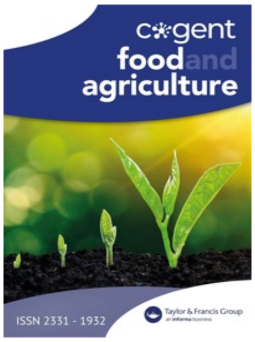

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Potential of granitoid rock powder to enhance soil fertility and crop nutrition

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ABSTRACT

The use of granitoid rock as a soil remineralizer has gained attention for its potential to enhance soil fertility and improve crop nutrition in agriculture. This study evaluates the impact of granitoid rock on the chemical properties of Typic Quartzipsamment soil and the growth and nutrient uptake of maize (*Zea mays*) and common bean (*Phaseolus vulgaris*) plants. Granitoid powder from four different origins was applied at rates of 0, 10, 20, 30, and 40 t ha^{-1} in a controlled greenhouse experiment, which lasted 65 days after plant emergence (until flowering stage). Results showed a linear increase in soil concentrations of phosphorus, potassium, calcium, and magnesium with increasing granitoid rock powder rates, leading to higher base saturation levels. In maize and bean plants, granitoid rock powder application significantly increased shoot dry mass (g plant^{-1}), plant height (cm), and stem diameter (mm). Nutrient uptake, calculated as the total content of macro- and micronutrients in the shoot (mg plant^{-1}), also increased, particularly at the highest rate (40 t ha^{-1}). These results demonstrate the effect of granitoid rock powder on a sandy, quartz-rich, nutrient-poor soil, which likely enhanced the positive plant responses. The findings indicate that granitoid rock powder can be an effective and sustainable nutrient source, gradually releasing nutrients and contributing to agricultural productivity and environmental conservation. However, further studies in different soil types and under field conditions are necessary to confirm its agronomic potential on a broader scale.

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1. Introduction

An urgent agricultural dilemma is the need to boost or uphold yields while preventing further harm to Earth's environmental systems, particularly its soils (Swoboda et al., 2022). Global soil degradation, primarily driven by agriculture, continues at an alarming pace, rendering approximately 10 million hectares of cropland unproductive each year (Prăvălie, 2021). Meanwhile, the availability of additional arable land is limited, and the trajectory of crop yields is either declining or stagnating in many regions, exacerbated by the looming impacts of climate change (Manning, 2015). This situation necessitates profound advancements in sustaining soil health and crop production to mitigate the considerable pressure on existing farmlands caused by agricultural intensification (Conceição et al., 2022).

The quest for more sustainable agricultural practices has become a central challenge in modern agriculture. The excessive use of chemical fertilizers has led to environmental and public health concerns, adversely affecting soil quality (Oliveira et al., 2023). The use of silicate rock powder, commonly referred to as a soil remineralizer, has gained attention as a sustainable alternative nutrient source. It is important to contextualize the term "rock powder," as it broadly encompasses any finely ground rock material,

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which may vary significantly in composition and potential as a fertilizer (Oliveira et al., 2025). These materials differ in their capacity to supply nutrients, improve soil properties, and influence crop productivity, depending on their mineralogical and chemical characteristics. Silicate rock powders, in particular, not only release essential nutrients for plant growth but also enhance soil quality, offering a dual benefit of increased agricultural productivity and reduced environmental impact (Burbano et al., 2022; Holsback et al., 2026; Medeiros et al., 2021; Plata et al., 2021). This variability underscores the importance of research focused on characterizing these materials to optimize their use and validate their effectiveness in specific agricultural contexts, further justifying the need for studies in this area. Moreover, the recent conflict escalation between Russia and Ukraine has resulted in a global shortage of chemical fertilizers, prompting increased interest in research on the use of silicate rock powder for soil fertility management. This renewed focus underscores the importance of exploring alternative approaches to agricultural sustainability amidst evolving geopolitical dynamics (Conceição et al., 2022; Daniell & van Tonder, 2023; Oliveira et al., 2025).

Silicate rock powders are gaining attention across various sectors, with studies looking into "enhanced weathering" to capture CO_2 through their weathering process (Beerling et al., 2020). Notably, in tropical regions like Brazil, significant progress has been made, especially with the "Rochagem" movement, which has promoted the use of rock powders in agriculture (Conceição et al., 2022; Nogueira et al., 2021). Organic farming, which relies on natural inputs, has also embraced rock powders, leading to a rise in demand for organic-friendly soil amendments (Abbott and Manning 2015). Moreover, rock powders are widely produced as mining by-products globally, offering an opportunity to repurpose them as agricultural inputs. These various aspects highlight both global pressures and potentials, emphasizing the need for a thorough evaluation of silicate rock powders and their role in addressing modern agricultural challenges (Daniell & van Tonder, 2023; Nogueira et al., 2021). Nevertheless, it is crucial to choose the appropriate silicate rock powder that suits soil conditions and meets the specific needs of the plants being cultivated, emphasizing the potential utilization of granitoid powder.

Granitoid is a coarse-grained intrusive igneous rock, classified according to the standards of the International Union of Geological Sciences (IUGS) as containing predominantly quartz (20–60%), alkali feldspar (35–90%), and minor amounts of plagioclase and mica (Le Maitre, 2002). Its mineral composition supplies essential elements such as potassium (K), calcium (Ca), and magnesium (Mg). Through natural weathering processes, granitoid gradually releases these elements into the soil, acting as a slow-release, natural source of plant nutrients (Silva et al., 2018).

Although several studies have reported variable effects of granitoid powder application on soil fertility and plant growth, the underlying causes for such variability are often linked to differences in mineralogical composition, weathering rates, particle size, and interactions with specific soil and climatic conditions (Bolland & Baker, 2000; Hinsinger et al., 1995; Silva et al., 2013; Swoboda et al., 2022). Given this complexity, more detailed investigations are required to clarify how granitoid powder from different geological origins behaves under tropical conditions. In this context, we hypothesize that the agronomic effectiveness of granitoid powder varies depending on its origin and application rate. Therefore, this study aims to evaluate the effect of granitoid powder from different sources and at increasing rates on the chemical attributes of a Typic Quartzipsamment soil and on the growth and nutrient accumulation of maize and common bean plants under greenhouse conditions.

2. Material and methods

2.1. Soil sampling and characterization

The greenhouse experiment was conducted at the Federal Institute of Mato Grosso do Sul (Nova Andradina, MS, Brazil). Soil classified as Typic Quartzipsamment (TQ) was collected from the 0–20 cm layer of an area under native vegetation, free from agricultural or urban contamination. This soil type is predominant in the Cerrado biome and is characterized by low fertility and sandy texture. Samples were air-dried, homogenized, and passed through a 4 mm sieve before use. Particle size analysis revealed 82.7% sand, 2.6% silt, and 14.7% clay. The baseline chemical composition indicated low natural fertility and high acidity, as summarized in Table 1.

Table 1. Chemical attributes of soil samples used in the experiment.

pH ($CaCl_2$)	SOM ($g\ kg^{-1}$)	P ($mg\ kg^{-1}$)	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H^++Al	CEC	m (%)	BS (%)
			cmolc kg^{-3}							
3.91	9.57	2.64	0.006	0.10	0.03	0.42	2.15	2.30	75	5.9

SOM = soil organic matter; CEC = cation-exchange capacity; m, aluminium saturation = [Al/(Al + K+Ca + Mg)]; BS, base saturation = [(K + Ca + Mg)/(CEC)].

2.2. Granitoid rock powder analysis

Granitoid rock powder samples were obtained from four quarrying sites operated by Polimix Concreto LTDA in Brazil, located in Bacabeira (MA), Duque de Caxias (RJ), Jaboatão dos Guararapes (PE), and Santana do Paranaíba (SP). Each powder was analyzed for its chemical and mineralogical composition to quantify the major oxides (Tables S1 and S2). Concentrations of potentially toxic elements complied with Brazilian environmental regulations (BRASIL, 2022). The residue showed an abrasion pH of 8.76 and mineralogical features typical of granitoid rocks. Granulometric analysis indicated that all material passed through a 2 mm mesh, with 90% below 0.84 mm and 82% below 0.30 mm.

2.3. Soil incubation procedure

A preliminary incubation assay was carried out to assess changes in soil chemistry following granitoid powder application. Each experimental unit consisted of a 5.5 L polyethylene pot containing 5 kg of soil. The experiment followed a completely randomized design in a 5 × 4 factorial arrangement, with five application rates (0, 10, 20, 30, and 40 t ha^{-1}) and four rock sources, totaling 40 units per material. The soil-rock mixtures were incubated at 25 °C for 60 days, maintaining moisture at approximately 70% of field capacity through weekly addition of deionized water. After incubation, soil samples were collected, air-dried, sieved (< 2 mm), and stored for subsequent chemical analyses.

2.4. Growth analysis of maize and common bean

Following incubation, maize (*Zea mays*, hybrid Feroz VIP) and common bean (*Phaseolus vulgaris*, cv. Pérola) were cultivated in the same pots. These genotypes were selected for their regional adaptability and stable growth under controlled conditions. A randomized block design was adopted, maintaining the same treatment structure as in the incubation phase (five rates × four rock types × four replicates).

Baseline fertilization was applied uniformly to all pots: 125 mg dm^{-3} N, 25 mg dm^{-3} P, and 75 mg dm^{-3} K, complemented by a micronutrient solution containing 0.5 mg kg^{-1} B, 2.0 mg kg^{-1} Cu, 3.0 mg kg^{-1} Mn, and 4.0 mg kg^{-1} Zn, as recommended for Cerrado soils (Sousa & Lobato, 2014). No lime or pH-corrective amendments were added. Plants were irrigated daily with deionized water to maintain moisture near 70% of the water-holding capacity.

At 65 days after emergence (flowering stage), plant height was measured using a ruler, and stem diameter was determined 10 cm above the soil surface with a digital caliper. Shoots were harvested, washed, oven-dried at 60 °C for 72 h, weighed, and ground in a Wiley-type mill (40-mesh) for chemical analysis.

2.5. Nutrient and soil chemical analyses

For the plant shoot samples of maize and beans, 0.5 g of dry weight was subjected to wet digestion with concentrated nitric acid (HNO_3, 65%) and perchloric acid ($HClO_4$, 70%), following the procedures described by Malavolta et al. (1997). Nitrogen concentration was determined by steam distillation in the sulfuric digestion extract (Kjeldahl method) according to Bremner (1996). All analyses were performed in triplicate to estimate analytical precision, using reagent blanks, certified reference materials, calibration with standard solutions, and recovery tests of elements added to the samples, ensuring the reliability of the results. Shoot concentrations of potassium (K), calcium (Ca), magnesium (Mg), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) were determined using atomic absorption spectrophotometry (AAS) as described in AOAC (2016). Phosphorus (P) concentration was determined by colorimetry (Murphy & Riley, 1962), and sulfur (S) concentration was determined by turbidimetry (Santos et al., 2017; Tabatabai, 1974). Although the potassium dichromate method is not widely used in many jurisdictions due to health concerns, it is still permitted and commonly employed in Brazil, provided that strict laboratory safety procedures are followed to prevent human exposure (Embrapa, 2017).

The soil samples were subjected to chemical analysis following the protocols outlined by Raij (2011). The pH was determined potentiometrically in air-dried thin soil (ADTS) suspensions using a 0.01 mol L^{-1} $CaCl_2$ solution at a 1:2.5 ratio. Organic matter content was determined by oxidizing the sample with $K_2Cr_2O_7$ in the presence of H_2SO_4, followed by titration of the excess dichromate with a 0.4 mol L^{-1} $Fe(NH_4)_2(SO_4)_2.6H_2O$ solution. Exchangeable aluminum (Al^{3+}), exchangeable calcium (Ca^{2+}), and exchangeable magnesium (Mg^{2+}) were extracted using a 1.0 M KCl solution and quantified using atomic absorption spectrophotometry (AAS). Exchangeable potassium (K^+) and phosphorus (P) were extracted using the Mehlich-1 method, with K^+ determined by flame photometry and P determined by colorimetry. The potential acidity (H + Al) was estimated using the pH SMP method. Subsequently, the sum of bases (SS), cation exchange capacity (CEC) at pH 7.0, and base saturation (BS%) were calculated based on the obtained results.

All soil chemical analyses were performed in triplicate. Quality control included reagent blanks, certified reference materials, and calibration with standard solutions. Recovery tests were conducted for selected elements by adding known amounts to the samples, with results within the acceptable range (90–110%), ensuring the accuracy and reliability of the measurements.

2.6. Statistical analysis

Data were analyzed by analysis of variance (ANOVA), and treatment effects were considered significant at $p < 0.05$. Normality and homogeneity of variance were verified by the Shapiro–Wilk and Hartley tests, respectively. When significant interactions occurred between granitoid source and application rate, regression models were fitted, and the best-fit equation was selected based on significance of regression coefficients and coefficient of determination (R^2). Statistical analyses were performed using SAS software, version 9.1 (SAS Institute Inc, 2004).

3. Results

3.1. Soil chemical properties after incubation

The results of soil incubation with different rates of granitoid powder demonstrated changes in the exchangeable chemical properties of Typic Quartzipsamment (TQ) soil after 60 days (Figure 1). Significant differences were observed both among the types of granitoid powder ($F3.12 = x$; $p < 0.05$) and among the applied rates ($F4.12 = x$; $p < 0.05$). Additionally, a significant interaction was observed between the types of granitoid powder and the applied rates ($F3.12 = x$; $p < 0.05$). Higher rates of granitoid powder (40 t ha^{-1}) resulted in average increases of up to fivefold for P, threefold for K, fourfold for Ca, and twofold for Mg compared to the zero rate.

The granitoid powders from Jaboatão dos Guararapes (JG-PE) and Santana do Paranaíba (SP-SP) showed the highest increases in P, with an average increase of 43% at the highest rate compared to the material from Bacabeira (B-MA) and 150% higher compared to Duque de Caxias (DC-RJ), which showed the smallest increments (Figure 1A). For K levels, the granitoid powders from JG-PE, SP-SP, and B-MA exhibited similar results, with an average increase in K concentration of 78% compared to DC-RJ (Figure 1B). Regarding Ca levels and base saturation (BS), the material from JG-PE stood out, with an average increase of 69% for Ca and 67% for BS compared to the other materials at the highest rate (Figure 1C and E). For Mg levels and base saturation, the powders from JG-PE and SP-SP also presented the highest increments across all evaluated rates (Figure 1D and F).

3.2. Effect of treatments on common beans

Bean plants responded positively to the application of granitoid powder, exhibiting a quadratic behavior for shoot dry mass and for the total concentrations of micronutrients (B, Cu, Fe, Mn, and Zn) in the

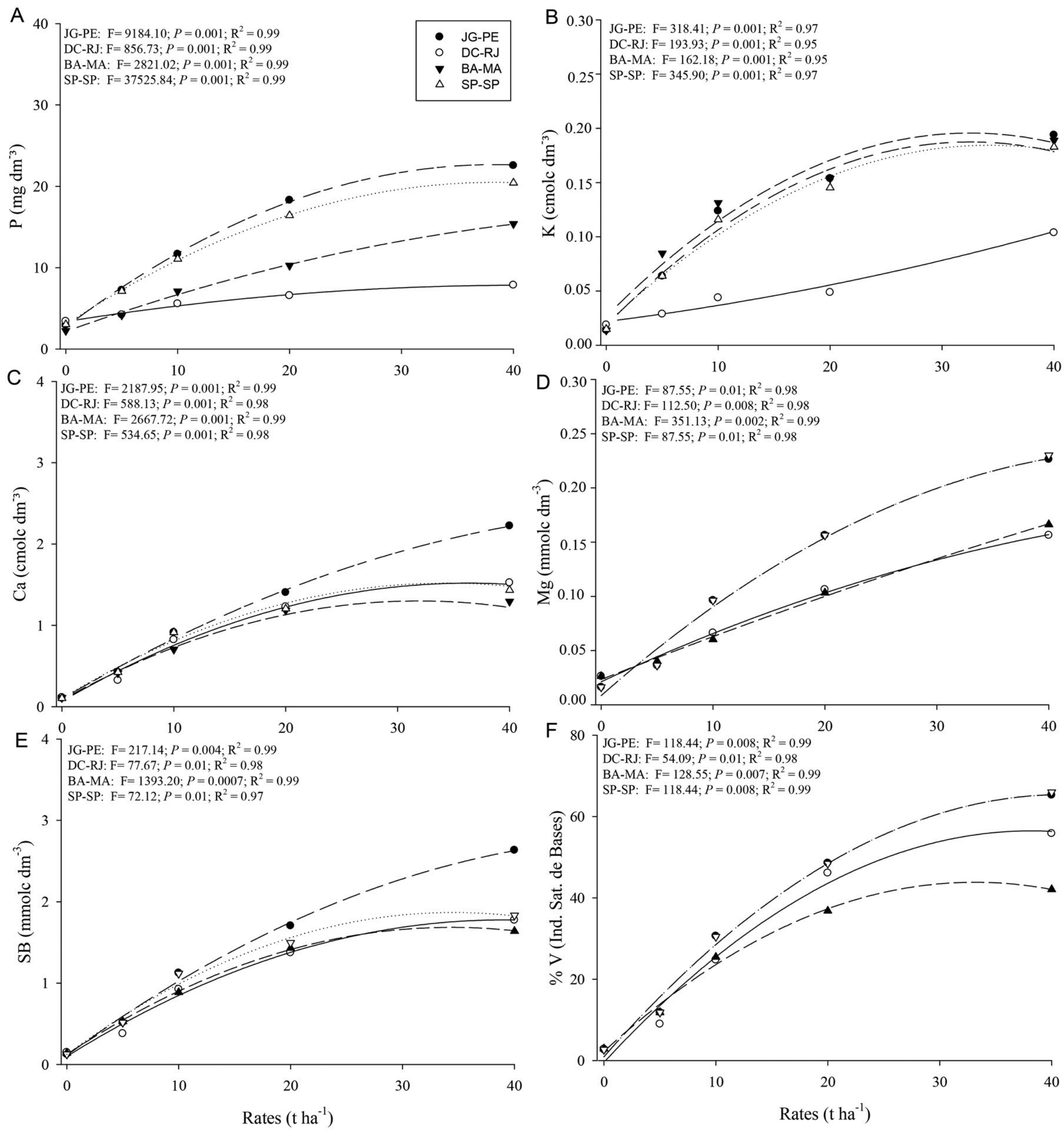

Figure 1. Phosphorus (P) content [A], potassium (K) content [B], calcium (Ca) content [C]; magnesium (Mg) content [D], sum of base (SB) [E]; and base saturation index (BS%) [F] obtained in Typic Quartzipsamment (TQ) and after 60 days of incubation with five rates of granitoid powder from four different origins (JG-PE = Jaboatão do Guararapes-PE; DC-RJ = Duque de Caxias-RJ = Bacabeira-MA; and SP-SP = Santana do Paranaíba-SP).

shoots as a function of increasing granitoid powder rates (Figure 2). The highest rate increased the shoot dry mass by more than seven times compared to the control plants, along with an average concentration of seven times more B, eleven times more Cu, and two times more Fe, Mn, and Zn.

Among the materials evaluated, SP-SP and JG-PE stood out by promoting a 50% increase in shoot dry mass compared to the other treatments at the highest rate (Figure 2A). These materials also resulted in higher concentrations of micronutrients in the leaves of bean plants at higher rates, resulting in increases of 33% for B, 26% for Cu, 42% for Fe, 31% for Mn, and 55% for Zn compared to the granitoid powders DC-RJ and B-MA.

The application of granitoid powder also increased macronutrient concentrations in bean plant leaves, showing a quadratic behavior as a function of increasing rates (Figure 3). The highest rate resulted in up to threefold increases for N and P, fourfold for K and S, and fivefold for Ca and Mg compared to control plants.

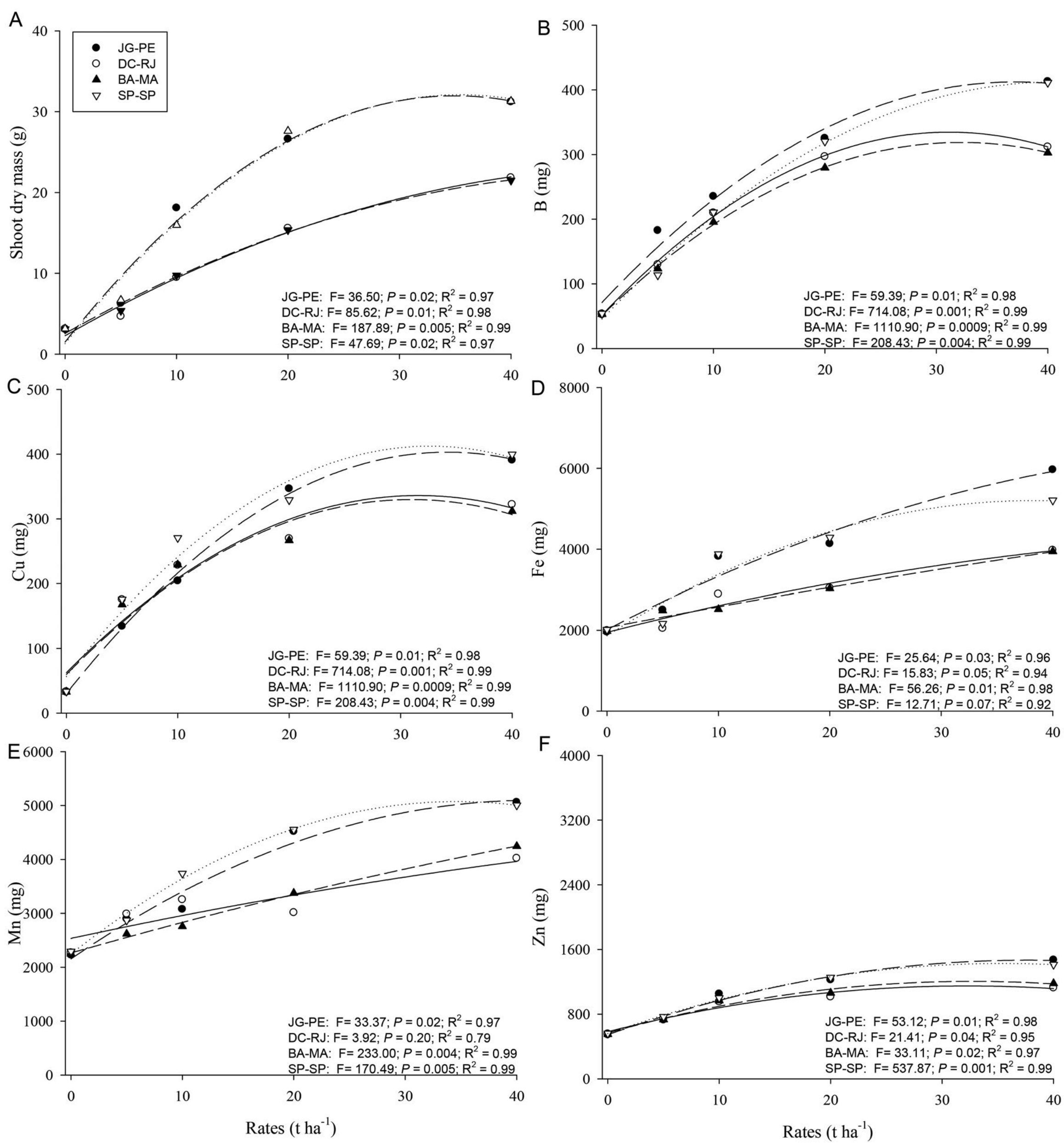

Figure 2. Accumulation of dry mass [A], boron concentration (B) [B], copper concentration (Cu) [C]; iron concentration (Fe) [D], manganese concentration (Mn) [E]; and zinc concentration (Zn) [F] of bean plants grown in Typic Quartzipsamment (TQ) for 45 days and subjected to five rates of granitoid powder from four different origins (JG-PE = Jaboatão do Guararapes-PE; DC-RJ = Duque de Caxias-RJ; BA-MA = Bacabeira-MA; and SP-SP = Santana do Paranaíba-SP).

The materials SP-SP and JG-PE also stood out for presenting higher concentrations of N, P, Ca, and Mg, with increases of 47%, 40%, 25%, and 60%, respectively, compared to the other treatments. For K, no significant differences were observed among the materials. Sulfur, however, was more influenced by the JG-PE material, which showed a 20% increase compared to SP-SP and 44% compared to the DC-RJ and B-MA materials.

3.3. Effect of treatments on maize plants

In maize plants, the application of the highest rate of granitoid powder resulted in an average increase of 220% in shoot dry mass compared to the zero rate (Figure 4A). Foliar total micronutrient concentrations (B, Cu, Fe, Mn, and Zn) also showed a quadratic behavior as a function of increasing rock powder rates (Figure 4).

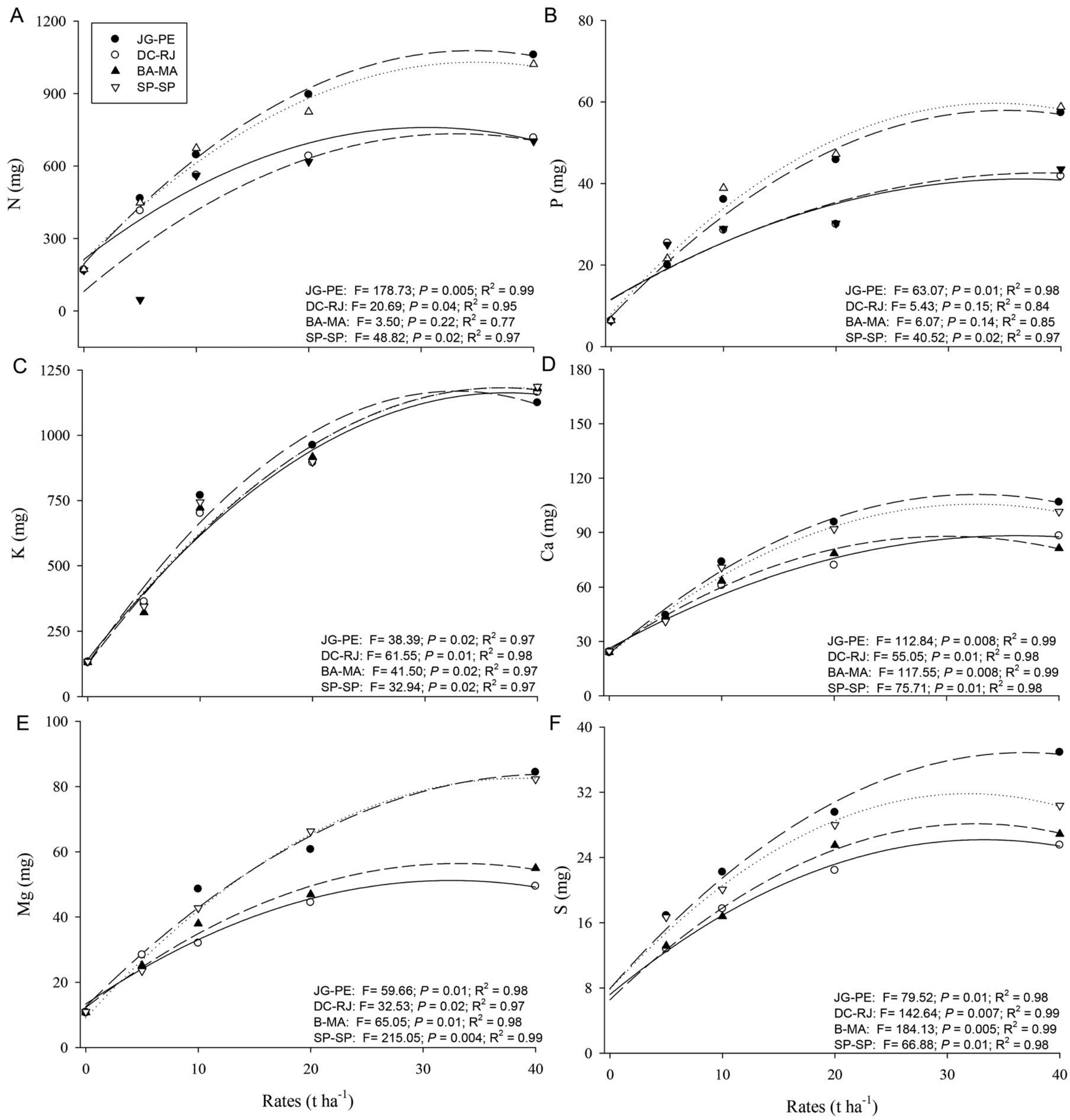

Figure 3. Nitrogen (N) concentration [A], phosphorus (P) concentration [B], potassium (K) concentration [C]; calcium (Ca) concentration [D], magnesium (Mg) concentration [E]; and sulfur (S) concentration [F] of bean plants grown in Typic Quartzipsamment (TQ) for 45 days and subjected to five rates of granitoid powder from four different origins (JG-PE = Jaboatão do Guararapes-PE; DC-RJ = Duque de Caxias-RJ; BA-MA = Bacabeira-MA; and SP-SP = Santana do Paranaíba-SP).

The SP-SP granitoid powder stood out for providing the highest concentrations of B, Cu, Fe, and Zn in the leaves of maize plants compared to the other treatments. For Mn concentration and shoot dry mass, treatments with SP-SP and JG-PE powders showed similar performances, with an average increase of 100% in Mn concentration and 59% in shoot dry mass compared to the other granitoid powders (Figure 4A and E).

Macronutrient concentrations in maize plants also increased with the application of granitoid powder, showing a quadratic behavior as a function of the applied rates (Figure 5). Granitoid powders from the SP-SP and JG-PE regions were the most efficient at higher rates, resulting in average increases of 19% for N, 36% for P, 114% for Ca, and 68% for Mg compared to powders from the DC-RJ and B-MA regions. For K concentration, as observed in bean plants, no significant differences were found among the treatments with different granitoid powders (Figure 5C). The SP-SP granitoid powder exhibited the highest S concentration in the leaves compared to the other treatments (Figure 5F).

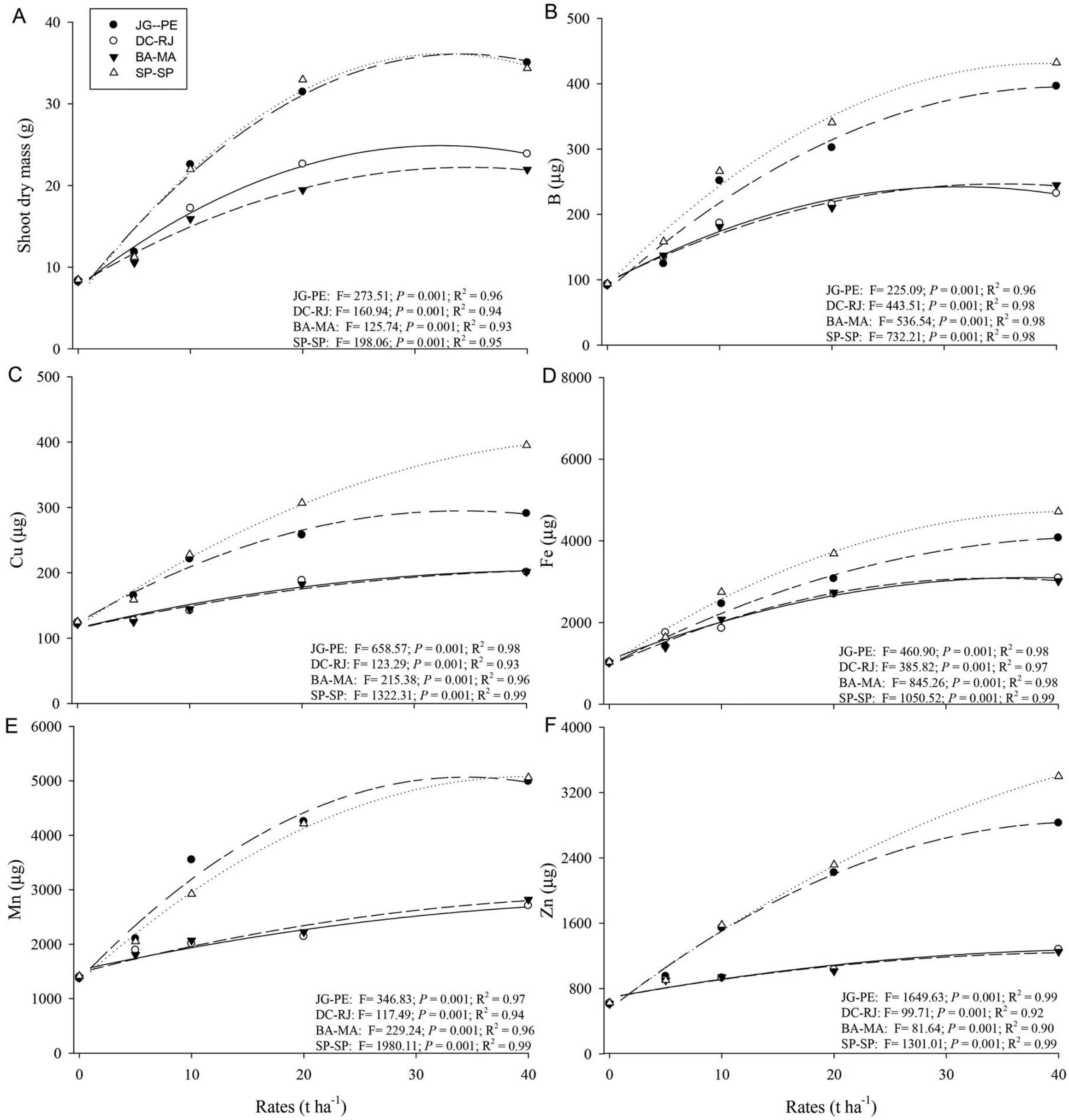

Figure 4. Accumulation of dry mass [A], boron concentration (B) [B], copper concentration (Cu) [C]; iron concentration (Fe) [D], manganese concentration (Mn) [E]; and zinc concentration (Zn) [F] of maize plants grown in Typic Quartzipsamment (TQ) for 45 days and subjected to five rates of granitoid powder from four different origins (JG-PE = Jaboatão do Guararapes-PE; DC-RJ = Duque de Caxias-RJ; BA-MA = Bacabeira-MA; and SP-SP = Santana do Paranaíba-SP).

4. Discussion

The results obtained from the application of granitoid powder in Typic Quartzipsamment soils demonstrate a significant improvement in soil chemical properties and an increase in crop productivity, such as maize and beans. These findings are consistent with recent studies that highlight the potential of rock residues, such as granitoid powder, to improve soil fertility and plant nutrition (Swoboda et al., 2022). The application of granitoid powder as a soil remineralizer and its effects on soil fertility and plant growth provides valuable insights into sustainable agricultural practices. The results of this study demonstrate that granitoid powder has significant potential in enhancing soil properties, improving nutrient availability, and promoting the growth of crops such as maize and common beans.

Soil acidity is a common problem in tropical and subtropical regions, where acidic soils can hinder nutrient availability and lead to aluminum toxicity, which negatively affects root development and plant

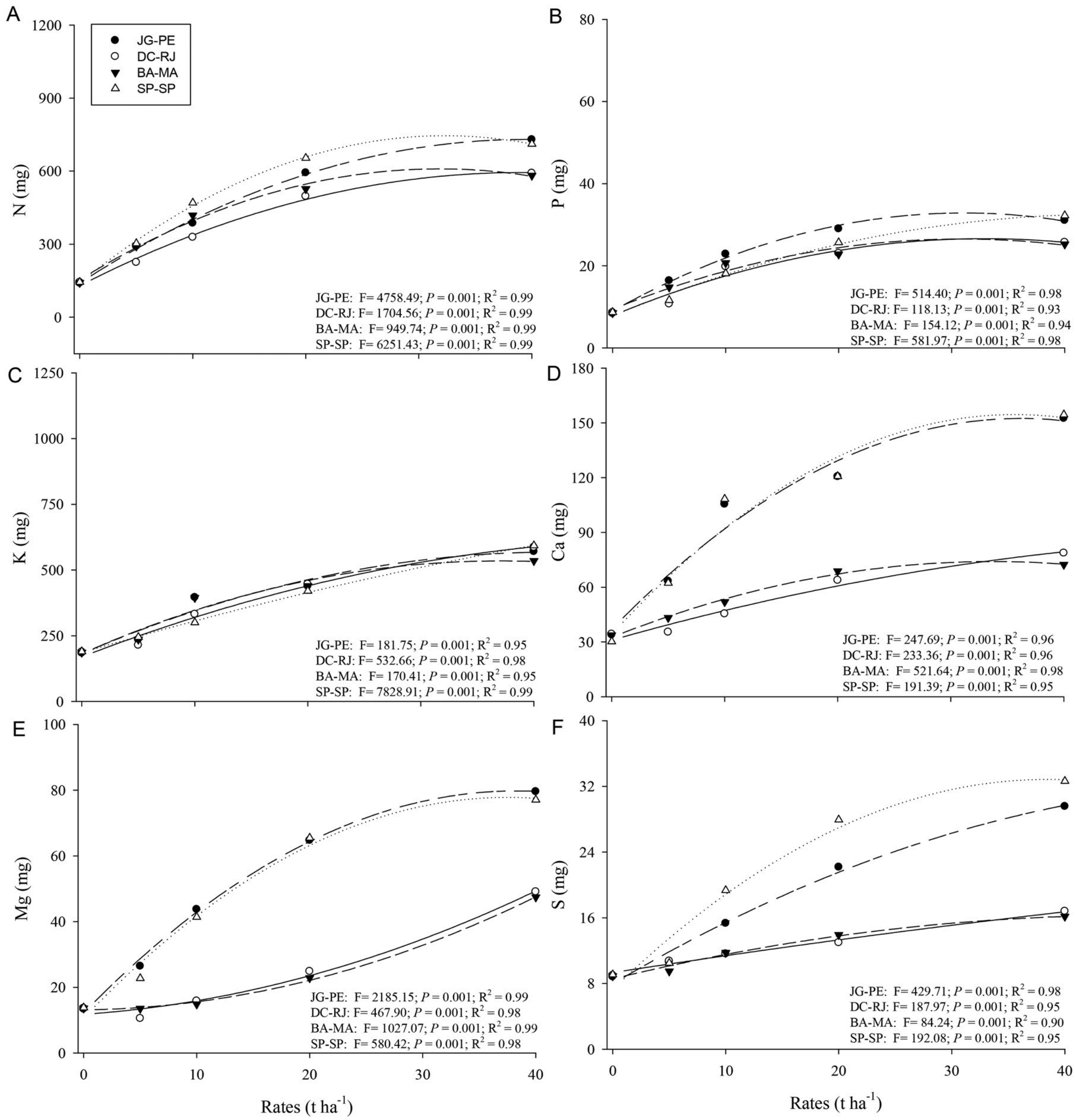

Figure 5. Nitrogen (N) concentration [A], phosphorus (P) concentration [B], potassium (K) concentration [C]; calcium (Ca) concentration [D], magnesium (Mg) concentration [E]; and sulfur (S) concentration [F] of maize plants grown in Typic Quartzipsamment (TQ) for 45 days and subjected to five rates of granitoid powder from four different origins (JG-PE = Jaboatão do Guararapes-PE; DC-RJ = Duque de Caxias-RJ; BA-MA = Bacabeira-MA; and SP-SP = Santana do Paranaíba-SP).

growth (Butterly et al., 2022). In this study the initial soil pH ($CaCl_2$) was 3.91, confirming that the soil was strongly acidic prior to the experiment. After incubation, granitoid powder application significantly increased soil pH compared to the control, indicating its potential to neutralize soil acidity. This effect is likely due to the release of base cations (e.g. Ca^{2+}, Mg^{2+}) during the weathering of granitoid minerals, which neutralize hydrogen ions in the soil solution (Khan & Rana, 2020; Ramos et al., 2022). All treatments received a uniform basal fertilization to ensure adequate nutrient supply and allow proper plant development, as granitoid powder alone rates not fully meet crop nutritional requirements. Therefore, the positive effects observed can be attributed to the interaction between basal fertilization and the increasing rates of granitoid powder, which improved soil chemical conditions and enhanced nutrient availability. The clear rate–response relationships observed for pH, nutrient concentrations, and plant growth indicate that granitoid powder played a decisive role in the improvements measured, going beyond what could be achieved by basal fertilization alone.

While the study demonstrated the positive effects of granitoid powder on soil fertility and crop growth, it is important to consider the factors that may influence its effectiveness. The mineral composition of granitoid powder can vary depending on its geological origin, which in turn affects its nutrient content and weathering rates (Liu et al., 2023). In this study, granitoid powder from four different locations (Bacabeira-MA, Duque de Caxias-RJ, Jaboatão do Guararapes-PE, and Santana do Paranaíba-SP) was used, and the results suggest that the origin of granitoid powder plays a role in its effectiveness as a soil amendment.

Soil properties, such as texture and organic matter content, also influence the response to granitoid powder application. For instance, sandy soils like Typic Quartzipsamment may benefit more from the addition of granitoid powder due to their low nutrient retention capacity. Conversely, soils with high organic matter content and existing nutrient reserves may show a less pronounced response to granitoid powder application. Understanding these interactions is crucial for optimizing the use of granitoid powder in different soil types and agroecological conditions.

The observed increases in concentrations of P, K, Ca, and Mg in soil and plant tissues following the application of granitoid powder likely result from both the gradual nutrient release from the material and improved nutrient retention and cycling in the amended soil, highlighting that not all nutrient increases are solely attributable to granitoid powder weathering. Since basal fertilization was constant across all treatments, the dose-dependent improvements in nutrient availability and uptake indicate that granitoid powder acted as a complementary input, enhancing soil chemical properties and promoting more efficient use of the applied fertilizers, without the negative effects commonly associated with conventional chemical fertilizers (Swoboda et al., 2022).

Recent studies, such as Conceição et al. (2022), indicate that the addition of rock powder can improve soil structure, increase water retention, and provide a sustainable source of essential nutrients. One of the most prominent findings of this study is the positive impact of granitoid powder on soil chemical properties. An increase in soil P, K, Ca, and Mg concentrations was observed with the increasing rates of granitoid powder. These results align with previous research, which suggests that silicate rock powders, including granitoid, can act as a slow-release source of essential nutrients (Khan & Rana, 2020).

The mineral composition of granitoid, rich in feldspar, mica, and other minerals, provides a wide range of nutrients, contributing to soil fertility over time. However, compared with granitic materials, other silicate rocks, such as basalt or other mafic lithologies, generally weather more rapidly and may release nutrients more readily due to their higher mineral reactivity and lower quartz content (Conceição et al., 2022; Luchese et al., 2023). Nevertheless, the slower weathering of granitic rocks may offer the advantage of a more gradual nutrient release, which contributes to maintaining soil fertility in the long term.

The observed improvements in BS% and the sum of bases indicate that granitoid powder can effectively enhance soil cation exchange capacity (CEC). This is particularly important in sandy soils, such as the Typic Quartzipsamment used in this study, which typically have low organic matter content and limited nutrient retention capacity. By increasing the availability of key nutrients and raising soil pH, granitoid powder contributes to creating a more favorable environment for plant growth, promoting nutrient uptake, and enhancing soil fertility. This suggests that granitoid powder not only improves nutrient availability in the soil but also facilitates greater nutrient absorption by plants, resulting in more robust and productive growth.

The increase in shoot dry mass observed in this study can be interpreted as a proxy for greater yield potential, since this parameter is positively correlated with grain yield in maize and common bean crops (Fageria, 2014; Taiz et al., 2017). Furthermore, higher foliar concentrations of micronutrients such as B, Cu, Fe, Mn, and Zn may be associated with yield improvements, given their key roles in physiological and biochemical processes involved in plant development and production (Alloway, 2008; Zewide & Sherefu, 2021).

The use of granitoid powder as a soil remineralizer is a promising and sustainable strategy for managing soil fertility and enhancing agricultural practices. Unlike synthetic fertilizers, which provide immediate but short-lived nutrient availability and can lead to environmental issues such as nutrient leaching and eutrophication of water bodies, granitoid powder may offer a gradual release of nutrients, as suggested in previous studies. While this potential supports long-term soil fertility and reduced environmental risk, further research is needed to evaluate its performance in comparison to conventional fertilizers. This gradual nutrient release supports long-term soil fertility while minimizing the risk of environmental contamination, making it an effective alternative or supplement to conventional chemical fertilizers (Manning, 2015). Furthermore, the study's findings that granitoid powder application significantly improved nutrient uptake in maize and common bean plants underscore its potential to reduce dependency on synthetic fertilizers.

Given the current global challenges in fertilizer supply chains, especially following geopolitical events like the Russia-Ukraine conflict (Daniell & van Tonder, 2023), the exploration of local, naturally occurring mineral sources such as granitoid becomes increasingly relevant. Granitoid powder, as a by-product of mining activities, may represent a low-cost, regionally available alternative for nutrient supply. In addition to contributing to soil fertility, its use also aligns with the principles of the circular economy by valorizing a mining by-product as an agricultural input. However, its economic viability should be confirmed through cost–benefit studies across different cropping systems.

The application of granitoid powder has proven effective in improving soil chemical properties and promoting the growth of agricultural crops. These results reinforce the use of granitoid powder as a viable and sustainable alternative for managing soil fertility, especially in contexts where access to chemical fertilizers is limited or undesirable due to environmental concerns.

The increase in nutrient accumulation, especially for N, P, K, Ca, e Mg in both maize and common bean plants, further supports the efficacy of granitoid powder as a soil amendment. The observed increases in micronutrient concentrations, such as B, Cu, Fe, Mn e Zn, also suggest that granitoid powder can enhance the overall nutritional status of crops. This improvement in plant nutrition is crucial for both crop yield and quality, as well as for human health, considering that micronutrient deficiencies in soils can lead to poor nutritional quality of crops (Oliveira et al., 2023).

The positive effects of granitoid powder on soil fertility and plant growth can be attributed to several mechanisms. In general, the mineral composition of granitoid powder provides a diverse range of nutrients that become available to plants over time through weathering processes. The slow weathering of minerals such as feldspar and mica releases essential nutrients, including K, Ca, and Mg, into the soil solution (Manning, 2015). This steady nutrient release helps maintain soil fertility and reduces the need for frequent fertilizer applications.

The differences in Ca among treatments are directly associated with the mineralogy of the rocks, particularly the composition of plagioclases, which range from albite to oligoclase. More calcic plagioclases have higher Ca contents and weather more rapidly in acidic soils, releasing this nutrient more effectively (Blum et al., 2002; Engvik et al., 2008). This explains the greater Ca input observed in the JG-PE and SP-SP materials, even without the supply of this element in the basal fertilization. Similarly, the differences in N and P, although applied uniformly to all pots, may be related to the improvement of soil chemistry promoted by granitoid powder, with increased pH, reduced Al^{3+}, and enhanced root growth, which favored nutrient uptake and the efficiency of N and P use (Butterly et al., 2022; Ramos et al., 2022; Taiz et al., 2017).

Granitoid powder has the potential to improve soil physical properties. Although not directly assessed in this study, previous research indicates that the addition of rock powders can enhance soil structure, water retention, and aeration (Ramos et al., 2020). Improved soil structure facilitates root growth and nutrient uptake, contributing to overall plant health and productivity. Moreover, the application of granitoid powder can influence soil microbial activity, particularly the activity of beneficial microorganisms involved in nutrient cycling. The presence of minerals in granitoid powder may support the proliferation of certain microbial communities, thereby enhancing nutrient availability through processes such as mineral solubilization and organic matter decomposition (Manning, 2015).

However, the study also highlights that the effectiveness of granitoid powder can be conditional. As noted in research by Swoboda et al. (2022), the release of nutrients from granitoid powder depends on factors such as particle size, soil acidity, and microbial activity. For example, fine-grained granitoid powder may weather more quickly and provide nutrients more readily than coarser particles. Moreover, the presence of certain soil microorganisms can facilitate the solubilization of minerals, enhancing nutrient availability. Therefore, to maximize the benefits of granitoid powder, it is essential to consider its mineralogical characteristics, soil properties, and the local soil microbiome.

The use of granitoid powder as a soil remineralizer aligns with the principles of sustainable agriculture and the circular economy. By recycling mineral-rich rock powder from mining operations, this approach not only valorizes a mineral-rich by-product but also provides an alternative to synthetic fertilizers. The slow-release nature of nutrients from granitoid powder supports long-term soil fertility, reducing the need for frequent fertilizer applications and minimizing the environmental impact of nutrient runoff.

The concept of soil health involves the soil's ability to function as a living ecosystem that supports plants, animals, and humans, integrating physical, chemical, and biological attributes (Rodríguez et al., 2022). In this context, the application of granitoid powder contributed to several indicators of soil health. The observed increase in soil pH and reduction in aluminum toxicity are fundamental for creating a more favorable environment for root development and microbial activity (Butterly et al., 2022; Naz et al., 2022). In addition, the increases in macronutrient levels such as P, K, Ca, and Mg, along with the rise in base saturation, indicate an improvement in the soil's chemical fertility, particularly in highly weathered tropical soils with low cation exchange capacity (Conceição et al., 2022; Oliveira et al., 2025; Ramos et al., 2022). Recent studies further support that the application of silicate rock powders can enhance nutrient retention, promote slow nutrient release, and support integrated soil health by improving microbial activity, cation exchange, and soil structure (Reis et al., 2024; Richardson, 2024). These results demonstrate that granitoid powder has the potential to promote soil health and crop productivity sustainably, especially in regions with nutrient-poor soils and near mining areas. However, further research is needed to explore its use across different agroecological zones and cropping systems. Long-term field trials would be important to assess the residual effects of granitoid powder on soil fertility, plant health, and its interactions with integrated management practices, such as organic matter application and cover crops.

Although this study focused primarily on the chemical effects of granitoid powder, it is important to consider that its addition to the soil may also influence physical properties, such as water retention, porosity, and bulk density. These changes can affect root development and nutrient uptake, thereby contributing indirectly to plant growth. Previous studies have suggested that rock powders can improve soil physical structure, particularly in sandy soils, by enhancing water-holding capacity and cation exchange (Plata et al., 2021; Ramos et al., 2020). Although not evaluated in this study, these potential physical effects should be considered in future studies.

Additionally, investigating the synergistic effects of granitoid powder with other soil amendments, such as organic matter, biochar, or microbial inoculants, could provide insights into integrated soil fertility management strategies. Understanding the role of soil microorganisms in granitoid powder weathering and nutrient cycling may also reveal new opportunities to enhance its effectiveness through microbial stimulation or inoculation.

From an economic perspective, the use of granitoid powder as a soil amendment could provide cost savings for farmers, especially in regions where access to synthetic fertilizers is limited or expensive. By providing a local and sustainable source of nutrients, granitoid powder can reduce the reliance on imported fertilizers and buffer farmers against market fluctuations. Moreover, its slow-release nature can reduce the frequency of fertilizer applications, lowering labor and input costs over time. Environmentally, the use of granitoid powder contributes to the reduction of fertilizer-related pollution. The gradual nutrient release minimizes nutrient leaching into water bodies, mitigating the risk of eutrophication and groundwater contamination. Additionally, by utilizing a mining by-product, granitoid powder use promotes circular economy principles and resource conservation, promoting a circular economy in agriculture.

An understanding of the environmental implications of rock powder use requires considering not only its agronomic efficiency but also its interactions with soil carbon dynamics and long-term sustainability indicators. Life cycle assessment (LCA) is an appropriate approach to quantify these impacts, as it integrates the potential for nutrient recycling, carbon sequestration, and the reduction of greenhouse gas emissions. Evidence from LCA-based studies (Lefebvre et al., 2019) indicates that the use of silicate rock powders can contribute to carbon sequestration through enhanced weathering processes and reduce the environmental footprint associated with the production and use of conventional fertilizers. Incorporating this type of analysis into future research could provide a more holistic evaluation of the environmental trade-offs and the true sustainability potential of granitoid-based fertilizers.

5. Conclusion

The application of granitoid powder has proven to be an effective strategy for enhancing soil fertility and increasing crop productivity. This study showed that granitoid powder significantly improves soil chemical properties, including increased levels of P, K, Ca, and Mg, while also raising soil pH and reducing aluminum toxicity. These changes create a more conducive environment for plant growth, particularly in acidic soils.

Granitoid powder also positively impacted the growth and nutrient uptake of maize and bean plants, leading to higher biomass production and better nutritional status. These findings align with recent research, demonstrating that rock dusts, such as granitoid, can serve as sustainable soil amendments by providing a slow-release source of essential nutrients, thereby reducing reliance on conventional chemical fertilizers and minimizing environmental impacts.

Overall, granitoid powder shows potential as an alternative input for improving soil fertility, with agronomic and environmental benefits. Its use may contribute to soil health and crop growth, thereby supporting more sustainable agricultural practices. However, further research is needed to evaluate its long-term effectiveness and economic feasibility under different soil and climatic conditions and cropping systems.

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Authorship contribution statement

CRediT: **Sidiney Moreira Fernandes**: Conceptualization, Data curation, Investigation, Methodology; **Gustavo Castoldi**: Software, Validation, Writing – review & editing; **Caroline Figueiredo Oliveira**: Investigation, Software, Writing – original draft; **Gutierres Nelson Silva**: Formal analysis, Methodology; **Wagner Henrique Moreira**: Formal analysis, Investigation; **Nericlenes Chaves Marcante**: Funding acquisition, Writing – review & editing; **Mathaus Antônio Elias Mandro**: Funding acquisition, Writing – review & editing; **Éder de Souza Martins**: Writing – review & editing; **Elcio Ferreira Santos**: Conceptualization, Data curation, Formal analysis, Funding acquisition, Project administration, Supervision, Writing – review & editing.

Disclosure statement

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Data availability statement

The data that support the findings of this study are available from the corresponding author, EFS, upon reasonable request.

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