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A meta-analysis of the agronomic benefits of silicate rock powders in Brazil in the context of a novel classification☆

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A R T I C L E I N F O

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A B S T R A C T

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. However, the research landscape remains fragmented, and there is currently no quantitative synthesis of tropical ASi assessments. We address this gap by synthesising 54 Brazilian crop trials through a meta-analysis structured around a recently proposed ASi classification. Pooled across all classes, ASi delivered significant ($p < 0.01$) gains in yield (+33%), aboveground biomass (+42%), exchangeable Ca (+38%), Mg (+35%) and K (+19%), soil pH (+4%), and P (+80%), confirming ASi as a robust multi-nutrient amendment for highly weathered tropical soils. The novel classification could empirically discriminate among the agronomic effects of the ASi classes. A conservative single-season economic analysis shows that basalt and phonolite powder can achieve a breakeven under real field conditions at moderate doses. We recommend minimum requirements for standardised methodologies and suggest real-world research designs to support broader ASi adoption. Our findings offer valuable insights for scaling the usage of ASi 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 characterised 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 fertilisers—most of which are imported, expensive, and partly unsuited

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to the chemical and physical characteristics of tropical soils (Sanchez, 2019). Soluble fertilisers 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 emphasised 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 remineralisers (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 fertilisers 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 mobilising 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 favourable 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 maximised under neutral to mildly alkaline conditions (Clarkson et al., 2024), highlighting the importance of identifying agricultural settings where agronomic benefits and bicarbonate formation are optimised.

Important synergies can also occur regarding the stabilisation 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 analysing 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 on 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., 2026). 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 for 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 fertiliser, petrofertiliser, and stone meal (or rock meal, Theodoro and Leonardos, 2006), which was coined as “rochagem” in Portuguese by Leonardos et al. (1976). The term ‘remineraliser’ gained popularity through the 1994 establishment of “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 remineraliser, 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, sulphate, 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 sulphates 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 sulphates) 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 study 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.

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 polymerisation 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. (2026) to facilitate the work with crushed silicate rocks and to enable the prediction of agronomic effects.

According to this classification, an ASi is composed of more than 50% silicates, whereas a subsequent classification is based on the base percent in the form of oxides: CaO, MgO, and K_2O. The sum of these oxides is referred to as the sum of $bases_{rocks}$ (SB_r), to distinguish it from the sum of bases in soil science (SB_s), which also includes sodium (Na) (Azevedo and Manning 2023). To qualify as a remineraliser, 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 (Fig. 1).

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 Supplementary table S1.

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

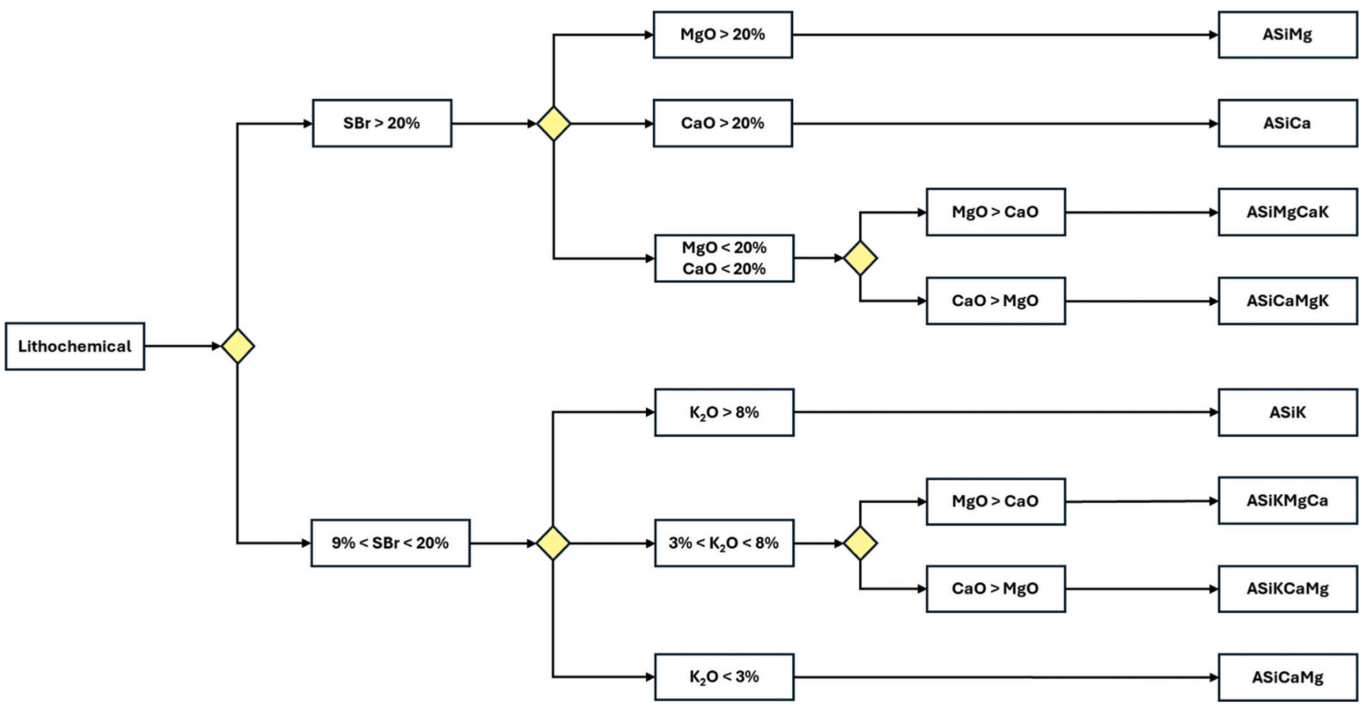

Fig. 1. Lithochemical classification of silicate agrominerals considering the sum of bases in the form of oxides ($SB_r = CaO + MgO + K_2O$) and the base contents after Martins et al. (2026). SB_r = sum of $bases_{rocks}$ as oxides ($MgO + CaO + K_2O$) after Azevedo and Manning (2023).

ASi are initially categorised 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 $SB_r \geq 20\%$, ASi are divided into:

Magnesium silicate agrominerals (ASiMg) — containing more than 20% MgO. 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., calcium paragranulites) and steel slags.

Calcium-magnesium-potassium silicate agrominerals (ASiCaMgK) — < 20% MgO, < 20% CaO, CaO > MgO; rich in calcium and derived from igneous rocks like anorthosites, calc-silicate metamorphic rocks (e.g., calc-schists), and steel slags.

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

When SB_r is between 9% and 20%, ASi are divided into:

Potassium silicate agrominerals (ASiK) — with more than 8% K_2O, derived from alkaline rocks like high-K syenites and phonolites, as well as 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 (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).

As outlined above, this classification is aligned with the recently enacted agricultural legislation for Brazilian fertilisers (Lei N° 12.890, 2013). In Brazil, soil remineralisers 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, remineralisers 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 (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.

Importantly, the classification is not merely descriptive. Martins et al. (2026) propose that it "enables the differentiation of potential short-, medium-, and long-term effects" and organise the eight classes along a reactivity gradient ordered by neutralisation potential (NP). At the reactive end of this gradient are the Mg- and Ca-rich ASi classes, derived from mafic and ultramafic rocks and carrying the highest NP, whereas at the least-reactive end are the K-rich ASi classes (ASiK), derived from alkaline felsic rocks and characterised by lower NP. The classification therefore makes specific, falsifiable predictions about the direct agronomic and soil effects of each class—the Mg-/Ca-rich end should deliver the largest effects on soil pH correction, base-cation supply, and base-cation uptake, while the K-rich end should deliver smaller effects on these endpoints but remain agronomically relevant as a K source.

1.3. Soil remineralisation in Brazil

The Rochagem movement in Brazil has been instrumental in using crushed rocks as soil remineralisers, 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 emphasised 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, sugarcane, and cassava—especially for smallholder farmers—had been shown through Brazil's Agrarian Reform programme. Simultaneously, the Brazilian Agricultural Research Corporation (EMBRAPA) began investigating the use of powdered rocks due to rising fertiliser costs and the country's heavy dependence on imports for its fertiliser 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 emphasised the need to establish technical parameters for regulating remineralisers (ABREFEN, 2025).

The research presented at these events reported that agrominerals can provide multiple agronomic and environmental benefits. They can be up to 80% cheaper than conventional fertilisers 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).

Official recognition came with the enactment of Federal Law 12,890/2013, which formally included "remineralizadores" within the legal framework for agricultural inputs alongside conventional fertilisers, lime, and soil conditioners. This was further detailed in Normative Instruction 5/2016 (IN 5/2016), which sets technical requirements for registration, classification, labelling, and commercialisation of silicate agrominerals in Brazil. The 20%-SB_r and 8% K_2O thresholds adopted by Martins et al. (2026) align directly with the regulatory categories of IN 5/2016, so the classification has an immediate practical use for producers, regulators, and farmers navigating the Brazilian fertiliser market.

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 fertilisers. Additionally, Brazil has become a central node in the scientific exploration of SRPs, with an increasing volume of field trials and case studies (Martins et al., 2026).

The movement also benefited from Brazil's robust mining sector, which consists of over 3300 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).

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 generalisable insights.

1.4. Aims of this study

The aim of this paper is to quantitatively synthesise the existing body of Brazilian ASi studies in the context of the recently proposed Martins et al. (2026) classification. We focus on soil fertility parameters, effects on plants, and the major variables influencing those effects, and present an analysis of agro-economic performance under Brazilian field conditions. Specifically, we address four research questions:

(i) What is the overall effect of ASi on crop biomass, yield, and key soil fertility parameters?
(ii) Can the Martins et al. (2026) classification predict agronomic effects according to the proposed reactivity gradient?
(iii) Is there a dose–response relationship, and which contextual moderators explain the heterogeneity of ASi effects?
(iv) What is the agro-economic performance of ASi under Brazilian field conditions?

By consolidating Brazil's unique experience with rock powders in agriculture, this paper aims to provide a quantitative foundation for scaling this practice in Brazil and across tropical agricultural systems worldwide.

2. Materials and methods

The synthesis was performed as a PRISMA-compliant systematic review (Page et al., 2021) followed by a three-level random-effects meta-analysis. The structure follows the quality-assessment criteria for soil and agricultural meta-analyses of Fohrafellner et al. (2023), and the variance framework follows Nakagawa et al. (2023). Sections 2.1–2.3 describe the literature search, study selection, and data extraction. Section 2.4 details effect-size and variance computation. Sections 2.5–2.8 explain the meta-analytic models that address each of the four research questions. Section 2.9 documents the software pipeline and reproducibility resources.

2.1. Literature search

We searched Scopus and Web of Science for peer-reviewed publications from January 1990 to February 2026. The search string was restricted to peer-reviewed studies in English and combined ASi-related terms (e.g. *remineraliz**, *rochagem*, *agromineral**, *rock powder*, *rock dust*, *basalt**, *phonolite*, *dacite*, *melilitite*, *wollastonite*, *olivine*, *dunite*, *andesite*, *glauconit**, *silicate**) with agronomic terms (*soil*, *crop**, *plant**, *agricultur**, *yield*, *biomass*, *productivity*, *fertiliz**, *amend**, *applicat**, *field experiment*, *greenhouse*). The reference list of one prior review (Swoboda et al., 2022) was screened via citationchaser, and snowballing was conducted on ResearchGate. The full search documentation is deposited as Supplementary file S1.

2.2. Study selection

We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol (Page et al., 2021); the flow diagram is provided as Supplementary file S1. The initial searches identified 1497 records (Scopus $n = 976$; Web of Science $n = 815$; Swoboda et al., 2022 $n = 165$; ResearchGate $n = 4$). Eligible studies were selected against the following inclusion criteria: (1) a silicate agromineral (ASi; > 50% silicates, $SB_r \geq 9\%$) was applied against a matched control group; (2) at least one of yield or aboveground biomass was reported; (3) sufficient information was given to assign the material to an ASi class; (4) experimental conditions were reported (field vs. greenhouse, application amount, duration); and (5) means and a measure of dispersion (SD, SE, or CV) were reported in sufficient detail to compute weighted effect sizes. Studies were excluded where (a) the primary amendment was a non-silicate mineral (e.g. limestone) or steel slag, or (b) co-application designs (rock powder combined with organic amendment) prevented isolation of the ASi-only effect. Three sequential screening stages were conducted. Major reasons for excluding records apart from the previously mentioned criteria were unclear methodologies, artificial growth substrates, liquid ASi treatments or insufficiently reported outcomes. The final eligible set comprised 54 studies and 2948 effect-size observations (Supplementary Table S2).

2.3. Data extraction and moderators

For each eligible study we extracted study metadata (author, DOI, year), geographic information, soil data (Brazilian, USDA, and WRB taxonomies; pH; organic matter content; clay content), crop species, experimental information (greenhouse vs. field, baseline fertilisation, negative or positive control), ASi material identification and lithochemistry, particle size, and application dose and method (surface broadcast vs. incorporated).

Outcome variables comprised yield (e.g. corn or soybean grain yield), aboveground biomass, belowground biomass, and aboveground tissue concentrations of N, P, K, Ca, Mg and Si. Soil outcomes included pH (H_2O, KCl, or $CaCl_2$), exchangeable H + Al, exchangeable Al, exchangeable Ca, Mg, K, P and Si, soil organic carbon (or organic matter), cation exchange capacity (CEC), and base saturation (V %). For every treatment–control pair within every outcome variable, the means, dispersion (SD, SE, CV, or MSE), and group sample size were collected. Each row of the extraction matrix corresponds to one matched treatment–control pair within one outcome variable; if a study contributed multiple doses, time points, or soil × crop combinations, all were retained as independent observations rather than averaged, with non-independence accommodated at the modelling stage.

Each rock material was assigned to one of the eight Martins et al. (2026) classes during extraction. Because three classes contributed very few studies (ASiCa, $k = 1$; ASiMgCaK, $k = 2$; ASiMg, $k = 2$), formal class-level inference was performed on a four-level analytical regrouping that preserves the chemical hierarchy of the original classification, resulting in the following new meta-classes: (1) ASiCaMg; (2) ASiK >8% K_2O (originally the "ASiK" class); (3) ASi 3–8% K_2O (merging ASiKMgCa and ASiKCaMg); and (4) ASi $SB_r > 20\%$ (merging ASiCa, ASiMg, ASiCaMgK and ASiMgCaK). The grouping respects the primary 20% SB_r partition of Martins et al. (2026).

Five contextual moderators were retained for the main importance analysis (section 2.7): ASi class (4 meta-groups); application dose (t ha^{-1}); trial duration (days); initial soil pH; and crop group (soybean, maize, sugarcane, rice, grass, other annual — sorghum, wheat, millet — and perennial — coffee, eucalyptus). Four further candidate moderators were considered but not retained in the main loop: soil clay percentage and pre-planting incubation duration both had too few observations for a robust Akaike loop, and were therefore evaluated separately as bivariate meta-regressions (Fig. 4). Soil type is dominated by Oxisols, leaving the categorical factor under-identified. Particle size was inconsistently reported and could not be coded reliably.

2.4. Effect-size and variance computation

The natural-log response ratio (lnRR; Hedges et al., 1999) was used as the primary effect-size statistic, calculated as:

$$ln\mathrm{RR}_i = \ln\left(X_{\mathrm{T,i}}/X_{\mathrm{C,i}}\right) \tag{1}$$

where $X_{\mathrm{T,i}}$ and $X_{\mathrm{C,i}}$ are the mean outcome values in the rock-powder treatment and the matched control arm of observation *i*, respectively. Positive *ln*RR values indicate enhancement relative to control. To facilitate interpretation, *ln*RR was converted to a percentage change (Bai et al., 2013):

$$p = \left(e^{ln\ RR} - 1\right) \times 100\% \tag{2}$$

The sampling variance of *ln*RR was computed following Hedges et al. (1999):

$$V_{ln\ RR} = s^2{}_T/\left(n_T \cdot X^2{}_T\right) + s^2{}_C/\left(n_C \cdot X^2{}_C\right) \tag{3}$$

where s_T and s_C are the within-arm standard deviations and n_T and n_C the replicate counts. Across the 2948 treatment–control comparisons, *s* was directly reported or back-calculated from ANOVA $CV_{\%}$ as $s = CV_{\%} \cdot X_{\mathrm{arm}}$ / 100 for 71% of observations; for the remaining 29%, complete-case exclusion would have biased the dataset toward better-documented studies (Kambach et al., 2020). We therefore reconstructed missing *s* from a sample-size-weighted pooled coefficient of variation, following Nakagawa et al. (2023):

$$s_{imp} = CV_{pool} \cdot X_{arm} \tag{4}$$

CV_{pool} was computed separately for each outcome and for treatment versus control arms, using a two-stage sample-size weighting (within-study, then between-study); for outcomes with fewer than five contributing studies, a compartment-level fallback (all plant or all soil outcomes pooled) was applied. Three variance specifications were carried forward: Model A applies CV_{pool} to all observations (primary specification); Model B is the complete-case alternative using reported *s* only; Model C is a hybrid using study-specific *s* where reported and CV_{pool} otherwise. Models B and C are reported as sensitivity comparisons in Supplementary Table S2.

The weighting factor for each observation was the inverse of its variance:

$$w_i = 1/V_{ln\ RR,i} \tag{5}$$

The overall (pooled) response ratio across observations was calculated as:

$$ln\mathrm{RR}_{++} = \Sigma\, w_i \cdot ln\mathrm{RR}_i / \Sigma\, w_i \tag{6}$$

with associated standard error:

$$\mathrm{SE}(ln\mathrm{RR}_{++}) = \sqrt{(1/\Sigma\, w_i)} \quad (7)$$

and 95% confidence interval (Hedges and Olkin, 2014):

$$95\%\mathrm{CI} = ln\mathrm{RR}_{++} \pm 1.96{\cdot}\mathrm{SE}(ln\mathrm{RR}_{++}) \quad (8)$$

Pooled estimates and their CIs were obtained from the three-level random-effects *rma.mv* model described in §2.5 (*metafor* R package; Viechtbauer, 2010). Effects were considered significant when the 95% CI of the pooled effect size did not overlap zero (Luo et al., 2006).

2.5. Meta-analytic model and overall effects

All pooled effect sizes were estimated from three-level random-effects models (Konstantopoulos, 2011; Cheung, 2014; Van Van den Noortgate et al., 2013) fitted with the *metafor* R package (Viechtbauer, 2010). The nested random structure accommodates the two principal sources of non-independence in the dataset: multiple observations within a single study sharing the same experimental setup (different doses, soil types, time points, or crops), and between-study heterogeneity from differences in climate, researcher, and rock provenance. Variance components were estimated by restricted maximum likelihood (REML) for all reported pooled estimates. Standard errors and confidence intervals were derived under the Knapp–Hartung small-sample correction (Knapp and Hartung, 2003; IntHout et al., 2014). Total heterogeneity (I^2) and the level-2 / level-3 partition were computed following Nakagawa and Santos (2012).

Approximately 80% of the eligible observations come from greenhouse, pot, or incubation trials. The forest plot therefore reports two pooled estimates per outcome rather than one—a greenhouse pooled *ln*RR and a field pooled *ln*RR, each fitted as its own intercept-only three-level model on the corresponding subset of observations. Field rows are displayed only for outcomes with ≥4 contributing field studies, because below that threshold the field pool does not meet the $k \geq 3$ minimum recommended for random-effects pooling (Fohrafellner et al., 2023).

2.6. Classification test

The classification test asks whether the four-level Martins et al. (2026) grouping explains variation in agronomic responses beyond a null intercept. For each of nine matched plant–soil outcomes we added ASi class as a fixed moderator to the three-level model (§2.5) and reported the omnibus Q_M *F*-test (Fig. 2). A class only entered the test for an outcome if it contributed ≥2 studies; classes with a single contributing study appear as *(only 1 study)* placeholders in the figure but are excluded from the F-statistic (Viechtbauer, 2010).

For panels in which the omnibus screened at $p < 0.05$, all six pairwise class contrasts were computed as linear combinations of *rma.mv* coefficients with Benjamini–Hochberg false-discovery-rate correction at $q = 0.05$ (Benjamini and Hochberg, 1995). Compact-letter displays were generated via *multcompView* (Graves et al., 2024) following Piepho (2004): classes sharing a letter are statistically indistinguishable at $\alpha = 0.05$ after correction. For yield and aboveground biomass we additionally calculated per-class intercept-only three-level models on the *positive-control* subset (sufficient data were only available for ASiK vs. KCl).

2.7. Moderator importance and dose–response

For the two pivotal plant-growth outcomes (yield and aboveground biomass), we ranked the relative importance of the five candidate moderators introduced in section 2.3 using Akaike-weight multi-model averaging (Burnham and Anderson, 2002)—the same approach adopted in recent ecological meta-analyses (Xu et al., 2025; Wang et al., 2026). An importance score ≥ 0.80 distinguishes moderators that contribute to model fit consistently across the candidate set from those whose contribution is conditional on which other moderators are present. To complement the importance ranking, we fit single-moderator three-level meta-regressions for the continuous moderators most consistently selected by the importance loop (Fig. 3).

Soil clay percentage and pre-planting incubation duration (time between rock powder application and planting) were considered a priori but excluded from the Akaike analysis because both were under-reported relative to the requirements of multi-moderator selection. Each was therefore evaluated separately as a single-moderator three-level random-effects meta-regression fitted by REML in metafor (Viechtbauer, 2010), under the same random-effects structure and Knapp–Hartung correction as in §2.5 (Fig. 4).

2.8. Economic analysis

To assess agro-economic performance under Brazilian field conditions, we compared the observed field-trial yield gains for the two most-studied ASi classes—ASiCaMg and ASiK—against per-hectare breakeven thresholds derived from current commodity prices and delivered rock-powder costs. The breakeven line answers, at a given dose D, what minimum percentage yield gain is required for the additional crop revenue to exactly offset the costs of the rock powderand its associated operational expenditures in a single season:

$$Breakeven\% = (D{\cdot}C_{\mathrm{rock}}) / (Y_{\mathrm{baseline}}{\cdot}P_{\mathrm{crop}}) \times 100$$

where C_{rock} is the delivered and applied rock-powder cost, Y_{baseline} the control yield, and P_{crop} the per-kilogram crop price. The formula is algebraically equivalent to the Net Margin zero condition of the Gomes and Ferraz-Almeida (2022) cost framework, which is the only Brazilian study in our dataset providing paired agronomic and economic data, and was verified against all four dose–profitability pairs in their Tables 1–2.

The delivered cost for basalt was set at R$73.97 t^{-1} (R$50 material plus R$24 for freight at 100 km and application, after Gomes and Ferraz-Almeida, 2022). Dacite was assumed to have the same cost per t^{-1} as basalt. Phonolite (ASiK) is a commercial specialty product, not a quarry by-product, and its delivered cost was set at R$323.97 t^{-1} (R$300 material plus R$24 freight and application). An average price of R$300 phonolite material was assumed, related to the price of the commercial phonolite based product 'Ekosil granel' (F.F.G. Bernardez, 2026, pers. comm.).

Soybean baseline yield (2618 kg/ha) and price (R$66.03/sc) were sourced from Gomes and Ferraz-Almeida (2022). Maize baseline yield (5613 kg/ha) and price data (R$50/sc) from Pinheiro et al. (2021).

The breakeven calculation currently excludes various potential factors that could shift the breakeven threshold in favour of ASi. These include (i) multi-season residual nutrient release; (ii) NPK-offset savings under reduced conventional fertilisation; (iii) gradual liming-equivalent co-benefits on soil pH; (iv) savings due to Si-mediated stress-resistance; and (v) any carbon-credit revenue under enhanced-weathering CDR accounting or from carbon savings associted with conventional input reductions.

2.9. Statistical software and reproducibility

All meta-analytic computations were performed in R 4.3 (R Core Team, 2024) called from a Python 3.10 kernel in Google Colab via the *rpy2* bridge (Gautier, 2024), so that every figure is reproducible end-to-end from a single notebook. R packages: *metafor* (Viechtbauer, 2010) for the three-level *rma.mv* models; *multcompView* (Graves et al., 2024) for compact-letter displays; and *dplyr* for data manipulation. Figure production used Python with *matplotlib*, *numpy*, *pandas* and *scipy*; the bivariate meta-regression panels of Fig. 4 use a Python implementation of the DerSimonian–Laird estimator that agrees with the canonical metafor R fit to within reporting precision. The dose–response scatter and forest-plot design follow Xu et al. (2025) and Wang et al.

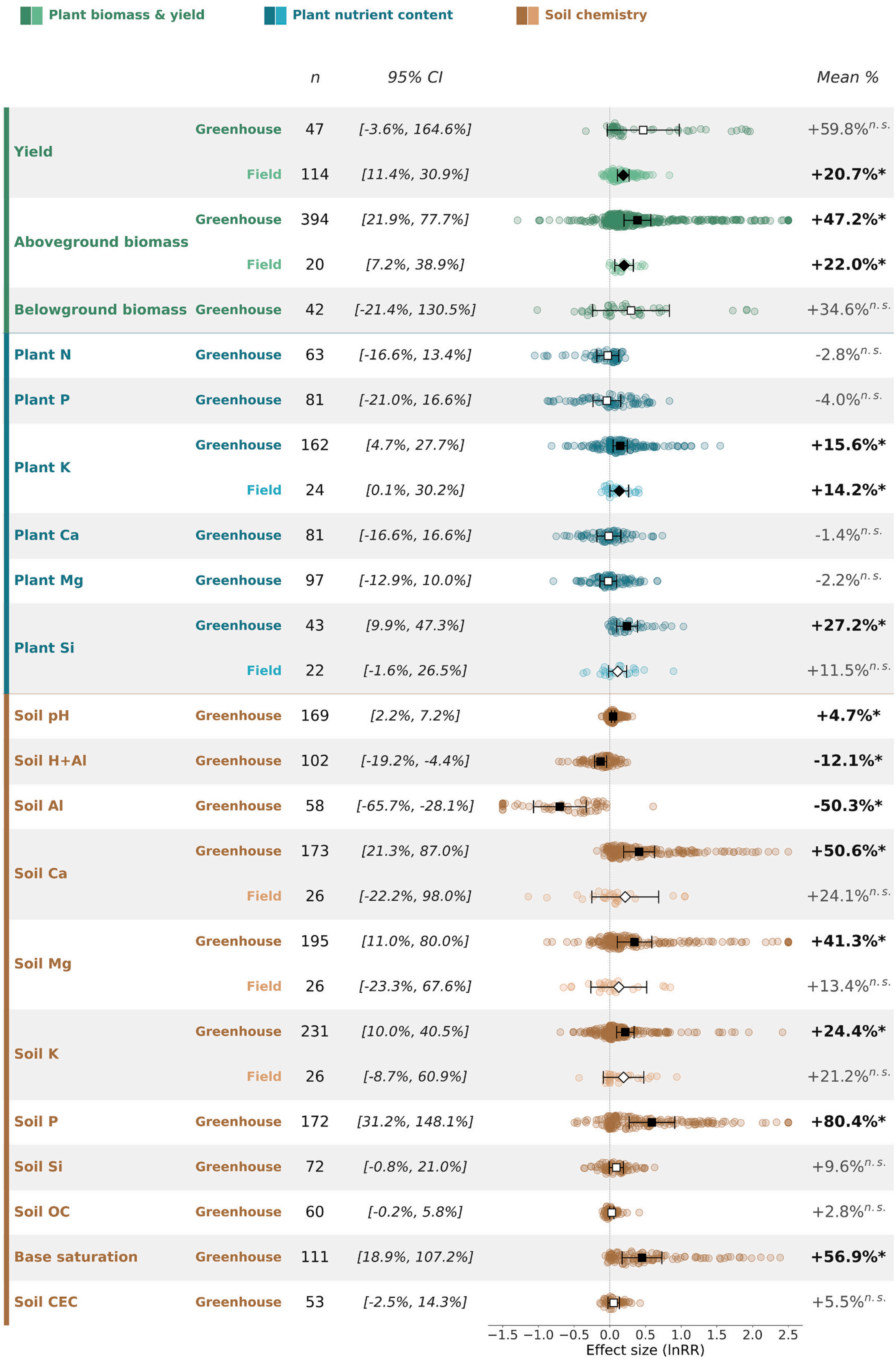

Fig. 2. Meta-analysis forest plot of the greenhouse and field pooled effects of silicate agrominerals across plant biomass and yield, plant nutrient content, and soil-chemistry outcomes. Scattered dots represent individual observations. Squared and diamond markers represent weighted means. Closed markers indicate statistically significant results ($p < 0.05$). Field rows are shown only when $\geq$ 4 studies contribute. Observation number (n) are shown for each category.

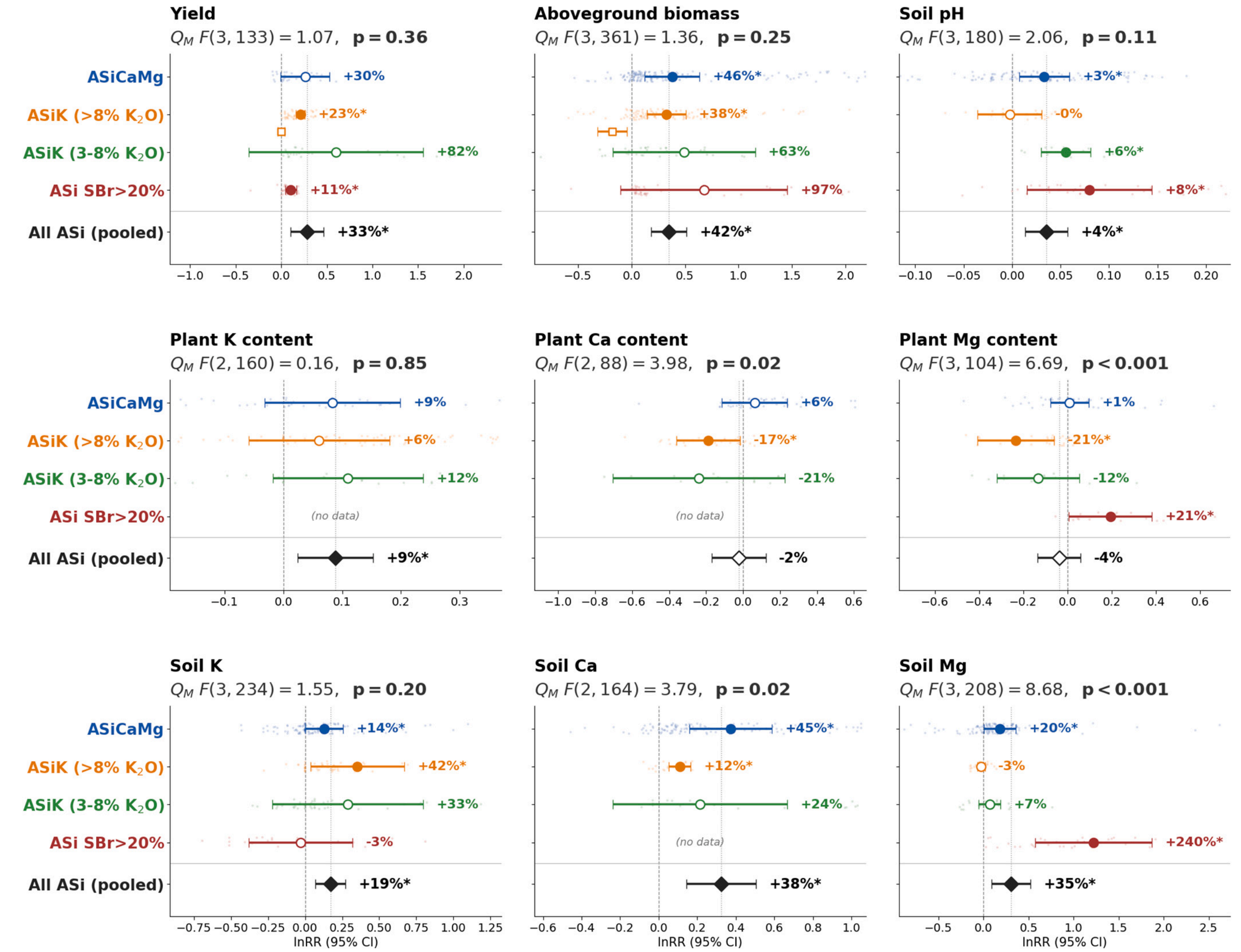

Fig. 3. ASi class contrasts across nine plant–soil outcomes. Each panel shows the pooled lnRR per ASi class and a mean diamond across qualifying classes (all against the negative control). A positive control (ASiK against KCl, squares) is shown for yield and aboveground biomass. The omnibus QM F-test in each panel header tests whether the class explains residual variance. The values in F(df1, df2) relate to df1 = number of classes in the model minus one (classes with <2 studies are excluded), df2 = total observations. Larger F values indicate stronger separation between class means relative to within-class noise (F≈1 means no signal, F>4 indicates clear separation). If $p < 0.05$: statistically significant difference between classes. Closed markers: statistically significant difference ($p<0.05$) between the class effect and the control.

(2026). The full upstream pipeline notebook that computes *ln*RR and the Nakagawa Model-A pooled-CV variance, and the figure-production notebooks are deposited at Zenodo (https://doi.org/10.5281/zenodo.21028485) under a CC-BY-4.0 licence.

3. Results

We organise the results around the four research questions: the overall effects of Brazilian ASi on plant and soil metrics and how they translate from greenhouse to field (section 3.1, Fig. 2), whether the Martins et al. (2026) classification predicts agronomic outcomes (section 3.2, Fig. 3), which contextual moderators explain the residual variance in yield and biomass (section 3.3 with Fig. 4, section 3.4 with Fig. 5); and whether observed field responses are economically viable under current Brazilian commodity prices (section 3.5, Fig. 6).

3.1. Overall effects on soil and plant endpoints

Across the 54 Brazilian studies, ASi increased yield (+20.7%) and aboveground biomass (+22%) significantly under field conditions. Under greenhouse conditions crop responses systematically increased for yield (+59.8%, n.s.) and aboveground biomass (+47.2%, $p < 0.0.01$). Plant nutrient responses showed the strongest increase for plant K (+ 15.6% and + 14.2%, field and greenhouse ($p < 0.0.01$) respectively) and Si (11.5% and 27.2% ($p < 0.01$), field and greenhouse, respectively). Other plant nutrients (N, P, Ca, and Mg) showed pooled decreases across all conditions.

Soil chemistry responded strongly under greenhouse conditions: bioavailable P (+80.4%), base saturation (+56.9%), and exchangeable Ca (+50.6%), Mg (+41.3%), and K (+24.4%) all increased significantly, soil pH increased by 4.7% ($p < 0.01$), and exchangeable acidity (H + Al) and exchangeable Al decreased significantly (−12.1% and − 50.3%, respectively). Three soil endpoints met the field-pool threshold of ≥4 contributing studies (Ca, Mg, and K), and each was directionally positive but did not reach significance at field scale.

The greenhouse-to-field attenuation is systematic across endpoints: plant K is essentially 1:1 from pot to field, aboveground biomass attenuates roughly two-fold, and yield attenuates roughly three-fold.

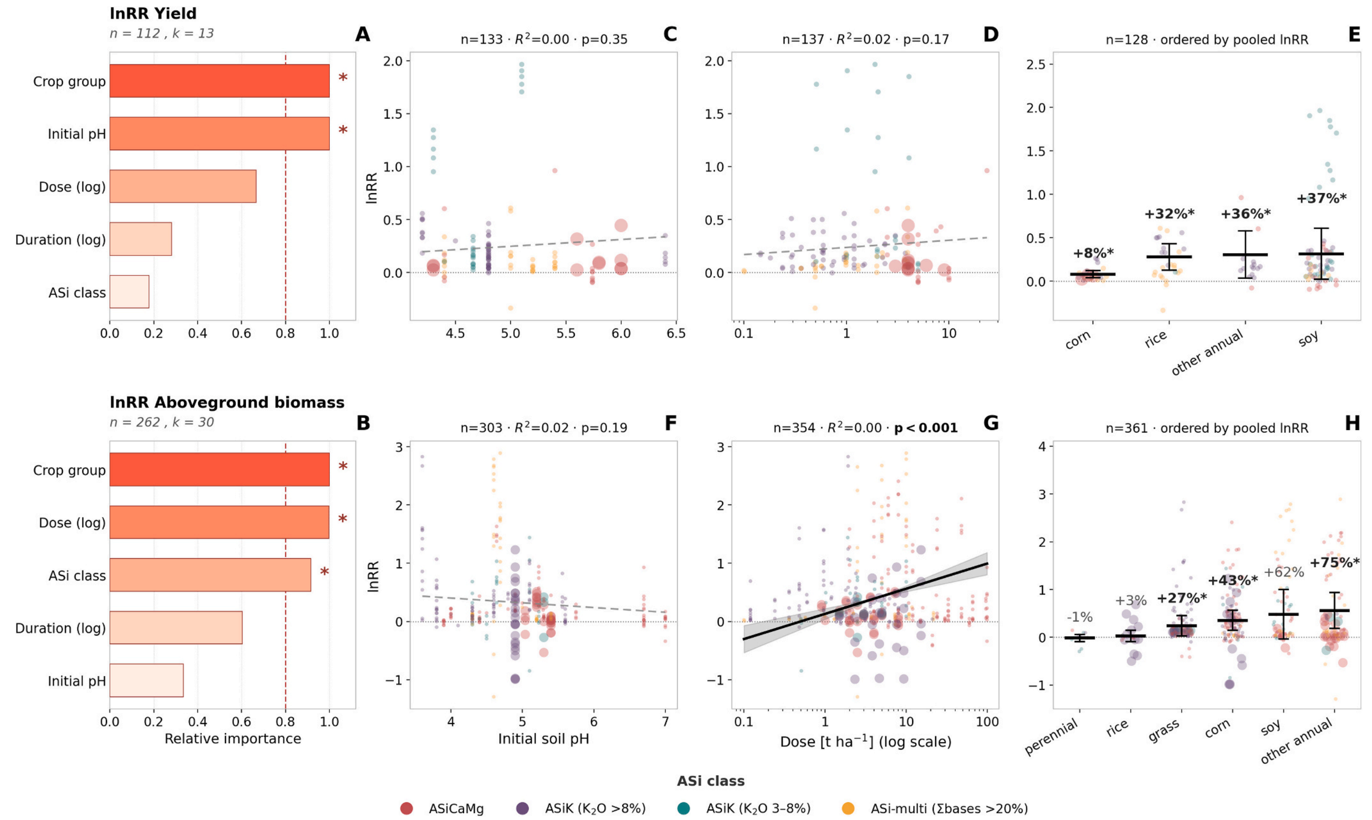

Fig. 4. Determinants of silicate agromineral (ASi) effects on yield and aboveground biomass. (A,B) Relative importance of moderators based on the sum of Akaike-weights from model selection using corrected Akaikes Information Criterion (AICc). Moderators with weights >0.8 are considered influential (*). (C,D,F,G) Univariate meta-regression of lnRR vs initial pH and applied doese, point size = observation weight (inverse of variance), shaded band = 95% CI, trend lines are solid when p<0.05. (E,H) Per-crop pooled lnRR (black bars) with 95% CI whiskers, crops are ordered by ascending lnRR. Labels above whiskers show % change relative to control. * indicates that the 95% CI excludes the zero intercept. R^2 represents marginal R^2, the proportion of variance explained by the moderator alone, excluding random-effect variance from between-study heterogeneity.

Table 2
Minimum reporting requirements for silicate-agromineral experiments.

Category	Details
Rock characterization	Chemical composition, mineralogy, and granulometry (particle size distribution)
Application details	Application amount (t ha^{-1}), application method (surface, mixed, specialized), incubation (application time between rock powder application and seeding)
Plant information	Botanical name; yield or biomass (reported as hectare equivalent); plant nutrient content
Soil characteristics	Soil texture; pH; organic matter; CEC, bioavailable macro- and micronutrient levels (preferably up to 60 cm depth, especially for perennial crops)
Experimental design	Detailed treatment description; site description (location, climate, cropping history)
Control treatments	Inclusion of both positive control (conventional fertilisation) and negative control (no fertilisation) where applicable
Statistical analysis	Clear description and tabulated comparison of treatments with appropriate statistical methods

3.2. *ASi class contrasts and the Martins classification*

The four-level analytical grouping of the Martins et al. (2026) classification discriminates significantly among classes for plant Mg, soil Mg, plant Ca, and soil Ca, but not for yield, aboveground biomass, soil pH, soil K, or plant K (Fig. 3). Each panel of Fig. 3 also reports a pooled all-ASi grand mean across qualifying classes (black diamond), which provides a common reference for the class estimates (grain yield +33%, aboveground biomass +42%).

The all-ASi mean pooled responses were positive and significant for yield, aboveground biomass, soil pH, plant K, soil K, soil Ca, and soil Mg. Plant Ca and plant Mg pooled near zero which is the consequence of opposing class-level signs (negative under both ASiK classes, positive under ASiCaMg and ASi SB_r > 20%) cancelling at the mean level.

The Mg and Ca panels show the strongest class differentiation. ASi SB_r > 20% delivers large positive plant-Mg and soil-Mg responses and separates from every other class on both endpoints. ASiCaMg delivers significantly positive soil Ca and a near-zero plant Ca, separating from the two ASiK classes on soil Ca. Both ASiK classes suppress plant Mg and plant Ca even though their soil Ca and Mg pools remain neutral or positive. The ASi SB_r > 20% soil-Mg effect is the largest class-differentiating soil-chemistry signal in the synthesis and provides the first empirical validation of the 20%-SB_r cut-off proposed by Martins et al. (2026).

In the panels where the omnibus (Q_M) test is non-significant (p > 0.05), several classes nevertheless deliver large within-class effects: ASiK >8% K_2O delivers significant yield, biomass, and soil-K gains; ASiCaMg delivers significant biomass and soil-K gains; ASi SB_r > 20% delivers a small but significant yield gain and a significant soil-pH lift. The targeted ASiK-vs-KCl positive-control comparison (square markers, Fig. 3) shows that ASiK is yield-equivalent to KCl on a single-season basis but inferior for aboveground biomass. ASi class is structurally associated with the baseline paradigm of the underlying primary studies (ASiK trials predominantly adopt KCl-substitution designs on amended NPK baselines; ASiCaMg and ASi SB_r > 20% trials predominantly use unamended controls). Insufficient data existed to conduct an appropriate class × baseline-type interaction.

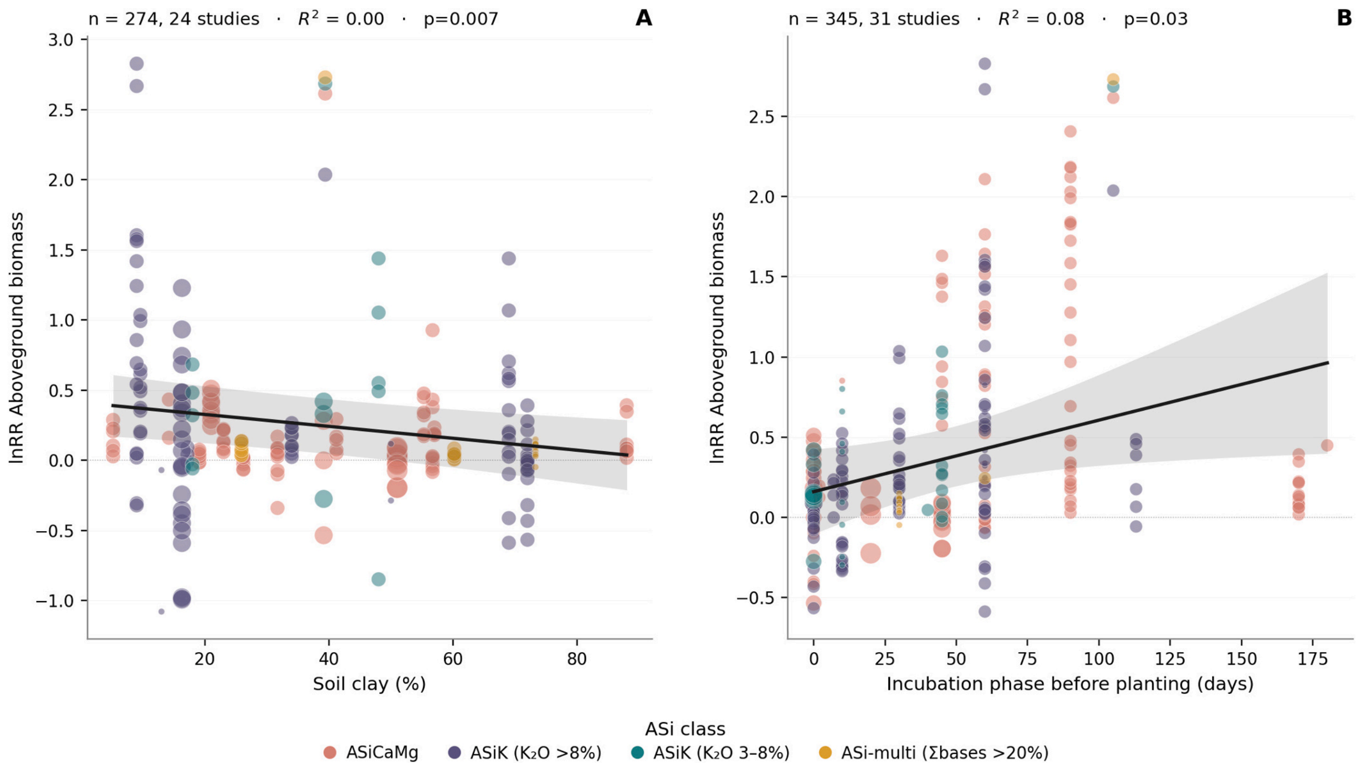

Fig. 5. Bivariate meta-regressions of aboveground-biomass lnRR against (A) soil clay content and (B) the duration of the pre-planting incubation phase. Marker size scales with the inverse of the sampling variance. Solid lines indicate a statistically significant slope ($p < 0.05$); shaded bands are 95% CIs, n = number of observations.

3.3. Drivers of the yield and biomass response

The Akaike-weight importance ranking identifies how well the moderators improve the ability of the underlying model to explain variation in the data (Fig. 4). Crop group and initial soil pH are the most important moderators of the field yield response, both reaching importance ≈ 1.0 (above the 0.80 threshold), followed by dose at intermediate importance and duration and ASi class below threshold. The univariate trends for initial soil pH and dose suggest a positive but insignificant relationship. For grain yield, corn pools at a small but significant gain (+8%), while there was a four to five times larger response in rice (+32%), other annuals (+36%, e.g. sorghum, millet, and wheat), and soybean (+37%).

For aboveground biomass, dose, crop group, and ASi class reach an importance of ≈ 1.0, while duration and initial pH fall below threshold (Fig. 3). The univariate regression shows a negative insignificant relationship between initial soil pH and aboveground biomass, and a positive statistically significant one between dose and aboveground biomass, although both trend lines are basically flat and do not bear much explanatory power ($R^2 = 0.00$ and 0.02, respectively). For aboveground biomass, perennial and rice showed almost no increase, grasses showed moderate gains, and corn, soybean (not significant), and other annual crops deliver the largest responses.

The low R^2 values do not contradict the high importance scores or significant *p*-values. Moderators with high importance consistently improve the multi-moderator model's fit, and significant p-values confirm reliable slopes, the low marginal R^2 in the univariate regressions indicates only that no single moderator alone captures much of the response variation. Together these results confirm the inherent complexity of ASi experiments and the multi-factorial nature of plant response to silicate-rock amendments.

3.4. Clay and pre-planting incubation

Soil clay content and pre-planting incubation phase are unevenly reported in the primary literature and were therefore analyzed outside the main moderator model, as single-moderator meta-regressions on aboveground biomass (Fig. 4).

Aboveground biomass declines weakly with increasing clay content (Fig. 4A): the slope is statistically detectable but the explained variance is essentially zero ($R^2 \approx 0.00$, $p \approx 0.007$). The directional signal is consistent with the larger native cation reservoir and higher buffering capacity of heavy-textured Oxisols, but the very low R^2 indicates that clay is not, by itself, a useful predictor of the proportional ASi response. The within-clay scatter is wide at every clay level, and the slope is significant only because the analysis pools several hundred observations. We therefore treat clay as a directional contextual moderator rather than as a quantitatively predictive variable.

Aboveground biomass increases with the duration of the pre-planting incubation phase (Fig. 4B). The relationship is positive, statistically significant ($p \approx 0.03$), and explains a modest fraction of variance ($R^2 \approx 0.08$). The slope is positive across all four ASi classes and is consistent with the slow-weathering kinetics of silicate minerals: trials with longer pre-planting incubation capture a larger fraction of the cumulative weathering-derived nutrient release than trials that plant immediately on application. Although the variance explained is modest, the directional signal is robust across classes and provides empirical support for incorporating an incubation phase into trial design.

We caution that both panels of Fig. 5 show wide scatter relative to the fitted lines. Read in isolation, the regression lines are easy to overinterpret. The interpretive weight in this synthesis lies with the directional consistency of these moderators across crops and classes—documented elsewhere in the literature—rather than with the precision of the bivariate fits.

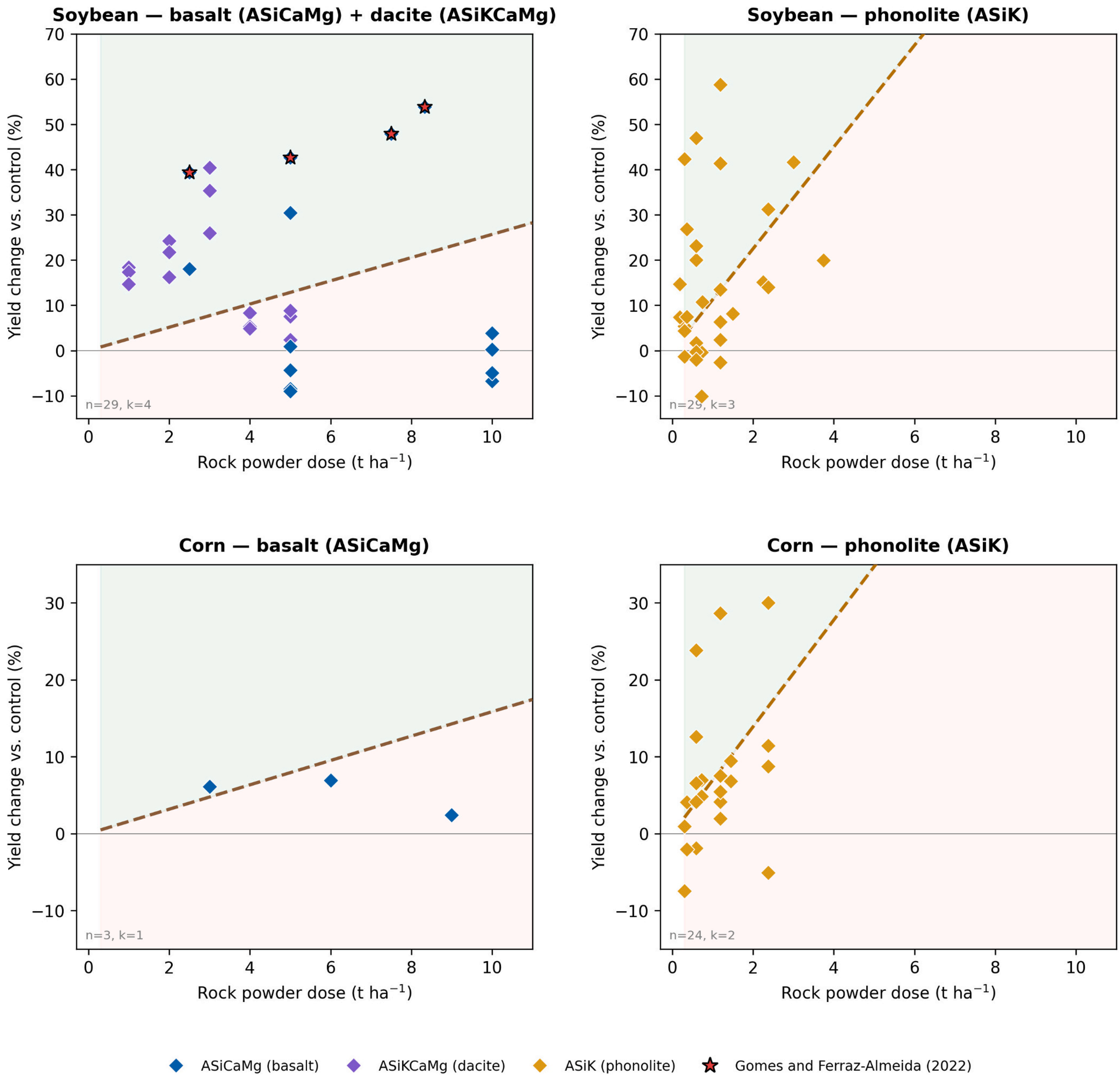

Fig. 6. Field-trial yield change versus rock-powder dose for four rock and crop combinations, with breakeven lines. Green shading: yield gain exceeds rock cost, transport, and application at the prevailing commodity price. Red shading: yield gain insufficient to recover the costs. In grey: n = observation number, k = study number. Economic cost framework adapted from Gomes and Ferraz-Almeida (2022).

3.5. Economic viability under current Brazilian commodity prices

The per-hectare single-season breakeven curves for four rock and crop combinations (Fig. 5) show that the agronomic and economic optimum coincide closely. Based on a single-season analysis, soybean and basalt (or dacite) mostly achieve breakeven at 1-5 t ha^{-1}. Soybean and phonolite and corn and phonolite both clear breakeven for a majority of observations at the 0.5–1.5 t ha^{-1} doses tested. Corn and basalt has only three field observations from a single study and should therefore be treated with caution. The 2–5 t ha^{-1} basalt range contains the highest density of above-breakeven observations.

4. Discussion

4.1. Crop response and soil–plant nutrient interactions

Our synthesis of Brazilian field experiments shows that ASi deliver significant gains for yield and aboveground biomass (Fig. 2). These gains correlated in most experiments with increases in soil Ca, Mg, K, and P. Despite these significant soil nutrient increases, the pooled plant concentrations of several major nutrients like N, P, Ca and Mg decreased (Fig. 2). 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, ionic uptake competition, or the resolution of another growth-limiting factor like improved water uptake, disease resistance, or root growth (Fageria, 2016).

Plant K increases are reported across various ASi classes, not only the ASiK class (Fig. 3). An interesting nuance is reported by Silveira et al. (2025), showing similar biomass gains for phonolite and KCl, although the rice shoot biomass K concentration was significantly lower for the phonolite treatment. One explanation could be that rice is engaging in 'luxury consumption', absorbing more K than it needs for growth, while phonolite releases just enough K to sustain equivalent biomass. This decoupling between growth response and nutrient concentration suggests that agronomic equivalence can be achieved under varying nutrient uptake dynamics. Similarly, de Almeida et al. (2022) report that olivine melilitite delivered yield and plant-K gains while Mehlich-1 soil K was non-significantly or negatively altered, with the lowest soil-K values recorded in the highest-yielding limestone/NPK treatment, indicating efficient nutrient uptake rather than supply failure. Several trials have shown that reducing or substituting conventional fertilisers through ASi can maintain yield while being agronomically favourable (Burbano et al., 2022; Dalmora et al., 2020; Rodrigues et al. 2024c; Seidel et al., 2021; Silveira et al., 2025).

These insights are important, since practitioners have often debated whether conventional fertilisers, carbonate rocks (limestone), or silicate rock powders are more suitable in agricultural settings (Martins et al., 2026). 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 optimise plant growth while sustaining soil health in the most sustainable manner. Achieving this requires identifying the most economical and environmentally appropriate combinations of ASi, conventional inputs and management practices. Sections 4.2 and 4.3 provide a discussion that helps to determine the most effective application strategies.

4.2. Utility and limits of the Martins classification

The classification reliably predicted Ca and Mg responses. All four panels (plant Mg, soil Mg, plant Ca, and soil Ca) discriminate significantly among classes, and the ASi $SB_r > 20\%$ soil-Mg effect separates from every other class by more than an order of magnitude, which is also related to the high Mg content in the tested rocks. This is the first empirical validation for the ASi 20%-SB_r classes (original classes ASiCa, ASiMg, ASiCaMgK and ASiMgCaK). The K-rich rock powder classes ASiK >8% K_2O (ASiK) and ASi 3–8% K_2O (ASiKMgCa and ASiKCaMg) had no pH effects whilst having the largest soil K increases, which agrees with the low predicted neutralizing power and the suggested use as a K-fertiliser. For yield, aboveground biomass, soil pH, and soil K, the four ASi classes do not differ from each other overall, even though several individual classes show significant effects on these outcomes. This indicates that class identity matters less than site-specific factors (clay content, dose, crop, baseline amendment, and trial duration) for predicting plant response. The classification therefore works well as a practical guide for predicting Ca, Mg, and pH responses, but yield and biomass require additional context to inform site-specific recommendations.

4.3. When and how ASi work best

Several conditions emerge under which Brazilian ASi are likely to deliver their most reliable agronomic gains: (i) Moderate-to-sandy soil texture: the clay-meta-regression slope is negative and directionally consistent across crops and classes, although the very low R^2 for the aboveground biomass regression (Fig. 5a) cautions against treating clay as a quantitatively predictive variable. (ii) Typical Brazilian soil pH: ASi deliver biomass gains across the typical soil pH range (pH 4.5–6.5) of Brazilian trials, with no statistically significant differences ($p = 0.19$) or strong variation ($R^2 = 0.02$) shown for initial soil pH and aboveground biomass correlations (Fig. 4) (iii) Moderate doses in the 2–5 t ha^{-1} range for ASiCaMg materials like basalt and dacite, and doses of 0.5–2.5 t ha^{-1} for ASiK rocks like phonolite. (iv) Pre-planting incubation correlated ($p < 0.03$, Fig. 5) positive with aboveground biomass suggesting that, where logistically feasible, ASi should be applied weeks to months before sowing rather than at planting. (v) ASi chemistry matching the soil-plant demand: ASiK should rather be employed as a K-source than a pH corrective, whereas ASi SBr > 20% can be primarily considered a pH corrective and limestone equivalent with additional Si-gains. ASiCaMg rocks such as basalts provide a balanced portion of both pH correction and macro- and micronutrient supply. (vi) Rock particle size could not be tested via the main meta-analysis pathway, although direct comparisons indicate increased effects with smaller particle sizes de Almeida et al. (2022), confirmed by earlier works from Gillman et al. (2001, 2002). (vii) Longer trial duration and multiple crop seasons increase the agronomic efficiency of ASi (Arrieta et al., 2020; Nogueira et al., 2021; Soratto et al., 2022; Tarumoto, 2019). This thus also implies that the economic calibration in section 3.5 is a lower bound rather than a best estimate of the ASi value proposition.

Opposed to this, limited responses can be expected for short experiments with coarse-grained rock powders applied to nutrient-rich, clayey soils with pH values over 6.5.

4.4. Phosphorus mobilisation

The single largest greenhouse response in the synthesis is the substantial increase in bioavailable P. Importantly, most ASi used contain little or no P. The signal is robust across Mehlich-1, Mehlich-3, and resin extractants and across all four ASi classes. de Aquino et al. (2020) and Luchese et al. (2021) further report ASi out-performing limestone on Mehlich-P at matched pH endpoints, ruling out pH alone as the only explanation for the effect. Four non-exclusive mechanisms are suggested (Schaller et al., 2024): Si-mediated displacement of P from Fe/Al-oxide sorption sites; reductive dissolution of P-bearing Fe oxides under altered hydraulic and redox regimes; microbial modulation of P acquisition (Bi et al., 2024); and the component of the pH response that reduces P fixation at the tropical end of the pH range. The Brazilian field literature does not yet allow these pathways to be disentangled at the synthesis level. Regardless of the mechanism, P mobilisation is one of the largest and most replicable co-benefits of ASi on highly weathered tropical soils.

This finding is highly relevant, as P is a major limiting nutrient in agriculture, and a limited resource as mineable deposits decline rapidly (Schaller et al., 2024). This is particularly relevant for the tropics, as P is easily immobilised in many highly weathered soils, rendering its supply ever more challenging. Refining our understanding of Si-optimised P fertilisation in the tropics thus bears considerable agronomic, economic, and environmental potential.

4.5. Limitations

Although the study pool comprised 54 articles and 2948 effect-size observations, the scope of meta-analytical depth was hindered by various factors. Reporting heterogeneity remains high, with various factors like particle size, clay content, incubation time, and rock characteristics often not being reported at all. Many studies measure total nutrient uptake rather than concentration, which renders meta-analytical approaches difficult, as concrete biomass data is necessary to back-calculate nutrient concentrations. Few studies provide comprehensive statistical information (mean, SD, replicates). Various important metrics like soil carbon pools (SOC, POC, MAOC) and soil biological indicators, or Si-mediated effects are rarely measured but bear great potential (Schaller et al., 2024; Xu et al., 2025). Several ASi classes remain represented by only one or two contributing studies and are excluded from moderator analysis. Field trials account for a minority of the experiments, and only seven of twenty outcomes meet the field-pooling threshold. Trial durations are short, with the median greenhouse duration well below one crop cycle, and the longest field trial is under two years, yet our incubation regression and the multi-season ASiK literature both indicate that response magnitudes and efficiencies scale with time.

Beyond the reported agronomic benefits, data on several potential co-benefits are rarely reported, which could however substantially strengthen the case for ASi in tropical systems. Mineral-driven SOC: Xu et al. (2025) report a global ERW-induced SOC increase of approximately 4% across 74 publications, with mineral-associated organic carbon rising by approximately 6%, dominated by Ca-mediated organo-mineral complex formation and microbial-biomass stimulation, and with the strongest positive responses in low-latitude warm-humid regions including Brazil. Furthermore, we did not find a single Brazilian enhanced rock weathering (ERW) study that analyzed inorganic CO_2 sequestration on the field scale (Clarkson et al., 2024). Crushed-rock weathering also delivers Si-mediated improvements in plant resistance to drought, heat, salinity, and pathogens (Meena et al., 2014; Schaller et al., 2024). Brazilian trials confirm the outlined Si-benefits: Da Da Cruz et al. (2024) reports reduced soybean parasite reproduction, whereas Pulz et al., 2008 found reduced potato lodging under water stress. As outlined above, trials spanning several growing seasons are scarce, but typically favour the agronomic efficiency of ASi (Arrieta et al., 2020; Nogueira et al., 2021; Soratto et al., 2022).

4.6. Minimum reporting requirements for future experiments

To reduce the limitations outlined in the previous section, we propose methodological harmonizations and qualitative improvements for future agromineral studies. A suggested overall approach for conducting ASi experiments is the consideration of the most important factor framework proposed by Swoboda et al. (2022, p.4) for a general orientation, in combination with a comprehensive reporting of the factors outlined in Table 2.

5. Conclusion

Our meta-analysis demonstrates positive and quantitatively meaningful effects of silicate agrominerals (ASi) on soil fertility and crop performance in Brazil. Pooled results show significant increases in yield and aboveground biomass with a systematic greenhouse-to-field attenuation. Besides significant pH ameliorations and base cation supply, bioavailable P substantially increased despite the typically low inherent P content of the materials, which bears substantial agronomic potential as P is a major limiting nutrient in the tropics. The novel ASi classification was empirically validated and its nutrient supply and pH effects agreed directionally with the predictions for each class. ASi performed best on moderately to sandy-textured soils at typical Brazilian pH levels (4.5–6.5), with a pre-planting incubation phase, and with the rock chemistry matching the soil-plant demand. Economic analysis indicates possible breakeven for a single-season basalt application of 2–5 t ha^{-1} for soybean and sugarcane and at 0.5–1.5 t ha^{-1} of phonolite for soybean and corn. Future methodological approaches are proposed to strengthen ASi's significant environmental and economic potential under real-world agronomic settings. We suggest overcoming ongoing debates of ASi versus conventional fertilisers 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.

CRediT authorship contribution statement

Philipp Swoboda: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Eder de Souza Martins:** Writing – review & editing, Resources, Methodology, Conceptualization. **Gisele Freitas Vilela:** Writing – review & editing, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Giuliano Marchi:** Writing – review & editing, Validation, Investigation, Data curation. **Luis Ferreira:** Writing – review & editing, Validation, Investigation, Formal analysis. **Carlos Augusto Posser Silveira:** Writing – review & editing, Validation, Investigation, Formal analysis, Conceptualization. **Mariane Chiapini:** Writing – review & editing, Investigation, Formal analysis. **Marcella Daubermann:** Writing – review & editing, Validation, Resources, Methodology, Formal analysis. **Mayra Maniero Rodrigues:** Writing – review & editing, Methodology, Formal analysis, Data curation, Conceptualization. **Matthew O. Clarkson:** Writing – review & editing, Supervision, Methodology. **Junyao Kang:** Writing – review & editing, Validation, Methodology. **Veronica Furey:** Writing – review & editing, Software, Methodology, Data curation. **David A.C. Manning:** Writing – review & editing, Validation, Supervision, Conceptualization. **Christina Larkin:** Writing – review & editing, Writing – original draft, Validation, Supervision.

Declaration of competing interest

Some of the authors work in a Brazilian company that deploys silicate rock powders to restore tropical soil health.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geodrs.2026.e01103.

Data availability

Data will be made available on request.

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