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Rock powder application combined with bacterial inoculation enhances the early growth of coffee plants

Rochagem associada à inoculação de bactérias auxilia no crescimento inicial de cafeeiro

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ABSTRACT

The use of rock powder combined with nutrient-solubilizing and growth-promoting bacteria represents a promising alternative for nutrient supply to the soil and improved crop development. This study aimed to evaluate the development of coffee seedlings treated with rock dust and inoculated with *Bacillus* species. Six types of rock powder (slate, black slate, gneiss, kamafugite, pyroxenite, and a mixture of mica schist and granite) were added to standard fertilizer in the presence or absence of a *Bacillus* mixture (*Bacillus subtilis* and *Bacillus amyloliquefaciens*) during coffee cultivation. We measured plant height, stem diameter, leaf number, shoot and root dry biomass, and nutrient levels in the soil and coffee leaves after. In the kamafugite treatment, adding a bacterial mixture increased plant height. When the bacterial application was considered alone, it resulted in an 85% increase in the plants' total dry biomass. Rock powder and bacteria showed a substantial interaction effect, particularly for nutrients. Gneiss and kamafugite treatments increased phosphorus availability in the soil, whereas bacterial presence boosted calcium and magnesium content. The combination of nutrient-solubilizing and growth-promoting bacteria and rock powder improved soil chemical properties and the early development of coffee plants.

Index terms: *Coffea arabica*; remineralizer; *Bacillus*; sustainable agriculture.

RESUMO

O uso de pó de rocha com bactérias solubilizadoras de nutrientes e promotoras de crescimento representa uma alternativa promissora para o fornecimento de nutrientes e melhor desenvolvimento das culturas. O objetivo do estudo foi avaliar o desenvolvimento de mudas de café com pó de rocha e *Bacillus*. Seis tipos de pó de rocha (ardósia, ardósia preta, gnaisse, kamafugito, piroxenito e uma mistura de mica xisto e granito) foram usados com o fertilizante padrão, na presença ou ausência de uma mistura de bactérias (*Bacillus subtilis* e *Bacillus amyloliquefaciens*) no cultivo do café. Avaluou-se altura das plantas, diâmetro do caule, número de folhas, biomassa seca da parte aérea e das raízes, teores de nutrientes no solo e nas folhas. No tratamento com kamafugito, a adição das bactérias aumentou a altura das plantas. Quando considerada isoladamente, a aplicação das bactérias resultou em um aumento de 85% na biomassa seca total das plantas. O pó de rocha e as bactérias mostraram um efeito de interação substancial, especialmente para os nutrientes. Os tratamentos com gnaisse e kamafugito aumentaram a disponibilidade de fósforo no solo, enquanto a presença das bactérias elevou os teores de cálcio e magnésio. A combinação de bactérias solubilizadoras de nutrientes e promotoras de crescimento com pó de rocha melhorou as propriedades químicas do solo e o desenvolvimento inicial das plantas de café.

Termos para indexação: *Coffea arabica*; remineralizador; *Bacillus*; agricultura sustentável.

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Introduction

Brazil is the world's leading producer and exporter of coffee. The country produced 55.1 million sacks of processed coffee from 2.24 million hectares of cultivated land in 2023 (Companhia Nacional de Abastecimento - Conab, 2023). Due to its prominent role, Brazilian coffee cultivation bears the burden of serving as a model for sustainable domestic and international production. Improving coffee plant productivity involves using massive amounts of soluble mineral fertilizers (Matiello et al., 2010), which are non-renewable geological resources with numerous adverse effects on the ecosystem because of their long-term or intensive application (Hatamian et al., 2018; Souri & Hatamian, 2019). Therefore, there is an increasing interest in finding alternatives to mineral fertilizers and achieving more sustainable crop production.

Anthropogenic activities during coffee cultivation can impact soil chemical, physical, and biological characteristics (Yang et al., 2020), making it crucial to review these practices. Using rock powder as an alternative fertilizer is promising for sustaining productivity and plant nutrition (Theodoro et al., 2021). Rock powdering involves applying ground rocks to the soil, providing new minerals that undergo weathering, enhanced by the formation of surfaces that interact and release nutrients without harming the soil microbiota (Martins, Martins & Hardoim, 2023). Compared to temperate soils, around 37% of tropical soils possess less than one-tenth of the weatherable mineral reserves (Swoboda, Döring & Hamer, 2022), emphasizing that remineralization is appropriate for Brazilian soils. Furthermore, it is an effective strategy for CO_2 sequestration because it releases cations, which generate alkalinity and convert CO_2 into dissolved inorganic carbon in soil (Beerling et al., 2020; Kelland et al., 2020).

Brazil is a global pioneer in the usage of rock powdering, which was regulated in 2016 by the Ministry of Agriculture, Livestock, and Food Supply (MAPA) Normative Instruction No. 5 of March 10, 2016 (Brasil, 2016). It also forms part of the National Fertilizer Plan, which outlines the sector's strategy for 2050. Several studies have validated the use of rock powder as a fertilizer, particularly as a source of K, Ca, and Mg (Gotz et al., 2019; Crusciol et al., 2022; Brasil et al., 2023; Araújo et al., 2024).

The literature shows that excessive fertilizer use impacts the efficiency and density of native populations of microorganisms that promote plant growth (Urgiles-Gómez et al., 2021). High soluble fertilizers, like KCl, can have a detrimental short-term effect on soil bacterial communities by generating significant microbial alterations within a month of application (Reis et al., 2024), as well as higher soil salinity (Souri, 2010; Souri, Neumann, & Römheld, 2009). Soils in the Brazilian Cerrado, where most coffee is grown, are weathered and low in fertility, as agriculture has altered the microbiome, disrupted nutrient flux, and interfered with biogeochemical processes (Procópio & Barreto, 2021). Therefore, incorporating microorganisms into farming systems, together with rock powder and organic fertilizers, is a promising strategy for enhancing these soils' chemical, physical, and biological properties.

The slow and steady release of nutrients from rock powdering is a well-established phenomenon. Thus, combining rock powder and exogenously applied rock-solubilizing microorganisms can enhance plant nutrient availability via accelerated weathering (Sattar et al., 2019; Krahl et al., 2022; Silva et al., 2023). *Bacillus* species form associations with plant roots, stimulating plant growth in various crop species. Plant growth-promoting bacteria (PGPB) can help plants grow by solubilizing and releasing minerals from the soil via hydrolytic enzymes and metabolites (Backer et al., 2018).

Our study investigated how rock powders from various sources combined with *Bacillus subtilis* and *Bacillus amyloliquefaciens* affect early coffee plant growth. We investigated the potential interactions between bacteria, rock powder, and coffee plants by focusing on nutrient availability and soil improvements. To the best of our knowledge, this is the first comprehensive study to evaluate the bioavailability of nutrients in coffee plants utilizing various rock powders and a combination of *Bacillus* species.

Material and Methods

Experimental site

The experiment was carried out in 2021 at the Federal Institute of Northern Minas Gerais, located in the Januária municipality, Minas Gerais, Brazil. The experiment used Red Latosol soil with a clayey texture from the municipality of Joaquim Felício/MG (Serra do Cabral), collected at a depth of 0-20 cm. The soil had the following chemical characteristics: pH-water= 4.5; K = 68 $mg.dm^{-3}$; P-Mehlich = 2.2 $mg.dm^{-3}$; Ca = 0.3 $cmolc.dm^{-3}$; Mg = 0.2 $cmolc.dm^{-3}$; Al = 0.8 $cmolc.dm^{-3}$; Cation Exchange Capacity (CEC) = 7.1 $cmolc.dm^{-3}$; and base saturation (V) = 10%.

Treatments and experimental design

The evaluated treatments for coffee cultivation included standard fertilizer (ST, control), standard fertilizer with the addition of KCl, and six other treatments with rock powder combined with standard fertilizer. The ST contained 30g dolomitic limestone (42% Ca, 6% Mg, 80% PRNT), 25g agricultural gypsum (17% Ca, 14% S), 20g thermophosphate (18% Ca, 7% Mg, 16% P, 10% Si), 100g tanned cattle manure, and 15g single superphosphate (18% P, 16% Ca, 10% S) per pot (volume: 7 dm^3).

Overall, we evaluated eight different fertilizer treatments: (1) ST; (2) ST + 15g KCl; (3) ST + 110g slate; (4) ST + 110g black slate; (5) ST + 110g gneiss; (6) ST + 110g kamafugite; (7) ST + 110g pyroxenite; and 8) ST + 77g mica schist + 33g granite. The amount of rock powder used in the experiment was calculated based on the available K content in the rock powders and the potassium requirements of the coffee crop. All rock powders exhibited comparable K_2O concentrations.

Each of these eight treatments was evaluated in the presence and absence of a bacterial mixture of *Bacillus subtilis* (PRO26, GenBank Accession number: PQ607727) and *Bacillus amyloliquefaciens* (PRO7, GenBank Accession number: PP903615), provided by a research and agricultural consultancy company. The bacteria were isolated from the *Zea mays* rhizosphere soil and have the potential to solubilize nutrients and promote plant growth. We employed a bacterial consortium to explore the microorganisms' various modes of action, nutritional requirements, and growth characteristics (Nunes et al., 2024). Table 1 shows the rock powders used in our study and their base compositions. Every rock powder utilized had a particle size permitted by the MAPA Normative Instruction (Brasil, 2016). This means that 50% of the particles could pass through a 0.3 mm sieve whereas 100% could pass through a 2.0 mm sieve.

Table 1: Chemical properties of the rock powders utilized in the experiment.

Rock powder	K_2O	CaO	MgO	P_2O_5	Company	Locality
	%					
Slate (SL)	3.8	1.7	3.5	0.20	Pevex Recicladora	Papagaios/MG
Black Slate (BSL)	3.4	3.2	3.2	0.20	Alto da Boa Vista Mineração	Papagaios/MG
Gneiss (GN)	3.0	3.8	2.3	0.20	Extração Mineração Patativa	Taiobeiras/MG
Granite (GR)	4.7	0.5	0.5	0.02	Goyas Britas	Itumbiara/GO
Kamafugite (KM)	3.5	4.6	4.2	2.20	KP Fértil	Carmo do Paranaíba/MG
Mica Schist (MX)	3.4	1.8	4.2	0.20	Briteng Britagem e Construções	Aparecida de Goiânia/GO
Pyroxenite (PX)	4.2	5.3	4.0	1.00	Ipirá Fertil	Ipirá/BA

Source: Data provided directly by the company or made available on the official website.

Our study used a completely randomized design in a 6x2 factorial scheme, including the ST and ST+KCl controls. Each experimental unit was a pot with a volume of 7 dm^3, filled with 5.5 dm^3 of soil. Each treatment included three pots, totaling 48 pots. The experiment was conducted in a greenhouse.

Applying rock powders and bacteria to Coffee seedlings

We mixed dolomitic limestone, agricultural gypsum, thermophosphate, and rock powders into the soil according to the experimental treatment. We then saturated the soil mix with water and incubated it for 10 days. Tanned cattle manure and single superphosphate were added separately after this period. KCl was also incorporated into the ST + KCl treatment on the same day. We used KCl specifically because it is Brazil's most regularly used potassium fertilizer. Coffee seedlings of the Catuaí 144 variety, with 4 to 6 pairs of fully expanded leaves, were transplanted two days afterward.

Seven days after transplantation, the first inoculation was conducted using a suspension comprising a combination of the two *Bacillus* species. Each pot received 50 mL of the suspension ($1x10^9$ CFU/mL) at the plant's base. Three additional inoculations with the exact dosage and volume were performed at two-week intervals. The plants were irrigated with water (pH = 6.0) until saturation point and initial runoff from the bottom of the pot.

Evaluations

We measured plant height, stem diameter, leaf count, and dry aerial biomass and conducted leaf and soil chemical analysis 126 days after coffee plant transplantation. Plant height (cm) was determined by measuring the length from the base of the stem to the insertion of the last pair of leaves using a measuring tape. Stem diameter (cm) was measured at 2 cm from the soil using a digital caliper. The number of leaves was counted per plant. After 72 h of drying at 60°C in a forced-air oven, the aerial part of the plant was separated from the root to determine dry biomass (g). Chemical analysis required 500 g of soil per plant and 10–15 healthy leaves per sample. Soil and leaf samples were transported to the LABOMINAS Laboratory in Manhuaçu/MG, where macro and micronutrient levels were determined.

Statistical analyses

The acquired data were subjected to analysis of variance (ANOVA) using the F-test ($p<0.05$). Detecting significant treatment effects prompted additional investigation of the interactions between fertilizers and bacteria. Fertilizer treatments were categorized using the Scott-Knott test at 5% significance, and the F-test of the ANOVA ($p<0.05$) was used to examine the effects of bacteria presence/absence. The Dunnett test was used at a 5% significance level when the absolute control was present. All analyses were performed using R statistical software (R Development Core Team, 2009).

Results and Discussion

Using *Bacillus* and fertilizer together significantly ($p\leq0.05$) affected the number of leaves, stem diameter, and plant height. When *Bacillus* was absent, the ST+PX and ST+MX/GR treatments produced the tallest plants, but the presence of *Bacillus* decreased plant height (Table 2). Both ST and ST+KM treatments were more successful in the presence of bacterial mix, increasing the plant height significantly. ST treatment paired with the bacteria produced more leaves than the other treatments.

We detected a direct association between plant height and stem diameter, with taller plants having larger diameters. The plants treated with ST + KCl exhibited the lowest values for the studied parameters, decreasing total plant dry mass (Table 3) and root growth. This effect can be attributed to the soil's high K concentration, which reduced both foliar Ca and Mg levels. Excess KCl in the soil can have a saline effect, hindering plant water absorption and nutrient uptake (Nunkaew et al., 2015; Martineli et al., 2022) due to competitive action. The soil's medium K, Ca, and Mg ratios were 10, 77, and 11, respectively.

Table 2: Average height, stem diameter, and number of leaves in *Coffea arabica* Catuaí 144 grown with rock powder in the absence (-) or presence (+) of *Bacillus* species after 126 days of growth.

Fertilization treatments*	Height (cm)		Stem diameter (mm)		Number of leaves	
	(-)	(+)	(-)	(+)	(-)	(+)
ST	19.89 Bb[1]	22,24 Aa	0.44 Bb	0.49 Aa	17.54 Ba	21.38 Aa
ST + KCl	17.82 Ac	18.00 Ac	0.39 Ac	0.41 Ac	13.52 Ab	13.21 Ac
ST + SL	16.83 Bc	20.60 Ab	0.41 Bc	0.45 Ab	16.52 Aa	16.29 Ab
ST + BSL	18.21 Bc	19.98 Ab	0.41 Ac	0.45 Ab	14.29 Ab	16.19 Ab
ST + GN	20.98 Ab	19.83 Ab	0.49 Aa	0.40 Bc	17.00 Aa	14.14 Bc
ST + KM	17.43 Bc	22.71 Aa	0,43 Ab	0.41 Ac	17.71 Aa	17.62 Ab
ST + PX	21.67 Aa	20.21 Ab	0.49 Aa	0.41 Bc	16.86 Aa	16.86 Ab
ST + MX/GR	22.64 Aa	18.68 Bc	0.48 Aa	0.40 Bc	16.43 Aa	16.52 Ab
CV (%)	11.95		12.49		23.43	
Average	19.86		0.44		16.38	

*ST (control) = standard; SL = slate; BSL = black slate; GN = gneiss; KM = kamafugite; PX = pyroxenite; MX/GR = mica schist/granite. [1/]Means followed by the same lowercase letters in the column (isolated effect of fertilizer treatment) do not differ significantly according to the Scott-Knott test at 5% significance; means followed by the same uppercase letters in the row for each characteristic (isolated effect of the absence/presence of bacteria) do not differ significantly according to the F test at 5% significance.

Table 3: Dry stem, leaf, and root mass in *Coffea arabica* Catuaí 144 plants after 126 days of cultivation with rock powder and the bacteria's absence (-) or presence (+).

Fertilization treatments*	Stem		Leaf	Root	Stem + Leaf	Total**
	------------------------	g. plant^{-1}	------------------------			
	(-)	(+)				
ST	3.12 Aa[1]	4.06 Aa	9.58 a[2]	3.98 a	13.17 a	24.49 a
ST + KCl	1.54 Ab	1.67 Ab	4.76 b	1.44 b	6.34 b	11.07 b
ST + SL	2.32 Ab	3.12 Aa	6.89 a	2.42 b	9.61 a	17.24 a
ST + BSL	2.44 Ab	3.06 Aa	7.54 a	3.12 a	10.30 a	19.12 a
ST + GN	3.61 Aa	2.99 Aa	8.11 a	2.69 b	11.41 a	19.66 a
ST + KM	2.98 Aa	3.81 Aa	8.37 a	3.88 a	11.77 a	22.02 a
ST + PX	3.43 Aa	3.20 Aa	8.13 a	3.20 a	11.44 a	20.15 a
ST + MX/GR	3.67 Aa	2.64 Ba	7.60 a	2.69 b	10.92 a	18.54 a
Absence	--	--	--	--	--	13.36 B[3]
Presence	--	--	--	--	--	24.72 A
CV (%)	18.69		19.47	34.22	18.61	20.4
Average	7.62		2.98	2.93	10.62	19.04

*ST (control) = standard; SL = slate; BSL = black slate; GN = gneiss; KM = kamafugite; PX = pyroxenite; MX/GR = mica schist/granite. ** Total = dry mass of stem, leaf, and roots; [1/]Means followed by the same lowercase letters in the column (isolated effect of fertilizer treatment) do not differ significantly by the Scott-Knott test at 5% significance; means followed by the same uppercase letters in the row (isolated effect of the absence/presence of bacteria) do not differ significantly by the F test at 5% significance. [2/]Means followed by the same lowercase letter in the column (isolated effect of fertilizer treatment) do not differ significantly by the Scott-Knott test at 5% significance. [3/]Different uppercase letters in the column (effect of bacteria) indicate significant differences by the F test at 5% significance.

Compared to the roots of plants without bacteria, the ST+BSL treatment with bacteria showed an increased number of fine roots. This could be attributable to enhanced nutrient availability and the likely effect of bacteria-produced hormones, such as auxin (Park et al., 2017) (Figure 1). Minerals found in slate, such as mica, chlorite, feldspar (Chiodi Filho, Rodrigues, & Artur, 2003), muscovite, clinochlore, and illite (Campos et al., 2004), may also contribute to this.

Figure 1: Roots of *Coffea arabica* Catuaí 144 plants at 126 days post-transplantation. Plants treated with standard fertilizer and black slate rock powder (ST + BSL), without (left) and with inoculated bacteria (right).

According to Bowen's reactivity series, minerals that crystallize at high temperatures, such as olivine and pyroxene, are more reactive. In contrast, minerals formed at lower temperatures, such as quartz and feldspar, have reduced reactivity. The presence of microbes optimizes the reactivity of slate minerals, which are naturally less reactive. Slate weathering is primarily defined by iron sulfide oxidation and gypsum formation (Cárdenes et al., 2014). The chemical oxidation of sulfide is a natural process that occurs mainly in well-aerated soils and can be accelerated by sulfur-oxidizing microorganisms. The weathering of carbonate minerals results in the creation of gypsum crystals. Since gypsum contains more volume than carbonates, it softens and destroys the slate's structure, contributing to weathering (Cárdenes et al., 2014).

Root form also varies with nutrient availability in the soil solution (Figure 2). Nutrient acquisition efficiency refers to the performance of the absorption mechanism and the growth of fine roots (< 2 mm). In contrast, utilization efficiency indicates the capacity for nutrient transport and biomass production per unit of absorbed nutrient (Pedrosa et al., 2013). In nutrient-rich soils, roots develop faster and have a higher turnover, increasing absorption area per biomass unit. Alternatively, roots develop morphologies, such as more extensive roots, that prevent nutrient loss in soils with limited nutrient availability (Fort et al., 2016). Thus, the presence of bacteria in the soil solution may increase nutrient availability, promoting the growth of fine roots. Root morphology, architecture, and physiology, including mineral nutrient uptake characteristics, can vary substantially depending on soil type, plant species, and climatic conditions (Saghaiesh & Souri, 2018; Souri & Neumann, 2018; Souri & Hatamian, 2019).

Combined treatment of bacteria and fertilizer significantly affected stem dry mass ($p<0.05$) (Table 3). In the absence of bacteria, standard fertilizer (control) and the treatments ST + GN, ST + KM, ST + PX, and ST + MX/GR increased stem diameters. All treatments, except for the ST + SL treatment, were grouped according to the largest diameters in the presence of bacteria. Except for the ST + MX/GR treatment, which resulted in a significant decrease in diameter, the presence of *Bacillus* produced no discernible alterations compared to their absence.

Fertilizer treatments exclusively affected the dry masses of the leaves, roots, and total aerial parts. The bacteria or interaction between the two had no separate effects on these characteristics. All fertilizer treatments produced similar amounts of leaf dry mass, except the ST + KCl treatment, which performed statistically lower results than the others. Total shoot dry mass exhibited a similar pattern. The treatments ST, ST + BSL, ST + KM, and ST + PX produced the highest root dry mass values.

However, both fertilizer and bacteria application had a significant isolated effect in terms of total dry mass. We observed no significant differences between the fertilizer treatments except for ST + KCl, which resulted in statistically lower values. In addition, we discovered that bacterial application resulted in an 85% increase in total dry mass compared to the control treatment.

B. subtilis and *B. amyloliquefaciens* are known to promote plant development and suppress plant diseases (Luo et al., 2022; Mahapatra, Yadav, & Ramakrishna, 2022; Di et al., 2023; Yang et al., 2024). The species *B. amyloliquefaciens* (BT42), isolated from the coffee plant rhizosphere, is associated with indole-3-acetic acid (IAA) and ammonia production, as well as phosphate and zinc oxide solubilization, all of which directly or indirectly promote plant growth (Kejela, Thakkar & Thakor, 2016). Inoculating a mixture of the two *Bacillus* species into the soil with rock powders improved plant growth characteristics, probably by increasing nutrient availability, plant assimilation (Table 4), and potential hormonal action (Kejela, Thakkar & Thakor, 2016).

The bacteria-rock powder interaction significantly affected most of the nutrients. Regardless of the presence of bacteria, the macronutrient levels in the soil and leaf tissue met the crop's minimum requirements, except for K (Figure 2). Bacterial presence increased the amount of P in the soil in the ST, ST + BSL, and ST + MX/GR treatments (Figure 2b), Ca in the ST + SL, ST + BSL, ST + KM, ST + PX, and ST + MX/GR treatments (Figure 2f), and Mg in the ST + SL, ST + BSL, and ST + KM treatments (Figure 2h). The ST + BSL and ST + KM treatments in the presence of bacteria increased P and Mg levels in leaf tissue, respectively (Figures 2a, 2g).

In the absence of bacteria, the ST + GN treatment imposed one of the highest amounts of P in the soil (Figure 2b), whereas ST + GN lowered P levels in the presence of bacteria. This decrease can be due to bacteria-plant competition for available phosphorus. Phosphate-solubilizing bacteria limit the amount of P available to plants by removing it from insoluble sources in various ways (Chen et al., 2016; Wei et al., 2018). Furthermore, regarding rock mineralogy, gneiss contributed significantly to soil chemistry by increasing K and Ca levels.

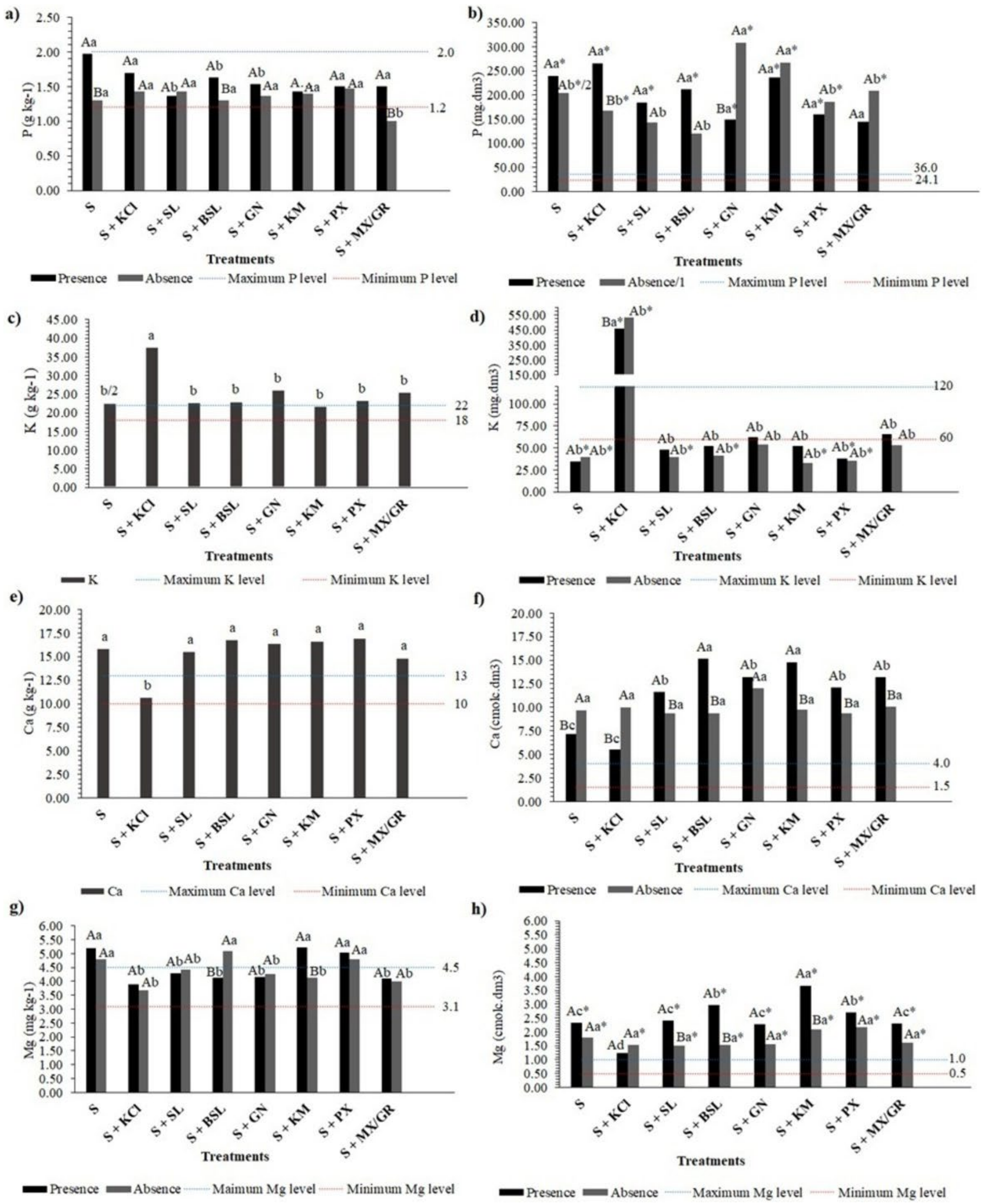

Figure 2: Foliar and soil nutrient levels in Catuaí 144 coffee plants after 126 days of cultivation, exposed to several fertilizer treatments comprising rock dust with or without the presence of solubilizing bacteria. a), c), e), g) Levels of foliar P, K, Ca, and Mg, respectively; b), d), f), h) Levels of soil P, K, Ca, and Mg, respectively. The maximum and minimum levels for each nutrient were defined according to Guimarães et al. (1999). For treatments in the presence of bacteria (black columns), means followed by the same lowercase letter within the treatments are not significantly different, according to the Scott-Knott test at 5% significance. For treatments without bacteria (gray columns), means followed by the same lowercase letter within the treatments are not significantly different, according to the Scott-Knott test at 5% significance. Within each treatment (fertilizer), means followed by the same uppercase letter indicate no significant differences, according to the Scott-Knott test at 5% significance.

Although bacterial presence in the GN treatment significantly reduced soil P concentration, leaf P levels remained adequate. Gneiss has been used in agroforestry for coffee cultivation (Medeiros et al., 2023). Adding 2 kg of gneiss powder per coffee plant increases base saturation, soil electrical conductivity, and Cu, Mn, and Zn levels, indicating that the rock provides adequate fertilizer for plants in agroforestry systems (Medeiros et al., 2023).

The ST + KM treatment exhibited increased phosphorus and magnesium levels in the coffee soil. Kamafugites are alkaline volcanic rocks with high CaO, K_2O, P_2O_5, and MgO content but low SiO_2, Na_2O, and Al_2O_3 (Foley et al., 1987). The presence of Ca and Mg oxides adds to the high Mg concentrations found in coffee soil containing this material. Furthermore, the rock powder has the highest P concentration among the materials investigated. The mineral composition of kamafugites includes micro to phenocrystals of magnesium olivine (Gomes & Ruberti, 2020). Olivines crystallize at higher temperatures and are more weatherable, which makes this rock powder more reactive under the current environment. When weathered, kamafugites form 2:1 clay like vermiculite and smectite. These clays improve the soil's CEC (Cation Exchange Capacity) and its ability to retain water (Ferreira et al., 2020).

Without bacteria, the ST + KCl treatment enhanced the soil's K and Ca levels (Figures 2d, 2f). However, the presence of bacteria had no discernible effect on foliar Ca and K levels (Figures 2c, 2e). K^+ availability can be sustained in soil solutions by displacing Ca^{2+} and Mg^{2+} cations, increasing K absorption and leaf accumulation (Martinez, Lucena & Bonilla, 2021). Minerals or related compounds may synergistically affect plant absorption, translocation, assimilation, and nutritional status (Souri & Hatamian, 2019; Ahmadi & Souri, 2020; Weih et al., 2021). K content in the standard fertilizer and rock powder treatments was below the minimum recommended average level for coffee (Figure 2d), even with organic fertilization and rock powders. This can be explained by adsorption in local soil exchanges or precipitation as a secondary mineral (Almeida et al., 2022). However, the foliar K content was acceptable across all treatments (Figure 2c).

Fe is the most critical micronutrient in coffee cultivation (Guarçoni & Fanton, 2011). In the current study, MX/GR and GN treatments showed the highest Fe amounts (Table 4). Granites release high levels of Si, Al, K, Fe, and Mg because of their chemical composition (Cheng et al., 2019; Zhang et al., 2019). However, gneiss might supply Fe through biotite (Santos et al., 2017).

According to the metrics of Guimarães et al. (1999) soil B levels were medium to good, with high Zn, Mn, and Cu levels in all treatments (Table 4). Except for Fe, the interaction between fertilizer treatment × bacteria substantially impacted the soil's micronutrient levels ($p < 0.01$).

The foliar tissue had low Zn (average of 4.51 mg/kg) and high B content (average of 138 mg/kg) while containing adequate amounts of Mn, Fe, and Zn. However, the highest Fe content was observed in soil incorporating mica schist /granite.

Table 4: Micronutrients in *Coffea arabica* Catuaí 144 soil after 126 days of cultivation with rock powder in the absence (-) or presence (+) of bacteria.

Fertilization treatments*	B		Zn		Mn		Cu		Fe
	mg.dm^{-3}								
	(-)	(+)	(-)	(+)	(-)	(+)	(-)	(+)	
ST	0.45 Aa/1	0.37 Aa	19.90 Aa	21.60 Aa	22.05 Ab	15.13 Bb	2.20 Aa	2.47 Aa	76.50 c
ST + KCl	0.37 Aa	0.35 Aa	19.67 Aa	20.40 Aa	18.40 Ab	12.00 Bb	2.23 Ba	2.60 Aa	74.83 c
ST + SL	0.33 Ba	0.43 Aa	17.70 Aa	20.60 Aa	23.67 Ab	26.13 Aa	2.00 Ba	2.43 Aa	85.33 b
ST + BSL	0.43 Aa*	0.37 Aa	17.53 Ba	23.53 Aa	20.90 Bb	25.97 Aa	2.20 Ba	2.77 Aa	96.33 b
ST+ GN	0.35 Aa	0.43 Aa	20.40 Aa	19.17 Aa	28.05 Aa	25.80 Aa	2.25 Aa	2.30 Ab	140.17 a
ST + KM	0.37 Aa	0.43 Aa	19.80 Aa	20.53 Aa	20.40 Ab	23.20 Aa	2.07 Ba	2.47 Ba	77.00 c
ST + PX	0.40 Aa	0.37 Aa	19.30 Aa	18.17 Aa	27.03 Aa	24.27 Aa	2.13 Aa	2.10 Ab	71.33 c
ST + MX/GR	0.43 Aa	0.37 Aa	22.26 Aa	20.37 Aa	21.67 Ab	22.23 Aa	2.50 Aa	2.27 Ab	150.0 a
Absence									89.37 B/2
Presence									103.5A

* ST (control) = standard; SL = slate; BSL = black slate; GN = gneiss; KM = kamafugite; PX = pyroxenite; MX/GR = mica schist/granite; 1/Means followed by the same lowercase letters in the column (isolated effect of the fertilizer treatments) do not differ significantly according to the Scott-Knott test at 5% significance; Means followed by the same uppercase letters in the row (isolated effect of the absence/presence of bacteria) do not differ significantly according to the F test at 5% significance; 2/Different uppercase letters in the column (effect of bacteria) differ significantly according to the F test at 5% significance.

The bacteria added to the coffee plants in this study acted as growth promoters and nutrient solubilizers, as evident due to morphometric, soil, and foliar chemical results. *B. subtilis* and *B. amyloliquefaciens* influence the availability of N, P, Fe, K, Ca, and Mg for plants, particularly in soils containing these elements in insoluble forms (Blake, Christensen & Kovács, 2021; Luo et al., 2022; Liu et al., 2020). Bioavailability mechanisms involve the conversion of complex forms of these nutrients into available forms via the secretion of phosphatases and low-molecular-weight organic acids, volatile organic compounds, ion-exchange reactions in the mineral matrix, and the formation of exopolysaccharides (EPS) to increase microbial populations (Chen et al., 2016; Radhakrishnan, Abeer & Abd-Allah, 2017; Tsotetsi et al., 2022; Wang et al., 2022; Wei et al., 2018).

The effectiveness of the introduced isolates, the formulation, and the soil application method all contribute to the efficacy of PGPB inoculation (Urgiles-Gómez et al., 2021). Thus, reinoculating the bacteria appears critical for their soil stability, as demonstrated in the study. Particle size is another crucial factor influencing the release of nutrients from rock powders. Finely powdered rock is more reactive because the surface area of contact increases as particle size decreases, boosting interaction with the roots and microbiota (Swoboda, Döring, & Hamer, 2022). Every rock powder used in our study had a particle size permitted by the MAPA Normative Instruction (Brasil, 2016).

Rock mineralogy influences soil reactivity and nutrient release. Our study evaluated seven rock powders, each with a unique mineralogical composition and reactivity in the soil. Martins, Martins, and Hardoim (2023) proposed a four-tiered classification of silicate mineral reactivity for use as remineralizers based on biological and chemical reactivity: high chemical and biological reactivity, high biological reactivity, low biological reactivity, and very low. The high and low biological reactivity classes, which include all the rock powders used in this study, are optimum for studying the role of bacteria in releasing nutrients from rock powder.

The incubation period and the gradual release of nutrients are crucial factors to consider when using rock powders. This is particularly beneficial for various reasons, including that progressive release minimizes nutrient losses through leaching and ensures a consistent supply of nutrients to plants. We determined that using nutrient-solubilizing bacteria is a crucial short-term strategy for achieving the desired results.

Conclusions

Nutrient-solubilizing bacteria plus fertilizer improved biomass regardless of the type of rock powder used. Gneiss and kamafugite treatments increased the amount of calcium and magnesium in the soil when bacteria were present while also improving phosphorus availability. The soil containing bacteria and rock powder showed no increase in potassium content. Overall, using rock powder with solubilizing microorganisms optimizes nutrient availability for coffee plants.

Author contributions

Conceptual idea: Rodrigues, T.T.M.S; Rodrigues, A.C.P.S. Methodology design: Rodrigues, T.T.M.S; Rodrigues, A.C.P.S. Data collection: Correa, J.S.; Gusmão Júnior, G.R.; Araújo, D.A.O. Data analysis and interpretation: Brito, O.G.; Correa, J.S.; Gusmão Júnior, G.R.; Araújo, D.A.O.; Rodrigues, T.T.M.S; Rodrigues, A.C.P.S. Writing and editing: Rodrigues, T.T.M.S; Correa, J.S.; Araújo, D.A.O.; Brito, O.G.

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