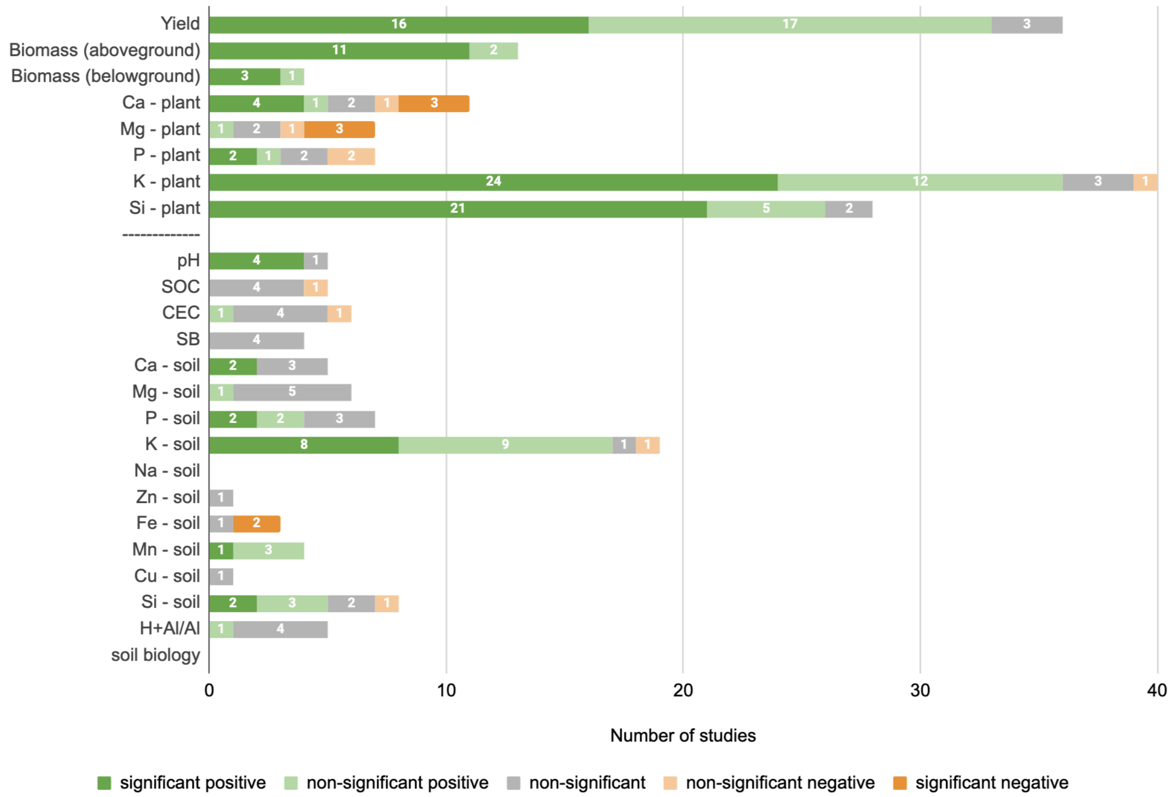

Figure 4. Summarized agronomic effects of 16 studies with potassium silicate agrominerals (ASiK) in Brazil. The count for significant positive (dark green), non-significant positive (light green), non-significant (gray), non-significant negative (light orange), significant negative (orange), and refers to comparisons to the negative control treatment.

2.3.1 ASiK effects on plants

Legumes

Finely ground (<0.074 mm) phonolite and a not further specified ASi with a high (13.8%) total K_2O content were broadcast applied in a field trial with a Typic Haplorthox/Haplic Ferralsol (Crusciol et al. 2022). The fields received an additional P fertilization at the beginning of the trial. Both ASiK resulted in similar results and partly higher yields as KCl, while K levels in leaves were statistically not significantly different among treatments, although Si levels were statistically higher with ASiK for bean. Results varied with the dose and were not always best for the highest dose. In a similar field trial with natural phonolite and molten and ground phonolite of the same fine particle size, Soratto et al.

(2022) reports about yield increases of common bean (*Phaseolus vulgaris*) on an Oxisol/Ferralsol. The agronomic efficiency was equal to KCl and the residual effects were better for the ASiK rocks, although the authors outline that the higher transport costs of the rocks might restrict their use to regional proximities when compared to KCl.

Maize

With biotite syenite doses up to 2.4 t ha^{-1}, (Busato et al. 2022) reports statistically significant biomass gains for maize grown on a Oxisol/Ferralsol. With a baseline nitrogen (N) and sulphur (S) fertilization, biotite increased plant growth by 25-100% compared to the control, whereas the best results were obtained with a combination with humic like acids. The two finely ground ASiK sources outlined in the previous section from Crusciol et al. (2022) increased maize yield in a field trial by about 8% compared to the control on the Typic Haplorthox/Haplic Ferralsol. Nepheline syenite and phonolite increased maize growth on a Typic Quartzipsamment/Haplic Arenosol and Rhodic Hapludox/Rhodic Ferralsol that were baseline fertilized and pH corrected before the treatments were applied (Nogueira et al. 2021). After 45 days, both K-rich treatments did not reach the same performance of KCl, which is likely explained by the short duration of the experiment. Santos et al. (2016) compared the effects of pure and modified metamorphosed glauconitic siltstone on a Typic Hapludox/Haplic Ferralsol in pot trials. The soils received a complete macro- and micronutrient baseline fertilization, except K. The effects were non-significant for maize with the untreated verdete rock, whereas the acidified and calcined verdete showed significantly better results for plant growth than the control, and similar to KCl.

Other grasses

Opposed to the non-significant findings for maize found by Santos et al. (2016), the authors found that grass (*Panicum maximum cv. Mombaça*) responded with significant yield gains for untreated verdete rock, which were strongly correlated with the K uptake.
Four different grass species (*Urochloa ruziziensis, U. decumbens, U. humidicola*, and *Andropogon gayanus*) were submitted to 8 t ha^{-1} phonolite in a greenhouse trial with clayey Oxisol/Ferralsol (Neto et al. 2024). All pots received a comprehensive baseline fertilization to raise pH and nutrient levels, except K. Grasses responded on average with 17.9% yield increases, whereas Urochloa decumbens stood out by promoting a substantially higher K availability in the remaining soil system than the cultivation of the other plant species. Marchi et al. (2024) found up to 500% yield increases in Urochloa grass yield grown on an Oxisol/Ferralsol after biotite syenite fertilization compared to the unfertilized control, which was furthermore increased once a baseline P fertilization was concomitantly applied. Similarly, Reis et al. (2024) and Tavares et al. (2018) report about positive but minor yield increases of grass grown on oxisol and fertilized with phonolite. For Tavares et al. (2018) the increases were statistically not significant, whereas for Reis et al. (2024) the *Urochloa brizantha* yield increased by about 4%, which was however superior than the KCl treatment. Rice (cultivar *Atalanta*) grown in pot trials with Oxisol/Ferralsol and Entisol/Arenosol responded with significant yield increases to glauconitic siltstone treatments (Arrieta et al. 2020). Although the relative agronomic effectiveness to KCl was lower in the first growth phase, it was superior to KCl in the second. Similar results were obtained by Violatti et al. (2019), who found that, for a pot trial with the grass *Urochloa brizantha* Braquiária cv. Marandú, the agronomic efficiency of glauconitic siltstone increased with time compared to KCl, with initially lower, but finally higher values. These results were confirmed for two soils, which both received a macro- and micronutrient baseline fertilization, except K.

2.4 Silicate agrominerals with <8% K_2O

2.4.1 Effects of ASi with <8% K_2O on soils

The application of silicate agrominerals with less than 8% K_2O, such as basalt and andesite rock powders, has been associated with generally positive outcomes for various soil parameters (see fig. 5). With some exceptions, these ASi classes have consistently increased pH, sum of bases, and the base cations Ca and Mg. Interestingly, although most of the analyzed rocks of these ASi classes contained less than 1% P_2O_5, there were almost exclusively positive increases in soil bioavailable P. Positive effects on soil K prevailed for the ASiKCaMg and ASiKMgCa classes containing tephrite, dacite, and mica schist (Cunha et al. 2022; Medeiros et al. 2025; Ramos et al. 2020). Basalts often increased soil K, although very high application rates such as employed by (Luchese et al. 2021; 2023) found non-significant and decreasing K values, whereas (Rodrigues et al. 2024a) found partly opposing trends, with very high application amounts (>50 t ha^{-1}) increasing soil K levels in an Oxisol/Ferralsol, but not the Entisol/Arenosol (Typic Quartzipsamment). Similarly, these very high basalt application amounts led to positive effects on soil organic carbon on the Oxisol/Ferralsol analyzed by (Rodrigues et al. 2024a, Rodrigues et al. 2024b) , but not the Entisol/Arenosol. An important difference to the previously discussed ASi classes is their more pronounced effect on soil micronutrients such as Zn, Fe, Mn, and Cu, which showed mixed to positive results, relating to their typically higher content of micronutrients compared to other ASi classes and rocks like wollastonite, dunites, and phonolites (Harley and Gilkes 2000). Soil biology was rarely measured and results were partly hard to categorize under positive or negative, such as Reis et al. (2024). A reduction in the number of nematodes was reported by Da Cruz et al. (2024), and an increase in acid phosphatase activity but decrease in β-glucosidase activity was seen by (Rodrigues et al. 2024c).

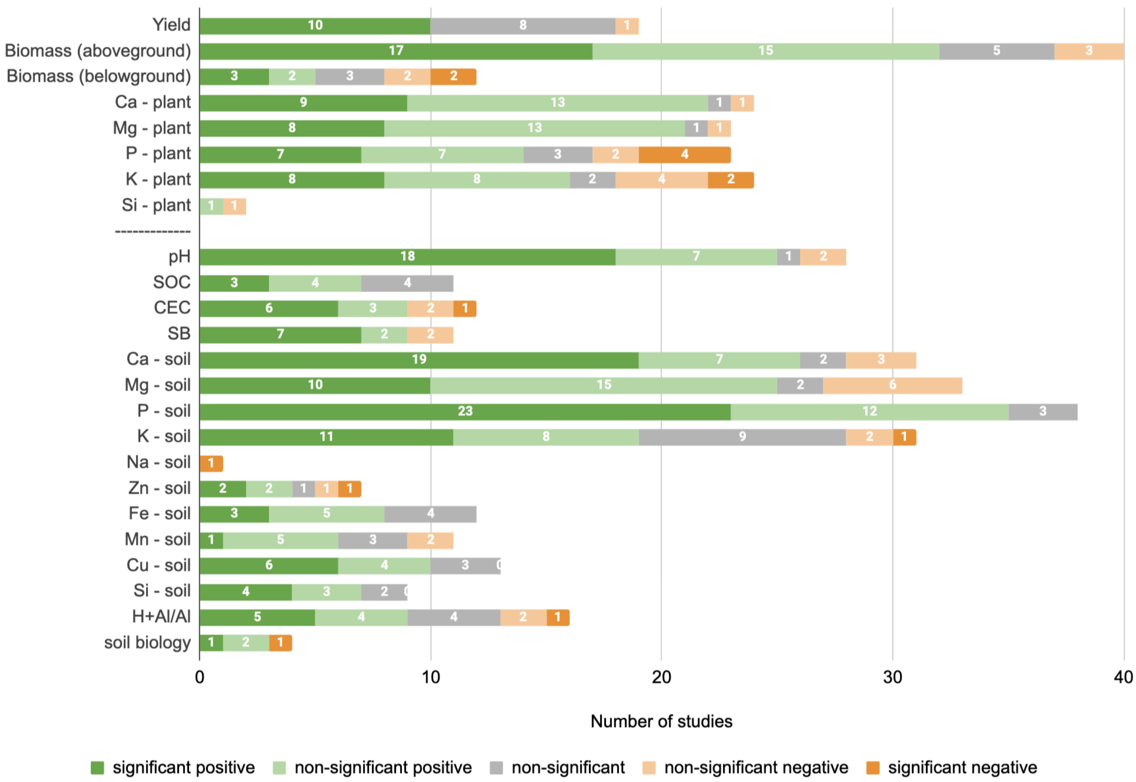

Figure 5. Effect of silicate agrominerals with <8% K_2O on plant productivity and soil parameters across multiple studies. The count for significant positive (dark green), non-significant positive (light green), non-significant (gray), non-significant negative (light orange), significant negative (orange), and refers to comparisons to the negative control treatment.

2.4.2 Effects of silicate agrominerals with <8% K_2O on plants

Legumes

Soil dependent effects on soybean growth were reported by Cunha et al. (2022), with tephrite application rates up to 10 t ha^{-1}, significantly increasing total dry matter on a Inceptisol/Cambisol, but not the Ultisol/Nitisol, whereas siltstone (up to 10 t ha^{-1}) had mixed effects on both soils. In contrast, olivine melilitite (a ASiMgCaK) doubled and tripled dry matter growth, whereas limestone out-yielded all rock powders. Da Cruz et al. (2024) reports beneficial effects of a basalt against the parasitic nematodes Meloidogyne javanica, whereas results for soybean dry matter production cultivated in a non-classified soil were non-significant, with positive trends for application amounts of 2 and 3 t ha^{-1}. For a field trial with Oxisol that received a baseline NPK fertilization, basalt powder linearly increased the yield of soybean for rates up to 10 t ha^{-1} compared to the control (Almeida and Gomes 2022). A comprehensive economic analysis demonstrated that rock powder increased the total revenue and improved the return rate, which is the relationship between net income and total cost, between 25.2% and 32.5%, with best results for 2.5 t ha^{-1}. Significantly positive soy plant dry mass yield gains were achieved in pot trials with acidic clayey soil with high basalt rates (>33 t ha^{-1}) by (Luchese et al. 2021; 2023), whereas effects were less pronounced for the sandy clay soil. In a completely randomized block trial on a Entisol/Neossolo that received a baseline NPK fertilization, a fine grained (100%<0.05 mm) basalt powder led to yield increases of over 200% for soybean, outyielding 3 t ha^{-1} of limestone (Meideiros et al. 2021). Ribeiro et al. (2025) reports mixed effects for soybean fertilized with basalt on a completely randomized field trial, with a yield reduction by about 5% on the Oxisol/Ferralsol, and a 15% increase on the Entisol/Neossolo, indicating soil texture as an important factor for the effectiveness.

Maize

After incubating Oxisol/Ferralsol and Entisol/Arenosol pots with basalt for 90 days, Conceição et al. (2022) found up to over 400% increases of shoot dry matter of maize plants cut after 55 days. Mixed results were found by Luchese et al. (2021) for maize fertilized with very high basalt doses (>33 t ha^{-1}) grown on a high pH clay (6.7, $CaCl_2$) and sandy soil (7.0, $CaCl_2$) pots. However, limestone treatments of up to 4t ha^{-1} had equally mixed and partly lower effects on biomass production. In contrast, Luchese et al. (2023) reported statistically significant increases in total dry matter for maize fertilized with similarly high doses of basalt, under a comparable experimental design. Key differences from Luchese et al. (2021) included lower soil pH, absence of phosphorus fertilization, a basalt source with a slightly higher sum of bases, and a 90-day incubation period prior to planting. In a field trial with a sandy Ultisol/Acrisol, basalt powder exceeded the effects of conventional NPK fertilization and significantly increased soybean yield for a dose of 2.5 t ha^{-1}, but not for 5 t ha^{-1} (Ribeiro et al. 2025). Unexpectedly, the control plots yielded higher results than the conventional fertilization plots. Seidel et al. (2021) reports no significant difference for basalt powder treatments compared to the control for maize grown on an Oxisol/Ferralsol, whereas a mixture of 8 t ha^{-1} basalt and 150 kg NPK outyielded the 300 kg NPK treatment in terms of above and belowground biomass. In a greenhouse experiment for which a Entisol/Arenosol was incubated with a residue powder from a basalt quarry (incomplete chemical characterization) for 90 days; after 40 days several plant growth parameters of maize increased for the basalt treatment compared to the control (both received conventional fertilization) (Silva et al. 2023). The best results were found for the reduced conventional fertilization (50%) plus rock powder and inoculation of Trichoderma harzianum. Significant increases in maize dry matter were observed by Ramos et al. (2020; 2021) for dacite powder rates of up to 7.2 t ha^{-1} grown in greenhouse Oxisol/Ferralsol pots.

Other grasses

Positive yield dry mass increases with basalt powder doses of up to 8 t ha^{-1} were observed after 674 days for a field experiment with mixed a native grassland species (Korchagin et al. 2022). For the grass species *Urochloa brizantha*, Marchi et al. (2024) and (Rodrigues et al. 2024a) found increases after high application doses of up to 96 t ha^{-1} on

Oxisol/Ferralsol and Entisol/Arenosol. In contrast, Reis et al. (2024) found non-significant and partly reduced yield for *Urochloa brizantha* treated with different basalt powders in Oxisol/Ferralsol pot trials. Sorghum (*Sorghum bicolor*) grown in succession after maize responded with significant dry mass yield increases for basalt powder treatments (2.5 - 5 t ha^{-1}) compared to the conventional fertilization in a field trial with Ultisol/Acrisol, indicating fertilization effects that exceed one crop cycle (Rodrigues et al. 2024c).

Other crops

Crushed amygdaloidal basalt powder significantly increased tomato (*Solanum lycopersicum L.*) yield on an Ultisol/Acrisol, with the results being statistically not different from the NPK fertilization (Dalmora et al. 2022). In a trial with eucalyptus (*Eucalyptus saligna*) grown on a clayey Ultisol, andesite powder lead to non-significant differences compared to the control, whereas a mixture of 3.3 t ha^{-1} dacite and 50% NPK yielded the same results as the 100% NPK treatment (Dalmora et al. 2020). A mixture of dacite and gabbro powder (30:70 ratio) with a triple superphosphate baseline fertilization had non-significant effects on black oat (*Avena strigosa*) growth, whereas bean (*Phaseolus vulgaris L.*) yield was increased at the dose of 7t ha^{-1} (Silva et al. 2022, 20). Minor positive increases in lettuce (*Lactuca sativa*) shoot fresh matter were reported by (Sousa et al. 2021) for mica schist doses of 2 t ha^{-1}, whereas the addition of effective microorganisms improved yields.

3 Discussion

3.1 ASi class and factor dependent effects

The near-absence of significantly negative results underscores the generally beneficial effects of silicate agrominerals in tropical agroecosystems. An important step to refine the effectiveness of ASi applications is to reveal trends for each ASi-class.

ASiCa and ASiMg are currently less explored but showed almost exclusively positive pH and yield increases, and can act as partial to complete limestone substitution with additional benefits like Si provision (Castro and Crusciol 2013).

ASiK can predominantly be considered as an alternative K source with moderate pH and micronutrient effects compared to KCl. As several trials have shown, many ASiK can compete with KCl when longer trial durations and appropriated granulometry are considered (Arrieta et al. 2020; Nogueira et al. 2021; Soratto et al. 2022).

The ASi with <8% K_2O such as basalts had mostly positive effects on pH and yield, and the overall effect range was wider and more nuanced, aligning with the wider variety of rocks tested. For example, unexpected yield increases occurring for replacing or reducing NPK suggest unexplored nutrient mechanisms (Dalmora et al. 2020; Rodrigues et al. 2024c; Seidel et al. 2021), which could potentially be explained through a combination of effects on pH, Si, macro- and micronutrients and biological stimulation. In this context, there is an increasing number of other tropical studies reporting positive results with the reduction or substitution of conventional fertilizers (Sidsi et al. 2025; Silveira et al. 2025).

These insights are important, since practitioners have often debated if either conventional fertilizers or silicate rock powders are more suitable in agricultural settings (Martins et al. 2024). We argue that this dichotomous framing fails to acknowledge the inherent complexity and site-specificity of agricultural systems, and that discussions should move beyond an either/or perspective. The primary goal should be to optimize plant growth while sustaining soil health in the most sustainable manner. Achieving this requires identifying the most economical and environmentally appropriate combinations of inputs and management practices. This study provides a foundation to further explore the potential of ASi and to determine the most effective application strategies to support a more sustainable agriculture.

Studies that tested various rocks within the same experimental design show that ASi with a higher sum of bases yielded better results (Cunha et al. 2022; Crusciol et al. 2022; Marchi et al. 2024; Rodrigues et al. 2021a), whereas other studies point to specific nutrient limitations like K—and not the overall sum of bases—being the limiting factor (Reis et al. 2024). Although the general suitability of highly weathered tropical soils for soil remineralization was confirmed, soil dependent effects were evident, with some studies reporting less improvements on clayey than on coarser grained soils (Violatti et al. 2019; Crusciol et al. 2019; Bossolani et al. 2021), whereas others report opposing trends (Rodrigues et al. 2021a; Rodrigues et al. 2024c; Luchese et al. 2021; 2023). This indicates that findings also have to be evaluated on a study specific basis.

For instance, in the study by Silva et al. (2022), despite an appropriate chemical composition of the gabbro-dacite mixture and application rates of up to 10t ha^{-1}, yields of black oat and bean did not significantly increase. The specific reasons might have been that they probably could not improve the extremely low fertility of the soils (pH_{H2O} 4.0 and 4.4, base saturation of 13.9% and 28%) combined with an unusually high organic matter content (50.9 and 60.3 dag kg^{-1}) that may have complexed the toxic Al and mitigated the effects of Si. Furthermore, the reported particle size was not further specified than being <1mm, which could theoretically contain large fractions of comparatively unreactive surface area. In this case, higher application amounts of fine grained basalt or olivine melilite could probably have been a more suitable choices for this soil. In this context, Almeida et al. (2022) furthermore confirmed that the factor particle size influenced the effects of the rock powder (olivine melilitite), with the finer treatment (100% <0.3mm) having significantly better effects than the coarser fraction (100%<2.0mm, 87%<0.84 mm sieve, and 60%<0.3 mm sieve).

3.2 Yield and soil-plant nutrient interactions

One aim of the joint analysis of soil, plant, biomass and yield effects was to deepen the understanding of their interactions. In many cases, increases of the macronutrients Ca, Mg, K and P in soils correlated with increases in biomass and yield. However, some studies showed opposing effects, where biomass and yield increases where accompanied by non-significantly altered or decreasing levels of one or more nutrients. This was for example the case for Almeida et al. (2022), who reports that the olivine melilitite (3.59% K2O) led to increases in yield and plant K content, but non-significant and decreasing effects on soil K. However, soil K was lowest for the highest yielding limestone and NPK treatment, which also led to the highest plant K content. This shows an effective recovery of K and indicates that non-significant changes or reduced Mehlich-1 soil K levels are not necessarily a negative outcome, but are rather a reflection of the nutrient extraction. Such biomass and yield increases concomitant with lower plant or soil nutrient concentrations can be caused by dilution effects, describing an increased absolute nutrient uptake which is however distributed across a greater biomass, thus leading to a diluted nutrient concentration (Marschner and Marschner 2012). The divergence between yield and nutrient status can also result from greater nutrient use efficiency or the resolution of another growth limiting, like improved water uptake, diseases resistance, or root growth (Fageria 2016). Increased root growth has been reported by several studies (Busato et al. 2022; Dalmora et al. 2022), which can strengthen the capacity of crops to withstand water stress and improve their nutrient uptake. Additionally, nutrient competition can alter tissue levels, and changes in biomass allocation (harvest index) may shift nutrient distribution within the plant (Marschner and Marschner 2012).

Overall, these results suggest that statistically non-significant changes in soil exchangeable nutrients after one growing cycle can also relate to an adequate nutrient uptake, indicating that soil nutrient levels should be considered alongside yield and plant nutrient levels. Trials with more than one growth cycle furthermore show that ASi can sustain and increase soil available nutrients like K compared to conventional sources like KCl (Arrieta et al. 2020), confirming that typical short-term agronomic trials are not suitable to capture the whole effect range of ASi (Korchagin et al. 2022).

3.3 Unexplored effects of silicate agrominerals

Beyond the agronomic effects synthesized, ASi are increasingly recognized for a range of additional ecosystem services that were not evaluated in this synthesis, but which may substantially enhance their overall value as soil amendments. Notably, ASi are central to enhanced rock weathering (ERW) strategies, which have the potential to capture and sequester atmospheric CO_2 at scale (Hartmann et al. 2013; Clarkson et al. 2024). Only one study (Medeiros et al. 2025) evaluated carbon sequestration in leaching columns with kamafugite, and found statistically non-significant effects for rock alone but significantly increased dissolved inorganic carbon when the rock was combined with compost, indicating important interactions with organic materials, which however have to be interpreted within a total carbon budget (Steinwidder et al. 2025; Sohng et al. 2025).

Furthermore, the bioavailable silicon released during weathering has been shown to improve plant resistance to both biotic and abiotic stresses (Meena et al. 2014; Schaller et al. 2024). Such Si-mediated effects were not the focus of the reviewed studies, although other research shows for example that ASiCa reduced potato stem lodging and boosted marketable tuber yield especially under water stress (Pulz et al. 2008, in Portuguese).

Although emerging research suggests that ASi can influence soil physical properties (e.g., porosity, aggregation, water retention; Costanzo et al. 2025), none of the analyzed studies evaluated such effects.

Similarly, despite the potential of ASi like basalt to stabilize organic matter through associations with newly formed mineral surfaces, this effect was not analyzed in any of the given studies (Buss et al. 2024). However, this mechanism should be further explored, particularly in long-term trials (Sohng et al. 2025), since the weathering of typical ASi like basalts produces poorly crystalline aluminosilicates and Fe/Al oxyhydroxides as secondary products, which are directly involved in the formation of mineral-associated organic matter (Buss et al. 2024).

Eventually, while many of these co-benefits remain outside the scope of the present study, their potential synergistic effects highlight the need for more integrated research (Buss et al. 2024). A comprehensive evaluation that includes these carbon, ecological, and resilience dimensions—particularly in light of emerging carbon markets and sustainability frameworks—may render ASi not only an agronomically effective but also an economically and environmentally superior amendment for tropical agriculture (Denny et al. 2023).

3.4 Limitations and minimum reporting requirements

Despite the prevalence of positive findings, refining our mechanistic understanding of certain soil-rock-plant interactions is still hampered due to the heterogeneity of study designs, rendering meta-analytic conclusions difficult and may obscure class-specific or context-dependent effects. Other reasons include limited long-term trials, incomplete rock and soil characterizations, and lack of economic analysis conducted for real farm settings. On the other hand, a positive bias in results reporting exists, as scientists are typically less incentivized to report negative results, which in turn were partly also caused by a poor selection of appropriate rocks and environmental conditions in the recent past . Therefore, methodological harmonizations and qualitative improvements are needed for future agromineral studies. A suggested overall approach for conducting agromineral experiments is the consideration of the most important factor framework proposed by Swoboda et al. (2022) for a general orientation, in combination with a comprehensive reporting of the following factors:

- agromineral characterization (chemistry, mineralogy, granulometry);
- application amounts and modus (surface, mixed, or specialized application);
- plants (botanical name, yield and/or biomass value as hectare equivalent, nutrient content);
- soil physicochemical characteristics (texture, pH, organic matter, bioavailable macro- and micronutrients up to 60 cm, particularly for perennial plants);
- experimental design (treatment and site description);
- positive (conventional fertilization) and negative (no fertilization) control when applicable;
- statistics (proper description and tabulation of statistical treatment comparisons)

This approach would promote a more robust and harmonized analysis of experiments. Apart from these requirements, it is furthermore relevant to discuss the presented study designs in the context of real-world agronomic settings. Additionally, rapid initial screening of potentially suitable rocks can be done via the method employed by Manning et al. (2017), in which the rock powder and high purity quartz is used instead of natural soil. This eliminates the variability of natural soil properties and allows the comparison of the crushed rock in isolation from field effects.

3.5 Future methodological considerations

For an optimization of the application of ASi under real-world agronomic settings, the experimental design must be considered. Most ASi studies in Brazil showed positive and significantly positive effects on plant growth and yield compared to an unfertilized ('negative') control, which is highly relevant for little or no-input agronomic systems mostly occurring for small scale farmers with little purchase power (Theodoro and Leonardos 2006).

In contrast, most commercial cash crops receive conventional fertilizers, and any given employment of ASi will have to be economical for the farmer compared to the status quo fertilization ('positive' control) - be it as (i) additional amendment on top of the conventional practice, (ii) or as partial to complete reduction of conventional inputs.

For (i), a comprehensive economic analysis showed that basalt powder (0, 2.5, 5.0, 7.5, and 10 t ha^{-1}) applied on top of a commercially managed soybean field positively influenced the total revenue, gross margin and net margin of the treatments, leading to a higher rate of return for the producer (Almeida and Gomes 2022). Yield gains on top of conventional fertilizations were reported in several other cases (Busato et al. 2022; Bossolani et al. 2021; Castro and Crusciol 2013; Almeida and Gomes 2022).

For (ii), promising results were also attained for ASi treatments with reducing conventional inputs compared to the conventional control (Burbano et al. 2022; Rodrigues et al. 2024c; Dalmora et al. 2020; Seidel et al. 2021), whereas other authors report mixed results when reducing conventional fertilizers (Galina et al. 2024).

Furthermore, longer trial durations are highly recommended. The trial duration of most experiments is still limited, which also disadvantages ASi when compared to fast-release nutrient sources like KCl. Several experiments show that the agronomic efficiency of agrominerals like ASiK is improving with time and can be superior compared to conventional inputs like KCl when longer trial durations are considered (Arrieta et al. 2020; Nogueira et al. 2021; Soratto et al. 2022). The mineralogy of rocks differ in their reactivity, with some releasing nutrients within a crop cycle, while others do not, meaning that the total K concentration of a rock cannot be directly equated with plant-available K or compared to soluble fertilizers such as KCl. The issue of slow nutrient release rates was in many studies also successfully circumvented through prior incubation time of the ASi before planting (Almeida et al. 2022; Arrieta et al. 2020; Conceição et al. 2022; Dalmora et al. 2022), which should be considered for future applications. Similarly, it will be beneficial to replicate the same experimental setup across different soil and climatic conditions.

3.6 ASi induced phosphorus supply

One of the most relevant findings of this study was the increase in bioavailable P, despite most ASi containing no or very limited P. The increased P availability could be linked to several Si-related mechanisms, as discussed by (Schaller et al. 2024): a Si induced mobilization of P bound to soil particles, such as e.g. Fe-oxides, or increased reductive dissolution of P-containing Fe oxides through a reduced hydraulic conductivity. ASi have also been shown to change microbial processes related to P acquisition (Bi et al. 2024). Furthermore, P availability is a pH governed effect (Sanchez 2019), which explains that limestone - although to a lesser extent when compared directly to ASi - can increase P availability (Cunha et al. 2022). The comparatively stronger effect of ASi compared to limestone on P availability was also found by other authors (de Aquino et al. 2020; Luchese et al. 2021), indicating other mechanisms than purely a pH effect.

Whilst this paper was initially not designed to consider this effect, the findings provide substantial evidence to underpin ASi's potential to optimize P nutrition in tropical soils. This is highly relevant, as P is a major limiting nutrient in agriculture (Sanchez 2019), and a limited resource as mineable deposits decline rapidly (Schaller et al. 2024). This is particularly relevant for the tropics, as P is easily immobilized in many highly weathered soils, rendering its supply ever more challenging. Refining our understanding of Si-optimized P fertilization in the tropics thus bears considerable agronomic, economic, and environmental potential (Schaller et al. 2024).

4. Conclusion

This study provides the first quantitative synthesis of silicate agromineral (ASi) experiments in Brazil in the context of a novel classification. Despite the diversity of study designs, rock types, and agroecological conditions, a consistent pattern emerges: ASi can significantly improve tropical soil health and crop performance. These findings substantiate the growing perception of finely ground silicate rocks as a highly suitable amendment for tropical agroecosystems. Categorizing agromineral research according to the novel classification system based on the rocks´ lithochemistry proved to be practical both from a scientific and farmer perspective. One major insight of this study is the capability of ASi to enhance P availability, despite the typically low inherent P content of the materials. Future methodological approaches are suggested to strengthen the emergent finding of ASi's significant environmental and economic potential under real-world agronomic settings. We suggest overcoming ongoing debates of ASi versus conventional fertilizers and instead focus on identifying the most suitable agronomic management combinations. As Brazil leads this frontier, the lessons and novel classification presented here provide a blueprint for the sustainable intensification of agriculture across the tropics.

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