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Agronomic contributions of the Silicálcio remineralizer in soybean cultivation

Contribuições agronômicas do remineralizador Silicálcio na cultura da soja

Contribuciones agronómicas del remineralizador Silicálcio en el cultivo de soja

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Eliana Paula Fernandes Brasil
Postdoctoral Researcher in Agronomy
Institution: Universidade Federal de Goiás (UFG)
Address: Goiânia, Goiás, Brazil
E-mail: elianafernandes@ufg.br

Adriana Rodolfo da Costa
Ph.D. in Agronomy
Institution: Universidade Estadual de Goiás (UEG)
Address: Santa Helena de Goiás, Goiás, Brazil
E-mail: adriana.costa@ueg.br

Isadora de Lima Araújo
Agronomist Engineer
Institution: Universidade Federal de Goiás (UFG)
Address: Goiânia, Goiás, Brazil
E-mail: isadoraaraujo@discente.ufg.br

Thiago de Godoi Araújo
Agronomist Engineer
Institution: Universidade Federal de Goiás (UFG)
Address: Goiânia, Goiás, Brazil
E-mail: thiagogodoivelgo@ufg.br

Thalles Martins Anastácio
Agronomist Engineer
Institution: Universidade Federal de Goiás (UFG)
Address: Goiânia, Goiás, Brazil
E-mail: thallesmartins@ufg.br

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Pelerson Penido Dalla Vecchia
Businessman
Institution: Grupo Roncador
Address: Rua Harmonia, 1250 – Sala 31 – Vila Madalena, São Paulo – SP, 05435-001, Brazil
E-mail: pelersondalla@gruporoncador.com.br

Carlos Magno Bretas de Oliveira
Institution: Grupo Roncador
Address: Rua T-36, n. 2174 – Setor Bueno, Goiânia – GO, 74223-052, Brazil
E-mail: carlos.oliveira@gruporoncador.com.br

ABSTRACT
High dependence on soluble mineral fertilizers, combined with production costs and environmental concerns, has stimulated the search for more sustainable alternatives for soil fertility management. Soil remineralizers stand out for promoting the gradual release of nutrients and improving soil physical, chemical, and biological attributes. This study evaluated the agronomic effects of a carbonate rock-based remineralizer, referred to as Silicalcio, on soybean (*Glycine max*) crops, considering soil fertility, plant nutritional status, and grain yield. The experiment was conducted under controlled conditions in sandy clay loam and sandy soils using a completely randomized design with eight treatments and four replications. The treatments consisted of rates of Silicalcio (equivalent to 60, 120, 180, 240, and 300 kg ha^{-1} of K_2O), the commercial remineralizer FMX (60 kg ha^{-1} of K_2O), potassium chloride (60 kg ha^{-1} of K_2O), and a control (no application). Plant biometric parameters, leaf K content, residual soil K content, and grain yield were evaluated. The results indicated increases in soil pH, Ca, and Mg contents, cation exchange capacity, and base saturation. Silicalcio had a significant effect on stem diameter, K availability, and grain yield, with values similar to or superior to those of conventional sources under certain conditions. Therefore, the Silicalcio remineralizer has potential to increase soil fertility and contribute to more sustainable production systems, promoting regenerative agriculture in tropical regions.

Keywords: Silicalcio, Soil Fertility, Potassium, *Glycine max*, Agricultural Sustainability, Tropical Soils.

RESUMO
A elevada dependência de fertilizantes minerais solúveis, associada a custos de produção e preocupações ambientais, tem estimulado a busca por alternativas mais sustentáveis para o manejo da fertilidade do solo. Os remineralizadores de solo destacam-se por promover a liberação gradual de nutrientes e por melhorar os atributos físicos, químicos e biológicos do solo. Este estudo avaliou os efeitos agronômicos de um remineralizador à base de rocha carbonática, denominado Silicálcio, na cultura da soja (*Glycine max*), considerando a fertilidade do solo, o estado nutricional das plantas e a produtividade de grãos. O experimento foi conduzido sob condições controladas em solos de textura franco-argiloarenosa e arenosa, utilizando delineamento inteiramente casualizado, com

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oito tratamentos e quatro repetições. Os tratamentos consistiram de doses de Silicálcio (equivalentes a 60, 120, 180, 240 e 300 kg ha^{-1} de K_2O), remineralizador comercial FMX (60 kg ha^{-1} de K_2O), cloreto de potássio (60 kg ha^{-1} de K_2O) e um controle (sem aplicação). Foram avaliados parâmetros biométricos de plantas, teor foliar de K, teor residual de K no solo e produtividade de grãos. Os resultados indicaram aumento do pH do solo, dos teores de Ca e Mg, da capacidade de troca catiônica e da saturação por bases. O Silicálcio teve efeito significativo sobre diâmetro de caule, disponibilidade de K e produtividade de grãos, com desempenho semelhante ou superior às fontes convencionais em determinadas condições. Portanto, o remineralizador Silicálcio apresenta potencial para aumentar a fertilidade do solo e contribuir para sistemas de produção mais sustentáveis, promovendo a agricultura regenerativa em ambientes tropicais.

Palavras-chave: Silicálcio, Fertilidade do Solo, Potássio, *Glycine max*, Sustentabilidade Agrícola, Solos Tropicais.

RESUMEN

La elevada dependencia de fertilizantes minerales solubles, asociada a los costos de La alta dependencia de fertilizantes minerales solubles, junto con los costos de producción y las preocupaciones ambientales, ha impulsado la búsqueda de alternativas más sostenibles para el manejo de la fertilidad del suelo. Los remineralizadores del suelo destacan por promover la liberación gradual de nutrientes y mejorar los atributos físicos, químicos y biológicos del suelo. Este estudio evaluó los efectos agronómicos de un remineralizador a base de roca carbonática, denominado Silicalcio, en el cultivo de soja (*Glycine max*), considerando la fertilidad del suelo, el estado nutricional de las plantas y el rendimiento de grano. El experimento se llevó a cabo en condiciones controladas, en suelos de textura franco arcilloarenosa y arenosa, utilizando un diseño completamente aleatorizado con ocho tratamientos y cuatro repeticiones. Los tratamientos consistieron en dosis de Silicalcio (equivalentes a 60, 120, 180, 240 y 300 kg ha^{-1} de K_2O), el remineralizador comercial FMX (60 kg ha^{-1} de K_2O), cloruro de potasio (60 kg ha^{-1} de K_2O) y un control (sin aplicación). Se evaluaron parámetros biométricos de las plantas, contenido foliar de K, contenido residual de K en el suelo y rendimiento de grano. Los resultados indicaron incrementos en el pH del suelo, los contenidos de Ca y Mg, la capacidad de intercambio catiónico y la saturación de bases. Silicalcio tuvo un efecto significativo sobre el diámetro del tallo, la disponibilidad de K y el rendimiento de grano, con un desempeño similar o superior al de las fuentes convencionales en determinadas condiciones. Por lo tanto, el remineralizador Silicalcio presenta potencial para aumentar la fertilidad del suelo y contribuir a sistemas de producción más sostenibles, promoviendo la agricultura regenerativa en regiones tropicales.

Palabras clave: Silicálcio, Fertilidad del Suelo, Potasio, *Glycine max*, Sostenibilidad Agrícola, Suelos Tropicales.

1 INTRODUCTION

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The growing intensification of agriculture and the high reliance on soluble mineral fertilizers have increased production costs and the economic vulnerability of agricultural systems, especially in tropical countries heavily dependent on imports, such as Brazil (Farias *et al*., 2020). The volatility of international input prices, combined with environmental concerns regarding the production and excessive use of conventional fertilizers, has stimulated the search for sustainable alternatives. In this context, the use of soil remineralizers has been widely discussed as a promising strategy for the gradual supply of nutrients and for promoting sustainable agricultural systems in tropical regions (Manning; Theodoro, 2023; Beerling *et al*., 2022). Novel soil remineralizers obtained from ground sedimentary carbonate rocks can potentially increase soil fertility and improve soybean nutrition.

Soybean (*Glycine max* L.) is one of the primary crops in Brazilian agriculture and one of the most important worldwide. Soybean production positively impacts the socioeconomic development of Brazil and is highly dependent on soil fertility to express its yield potential. Studies have reported that the application of soil remineralizers can contribute to the supply of macro- and micronutrients and promote improvements in soil chemical attributes, such as pH, cation exchange capacity, and base saturation, with positive effects on the development and yield of agricultural species cultivated in highly weathered soils (Ramos *et al*., 2021; Medeiros *et al*., 2021; Silva *et al*., 2022).

The effects of soil remineralizers on soybean cultivation still show variable responses due to factors such as rock mineralogy, material particle size, application rates, and edaphoclimatic conditions. Studies conducted in tropical environments have indicated that the slow release of nutrients requires medium- and long-term evaluations and appropriate experimental methodologies for the accurate interpretation and comparison of results with those from conventional soil fertilization systems (Almeida *et al*., 2022; Santos *et al*., 2023).

The application of soil remineralizers has relevant economic implications, especially due to the possibility of using regional mineral sources and mining by-products. Partial replacement of soluble fertilizers with soil remineralizers can reduce production

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costs and dependence on imported inputs while strengthening local production chains. This approach contributes to the economic and environmental resilience of agricultural systems, particularly in large-scale crops such as soybean (Manning *et al*., 2022; Silva and Lopes, 2024).

In this context, deepening the understanding of the agronomic and productive effects of remineralizers in soybean cropping systems in Brazil is essential, especially in soils of the Cerrado biome, for the development of more sustainable, efficient, and economically viable management strategies for tropical agriculture (Souza *et al*., 2023).

This study evaluated the agronomic effects of a carbonate rock-based remineralizer, referred to as Silicalcio, on soybean crops based on soil fertility, plant nutritional status, and grain yield.

2 THEORETICAL FRAMEWORK

2.1 RESEARCH ON SOIL REMINERALIZERS

The use of soil remineralizers has gained prominence as a sustainable alternative in Brazil, contributing to reduced dependence on imported fertilizers and improved fertility in tropical soils. This strategy is aligned with the Brazilian National Fertilizer Plan 2050.

These inputs were regulated by Law No. 12.890/2013, complemented by Normative Instructions No. 5 and No. 6/2016 of the Ministry of Agriculture and Livestock (MAPA), which establish technical criteria for registration and use. Remineralizers are mineralderived material subjected to physical processing; they can gradually release nutrients while improving the chemical, physical, and biological attributes of the soil.

The practice of applying rock powder has been extensively studied, particularly with materials such as basalt and phonolite, which are rich in macro- and micronutrients. These materials promote slow nutrient release and exert positive residual residual effects, such as increased fertility and improved soil structure (Souza *et al*., 2022; Van Straaten, 2023).

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Beyond their agronomic benefits, these remineralizers offer environmental and economic advantages, such as the use of mineral waste and reduced dependence on external inputs (Machado *et al*., 2023; Alovisi *et al*., 2024). Evidence of their contribution to soil carbon sequestration through enhanced weathering has also been documented (Guelfi-Silva *et al*., 2024).

However, their effectiveness depends on factors such as mineralogical composition, particle size, and edaphoclimatic conditions, which require careful application management and soil monitoring.

2.2 SOYBEAN

Soybean is one of the primary crops of Brazilian agribusiness and is fundamental to the national economy due to its high volume of production and export. In recent years, Brazil has consolidated its position as the largest producer and one of the main global exporters of soybean because of agricultural expansion, investments in technology, and increased production efficiency.

Despite its significant performance, soybean cultivation faces structural challenges, mainly related to nutritional management. The Brazilian production model is heavily dependent on imported mineral fertilizers, especially those based on phosphorus and potassium, which are essential nutrients for the proper development of this legume. In 2024, fertilizer imports in the country reached 44.3 million Mg, an 8.3% increase over the previous year (Conab, 2025). This dependence highlights the vulnerability of the agricultural system to international market fluctuations, high costs, and logistical risks, underscoring the need for strategies to reduce it and enhance sustainability.

The application of readily soluble, fast-release fertilizers, such as potassium chloride (KCl), predominates in the conventional nutritional management of soybean. Although effective, these inputs present limitations, including low agronomic efficiency due to leaching losses and rising costs for producers. Consequently, interest in sustainable alternatives that promote greater productive autonomy, reduce environmental impacts,

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and maintain high yields has grown. In this context, conservation management practices and the use of bioinputs and remineralizers have gained prominence.

Rock powders release nutrients gradually, with productive performance compatible with that obtained using soluble fertilizers (Brasil *et al*., 2023). Similarly, evaluations with the remineralizer Rekal showed grain yield equivalent to that obtained with potassium chloride, reinforcing the viability of applying rock powders as a nutritional management strategy for soybean (Brasil *et al*., 2025). These results strengthen the understanding that remineralizers can not only nourish the crop but also improve the soil over time, thereby contributing to more resilient and sustainable agricultural systems.

Despite these advances, scientific gaps remain regarding the use of soil remineralizers, particularly concerning the mechanisms of action of these materials under different edaphoclimatic conditions, their interaction with soil attributes, and long-term productive responses. Therefore, further research is needed on application rates and methods, as well as the mineralogical characteristics of the rocks used, to consolidate the use of these inputs in modern agriculture.

In this context and given the economic importance of soybean cultivation in Brazil, the challenges associated with its production require alternatives to the current soil fertilization model. A promising alternative is the use of soil remineralizers, which can gradually release nutrients and have the potential to promote the reduction of dependence on imported synthetic fertilizers.

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3 METHODOLOGY

The study was conducted under controlled conditions in a greenhouse located at (16°40'22"S, 49°15'19"W; average altitude of 730 m). The region has a mean temperature of 21 °C, with maximum and minimum temperatures of 29 °C and 15 °C, respectively, a mean annual relative humidity of 41.5%, a mean annual rainfall of 1,487.2 mm, and total annual sunshine duration of 2,645.7 h.

Two experiments were implemented using 9-L pots (0.009 m^3) filled with a sandy soil from Piranhas, Goiás, or a sandy clay loam soil from Goiânia, Goiás. Soil samples were air-dried, crushed, sieved through a 2-mm mesh, and subjected to chemical analysis for initial fertility characterization. The results indicated that the soils had low natural fertility, low pH, and low levels of phosphorus, potassium, calcium, and magnesium, as well as low cation exchange capacity and base saturation, which are characteristics typical of highly weathered soils from the Brazilian Cerrado biome.

The tested soil remineralizer, referred to as Silicalcio, was derived from ground sedimentary carbonate rocks. The product was supplied by a Brazilian company specializing in the mining and processing of limestone and dolomite, Calcário Vale do Araguaia – Mineração Taquari, a company belonging to the Roncador Group, located on the MT-250 highway, in the municipality of Nova Xavantina, Mato Grosso, Brazil. The recommended rate for soybean cultivation is equivalent to 60 kg ha^{-1} of K_2O. Potassium fertilizers were also used: a commercial rock powder remineralizer (FMX) registered with MAPA, and a soluble source of potassium chloride (KCl).

A completely randomized experimental design was used, with eight treatments and four replications. The treatments consisted of a control (no fertilizer application; T1), the Silicalcio remineralizer applied at increasing rates equivalent to 60, 120, 180, 240, and 300 kg ha^{-1} of K_2O (T2 to T6), the FMX remineralizer at the equivalent rate of 60 kg ha^{-1} of K_2O (T7), and a soluble source (potassium chloride – KCl) at 60 kg ha^{-1} of K_2O (T8).

Water was supplied uniformly across all treatments by an automated microsprinkler irrigation system to maintain soil moisture near field capacity throughout

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the soybean crop cycle. No other potassium source was applied during the experiment to isolate the effects of the evaluated sources. The remaining nutrients were supplied according to crop requirements to avoid nutritional limitations that could interfere with the results.

The following parameters were evaluated during the crop cycle: plant height, stem diameter at the collar, leaf potassium (k) content, residual soil K content, and grain yield. Plant height and stem diameter were measured at the reproductive stage with a graduated ruler and a digital caliper, respectively. Leaf samples for nutritional analysis were collected at the R1 to R2 reproductive stages; the plant material was dried, ground, and analyzed to determine K content following standard methodology. Soybean grain yield was determined as the mass of grains harvested per experimental unit, with values extrapolated to kg ha^{-1}. Soil samples were collected from each experimental unit at the end of the experiments to determine residual K contents and other chemical attributes following the methods recommended for soil fertility analysis.

The data were subjected to analysis of variance (ANOVA) at the 5% probability level. Means showing significant differences among potassium source treatments were compared using Tukey's test at the 5% level. Silicalcio rates were analyzed using regression analysis. All statistical procedures were performed using SISVAR software (Ferreira, 2019).

4 RESULTS AND DISCUSSION

4.1 RESPONSES OF SOYBEAN PLANTS GROWN IN A SANDY CLAY LOAM SOIL UNDER APPLICATION OF THE SILICALCIO REMINERALIZER

The initial sample (collected before the experiment) for the sandy clay loam soil showed pH 5.6 and low values of calcium (Ca), magnesium (Mg), phosphorus (P), potassium (K), cation exchange capacity (CEC), and base saturation (Table 1) according to Lobato and Souza (2004).

Soil pH ranged from 5.6 (initial sample) to 6.2 after application of the treatments

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(Table 1); these levels are considered adequate according to Lobato and Sousa (2004). The Ca levels were adequate in all treatments, ranging from 23 to 50 cmolc dm−3, and for Mg the values ranged from 0.8 to 1.7, where treatments T2, T3, T4, T5 and T6 presented high values and treatments T7 and T8 average values, according to Embrapa (2026). CEC showed the same pattern, with moderate levels ranging from 4.45 to 7.60 $cmol_c\ dm^{-3}$ in treatments T2 to T8 and a low level (3.11) in the control.

Table 1. Cation exchange capacity (CEC), magnesium (Mg) content, calcium (Ca) content, and pH in a sandy clay loam soil before the experiment and after application of different potassium (K) rates and sources to soybean crops. Goiânia, Goiás, Brazil.

Treatment (T)	pH ($CaCl_2$)	Ca ($cmol_c\ dm^{-3}$)	Mg ($cmol_c\ dm^{-3}$)	CEC ($cmol_c\ dm^{-3}$)
Initial sample	5.6	0.3	0.2	2.8
T1 (control)	5.4	1.2	0.4	3.11
T2	5.8	3.3	1.2	6.09
T3	6.0	4.5	1.5	7.24
T4	6.2	4.7	1.7	7.50
T5	6.2	5.0	1.4	7.60
T6	6.2	4.7	1.6	7.42
T7	6.1	2.3	0.8	4.45
T8	6.2	2.7	0.8	4.79

Source: Authors. Initial sample = soil sample before the experiment implementation; T1 = control (no application); T2 to T6 = Silicalcio remineralizer applied at increasing rates equivalent to 60, 120, 180, 240, and 300 kg ha^{-1} of K_2O, respectively; T7 = FMX remineralizer applied at 60 kg ha^{-1} of K_2O; and T8 = soluble potassium chloride (KCl) applied at 60 kg ha^{-1} of K_2O.

Soil fertility analysis of samples from the sandy clay loam soil with soybean revealed low P contents in the initial sample and the control but adequate contents in treatments with K sources (T2 to T8) (Table 2). K contents were moderate in the control and in treatments T2, T4, T5, and T6 (40 to 46 mg dm^{-3}) and adequate in T3, T7, and T8 (56 to 98 mg dm^{-3}) according to Lobato and Sousa (2004).

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Table 2. P content, K content, and base saturation in a sandy clay loam soil before the experiment and after application of different potassium (K) rates and sources to soybean crops. Goiânia, Goiás, Brazil.

Treatment (T)	P (mg dm^{-3})	K (mg dm^{-3})	Base saturation (%)
Initial sample	1.2	24.0	20.0
T1 (control)	1.2	44.0	55.0
T2	150.0	34.0	75.0
T3	170.0	56.0	85.0
T4	150.0	40.0	87.0
T5	170.0	40.0	86.0
T6	180.0	46.0	87.0
T7	170.0	98.0	74.0
T8	180.0	76.0	77.0

Source: Authors. Phosphorus (P) was extracted using the Mehlich-1 method; Initial sample = soil sample before the experiment implementation; T1 = control (no application); T2 to T6 = Silicalcio remineralizer applied at increasing rates equivalent to 60, 120, 180, 240, and 300 kg ha^{-1} of K_2O, respectively; T7 = FMX remineralizer applied at 60 kg ha^{-1} of K_2O; and T8 = soluble potassium chloride (KCl) applied at 60 kg ha^{-1} of K_2O.

Application of increasing rates of the Silicalcio remineralizer (T2 to T6) resulted in increases in base saturation (Table 2), with values ranging from 55% (control) to 87% (T4 and T6). Treatments with the FMX remineralizer (T7) and KCl (T8) showed base saturation of 74% and 77%, respectively, which fall within the range considered adequate for most agricultural crops according to Lobato and Sousa (2004).

Significant differences were observed among treatments in the sandy clay loam soil for stem diameter, leaf K and residual soik K contents, and grain yield (Table 3).

Table 3. Mean squares from the analysis of variance for plant height, stem diameter, leaf K content, residual soil K content, and grain yield for soybean grown in a sandy clay loam soil as affected by different K sources. Goiânia, Goiás, Brazil.

Source of variation	DF	Plant height (cm)	Stem diameter (cm)	Leaf K (g kg^{-1})	Residual soil K (mg dm^{-3})	Grain yield (kg ha^{-1})
K source	3	71.37^{ns}	2.68*	18.55*	4.258.64*	272.192.81*
Error	16	45.42	0.40	2.75	32.44	72.243.28
Total	19					
CV (%)	—	16.50	16.61	13.06	9.20	12.27

Source: Authors. DF = degrees of freedom; CV = coefficient of variation; * = significant at the 5% level; ns = not significant.

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Plant height did not differ significantly among treatments, with the lowest value (36.88 cm) recorded in the control and the highest (45.76 cm) in treatments with Silicalcio (Table 4). Almeida Júnior *et al*. (2020) reported no significant differences in technological variables of soybean plants (plant population, plant height, first pod insertion height, number of branches, and number of one-grain pods), y*et al*l tested agronomic characteristics remained at high levels and grain yield was above the national average; these results are consistent with those reported by Almeida Júnior (2022). According to Ferreira (2024), plant height showed no significant differences across both evaluated soil textures (medium CXbd and clayey LVd) or among rates of the Completo remineralizer and the control with the Ekosil remineralizer.

Larger stem diameters were observed in treatments with K sources: 4.22 mm for Silicalcio rates, 3.98 mm for FMX remineralizer, and 4.28 mm for soluble potassium chloride (KCl); these values differed significantly from the control (2.72 mm) (Table 4). Alovisi *et al*. (2020) evaluated a basalt powder based-remineralizer in soybean crops under field conditions and reported a maximum stem diameter of 7.9 mm at an estimated basalt powder rate of 2.54 Mg ha^{-1}.

Table 4. Biometric parameters of soybean plants grown in a sandy clay loam soil subjected to treatments with different potassium (K) sources. Goiânia, Goiás, Brazil.

K source	Plant height	Stem diameter
	cm	mm
Control (no application)	36.88 a	2.72 b
Remineralizer (Silicalcio)	45.76 a	4.22 a
Remineralizer (FMX)	39.26 a	3.98 a
Potassium chloride (KCl)	41.50 a	4.28 a

Source: Authors. Silicalcio remineralizer was applied at increasing rates equivalent to 60, 120, 180, 240, and 300 kg ha^{-1} of K_2O); FMX remineralizer and soluble potassium chloride were applied at 60 kg ha^{-1} of K_2O. Means followed by the same letter in a column do not differ significantly according to Tukey's test at the 5% level.

Residual soil K content differed significantly among K sources, with the lowest value (32.50 mg dm^{-3}, corresponding to 0.08 $cmol_c$ dm^{-3}) recorded for Silicalcio treatments and the highest (98.00 mg dm^{-3}, corresponding to 0.25 $cmol_c$ dm^{-3}) recorded for the FMX remineralizer treatment (Table 5).

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Souza *et al*. (2017) evaluated a biotite gneiss-based remineralizer and reported a maximum K availability of 0.16 $cmol_c\ dm^{-3}$ at a rate equivalent to 300 mg kg^{-1} of K. This value is more than double the content corresponding to the readily available K reserve in the soil under liming (0.07 $cmol_c\ dm^{-3}$) and approximately 30% of the content made available by the application of soluble potassium chloride (0.52 $cmol_c\ dm^{-3}$).

According to Sousa and Lobato (1996), moderate K contents range from 0.06 to 0.13 $cmol_c\ dm^{-3}$ for soils with clay content higher than 200 g kg^{-1}. The Silicalcio remineralizer evaluated in the present study significantly increased nutrient supply and improved soil fertility.

The treatments differed significantly in grain yield. The treatment with Silicalcio showed the highest mean (2,449.50 kg ha^{-1}) and differed significantly from the other treatments. The treatment with KCl showed the lowest mean grain yield (1,912.50 kg ha^{-1}). The control (2,104.50 kg ha^{-1}) and the treatment with the FMX remineralizer (2,298.00 kg ha^{-1}) did not differ significantly from each other, showing intermediate means.

Therefore, the remineralizer sources (Silicalcio and FMX) resulted in mean grain yields higher than or similar to that of the control and higher than that of the KCl source (Table 5).

Table 5. Leaf K content, residual soil K content, and grain yield for soybean plants grown in a sandy clay loam soil subjected to different potassium (K) sources. Goiânia, Goiás, Brazil.

K source	Leaf K (g kg^{-1})	Residual soil K (mg dm^{-3})	Grain yield (kg ha^{-1})
Control (no application)	14.20 a	45.00 c	2.104.50 ab
Remineralizer (Silicalcio)	14.50 a	32.50 d	2.449.50 a
Remineralizer (FMX)	10.90 b	98.00 a	2.298.00 ab
Potassium chloride (KCl)	11.15 b	72.00 b	1.912.50 b

Source: Authors. Silicalcio remineralizer was applied at increasing rates equivalent to 60, 120, 180, 240, and 300 kg ha^{-1} of K_2O); FMX remineralizer and soluble potassium chloride were applied at 60 kg ha^{-1} of K_2O. Means followed by the same letter in a column do not differ significantly according to Tukey's test at the 5% level.

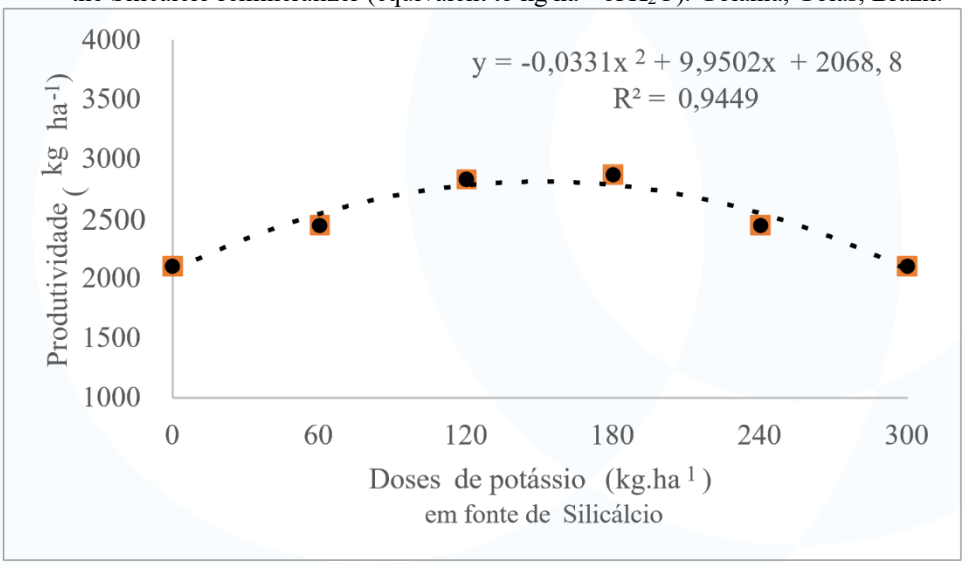
The average soybean yield in Brazil has varied across recent crop seasons. In the 2021 crop season, the average yield was 3,462 kg ha^{-1}, while the most recent estimates

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for the 2025/26 crop season indicate an average yield of 3,675 kg ha^{-1} according to the latest survey report of the Companhia Nacional de Abastecimento (CONAB, 2025).

The highest grain yield (2,871.0 kg ha^{-1}) as affected by increasing rates of Silicalcio was obtained at rate equivalent to 180 kg ha^{-1} of K_2O (Figure 1). Almeida Júnior *et al*. (2022) reported that the use of a mica-schist-based remineralizer in soybean crops in the Central-West region of Brazil resulted in the highest yield (3,614 kg ha^{-1}) at an application rate of 16.0 Mg ha^{-1}.

Figure 1. Grain yield of soybean plants grown in a sandy clay loam soil as affected by increasing rates of the Silicalcio remineralizer (equivalent to kg ha^{-1} of K_2O). Goiânia, Goiás, Brazil.



Source: Authors

4.2 RESPONSES OF SOYBEAN PLANTS GROWN IN A SANDY SOIL UNDER APPLICATION OF THE SILICALCIO REMINERALIZER

The initial sample (collected before the experiment) for the sandy soil showed pH 4.9, low levels of Ca, Mg, and CEC, very low P content, moderate K content, and low base saturation (Table 6) according to Lobato and Sousa (2004).

Soil pH value varied from 4.9 (initial sample) to 5.2 (control) and from 5.5 to 6.1 for treatments with K sources (Table 6). Ca and Mg contents were adequate in treatments T1 to T8, respectively, and low in the control (Lobato and Sousa, 2004). The lowest CEC

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was observed in the initial sample, followed by that in T8. Treatments T1, T2, T3, T4, and T7 showed moderate CEC values, while T5 and T6 showed the highest values, which were considered adequate.

Table 6. Cation exchange capacity (CEC), magnesium (Mg) content, calcium (Ca) content, and pH in a sandy soil before the experiment and after application of different potassium (K) rates and sources to soybean crops. Goiânia, Goiás, Brazil.

Treatments (T)	pH ($CaCl_2$)	Ca ($cmol_c\ dm^{-3}$)	Mg ($cmol_c\ dm^{-3}$)	CEC ($cmol_c\ dm^{-3}$)
Initial sample	4.9	0.9	0.3	2.75
T1 (control)	5.2	2.1	0.6	4.43
T2	5.8	3.5	1.3	6.85
T3	5.9	4.0	1.3	7.45
T4	6.0	4.9	1.4	7.39
T5	6.1	4.8	1.8	8.06
T6	6.1	5.2	1.8	8.06
T7	5.9	2.4	0.8	7.86
T8	5.5	0.8	0.5	3.94

Source: Authors. Initial sample = soil sample before the experiment implementation; T1 = control (no application); T2 to T6 = Silicalcio remineralizer applied at increasing rates equivalent to 60, 120, 180, 240, and 300 kg ha^{-1} of K_2O, respectively; T7 = FMX remineralizer applied at 60 kg ha^{-1} of K_2O; and T8 = soluble potassium chloride (KCl) applied at 60 kg ha^{-1} of K_2O.

Base saturation ranged from 78% to 87% with increasing Silicalcio rates (T2 to T6), while soil pH ranged from 5.8 to 6.1. Toscani and Campos (2017) reported that the application of rock powder without liming significantly increased base saturation in an Oxisol compared to the control, with values ranging from 36% to 63% and a mean of 51.25%.

Table 7. Phosphorus (P) content, potassium (K) content, and base saturation (%) in a sandy soil before the experiment and after application of different potassium (K) rates and sources to soybean crops. Goiânia, Goiás, Brazil.

Treatments (T)	P ($mg\ dm^{-3}$)	K ($mg\ dm^{-3}$)	Base saturation (%)
Initial sample	5.0	18	46
T1 (control)	6.0	50	64
T2	80.0	24	78
T3	47.0	20	83
T4	39.0	34	85
T5	75.0	30	87
T6	75.0	24	87
T7	78.0	20	76

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T8	52.0	56	63

Source: Authors. Phosphorus (P) was extracted using the Mehlich-1 method; Initial sample = soil sample before the experiment implementation; T1 = control (no application); T2 to T6 = Silicalcio remineralizer applied at increasing rates equivalent to 60, 120, 180, 240, and 300 kg ha^{-1} of K_2O, respectively; T7 = FMX remineralizer applied at 60 kg ha^{-1} of K_2O; and T8 = soluble potassium chloride (KCl) applied at 60 kg ha^{-1} of K_2O.

P contents were low in the initial sample (5 mg dm^{-3}) and in the control (6 mg dm^{-3}) (Table 7). The other treatments showed P contents higher than 18 mg dm^{-3} and were classified as high, indicating adequate P availability for soybean grown in sandy soils.

Low K contents were observed in the initial sample (18 mg dm^{-3}) and in T2 to T7 (values lower than 40 mg dm^{-3}). The control (50 mg dm^{-3}) and T8 (56 mg dm^{-3}) were classified as moderate for sandy soils. No K contents were classified as high in the evaluated samples.

Significant differences were observed among treatments in the sandy soil for plant height, stem diameter, Leaf K and residual soil K contents, and grain yield (Table 8).

Table 8. Mean squares from the analysis of variance for plant height, stem diameter, leaf K content, residual soil K content, and grain yield for soybean grown in a sandy soil as affected by different K sources. Goiânia, Goiás, Brazil.

Source of variation	DF	Plant height (cm)	Stem diameter (cm)	Leaf K (g kg^{-1})	Residual soil K (mg dm^{-3})	Grain yield (kg ha^{-1})
K sources	3	609.12*	32.25*	127.70*	3085.42*	2030884.45*
Error	16	13.09	0.80	2.77	288.12	44.599.36
Total	19				—	—
CV (%)		7.06	13.34	8.66	40.18	7.18

Source: Authors. DF = degrees of freedom; CV = coefficient of variation; * = significant at 5%; ns = not significant.

Plant height of soybean grown in the sandy soil was greater in treatments with Silicalcio (60.5 cm) and differed significantly from treatments with the FMX remineralizer (56.5 cm) and KCl (52.6 cm).

Treatments with K sources exhibited larger stem diameters than the control (2,92 mm) and did not differ significantly from each other, with values ranging from 7.7 to 8.20 mm (Table 9).

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Leaf K contents in soybean differed significantly among treatments with K sources, with the highest value recorded for KCl (25.10 g kg^{-1}), an intermediate value for the FMX remineralizer (21.6 g kg^{-1}), and the lowest value for the Silicalcio remineralizer (15.88 g kg^{-1}) (Table 10).

Adequate K content in plants regulates stomatal opening and closing and thereby supports the photosynthetic process, stimulating greater production of photoassimilates and, consequently, improving vegetative and reproductive development (Novais *et al*., 2007). Potassium is one of the main chemical elements required by soybean plants and occurs in low concentrations in Brazilian tropical soils, yet it exerts a direct effect on grain yield, as well as proteins and oil contents (Lima *et al*., 2017). In physiological terms, the main functions of K are related to the activation of enzymatic systems involved in respiration and photosynthesis (Taiz *et al*., 2017). Potassium application to soils is fundamental not only to increase yield but also for plant health management in several crops (Gabriel *et al*., 2016).

This nutrient is fundamental for plant growth and metabolism because it activates more than 50 enzymatic reactions (Borin *et al*., 2017). These results can be attributed to the influence of K on metabolic processes such as photosynthesis and the translocation of photoassimilates (Júlio *et al*., 2016).

Among treatments with K sources in the sandy soil, the highest residual soil K content was observed for KCl (63 mg dm^{-3}), followed by the Silicalcio (21.5 mg dm^{-3}) and FMX (20 mg dm^{-3}) remineralizer treatments (Table 10). K is present in the soil solution as K^+ and its absorption can be affected by the concentrations of Ca^{2+} and Mg^{2+} due to competitive inhibition, as these cations compete for the same binding site in the plant. The main forms of this nutrient in soil are primary minerals such as feldspar, muscovite, and biotite. Availability of K increases with rising soil pH because of the greater number of negative on soil colloids (Duarte, 2019).

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Table 10. Leaf K content, residual soil K content, and crop yield for soybean plants grown in a sandy soil subjected to different potassium (K) sources. Goiânia, Goiás, Brazil.

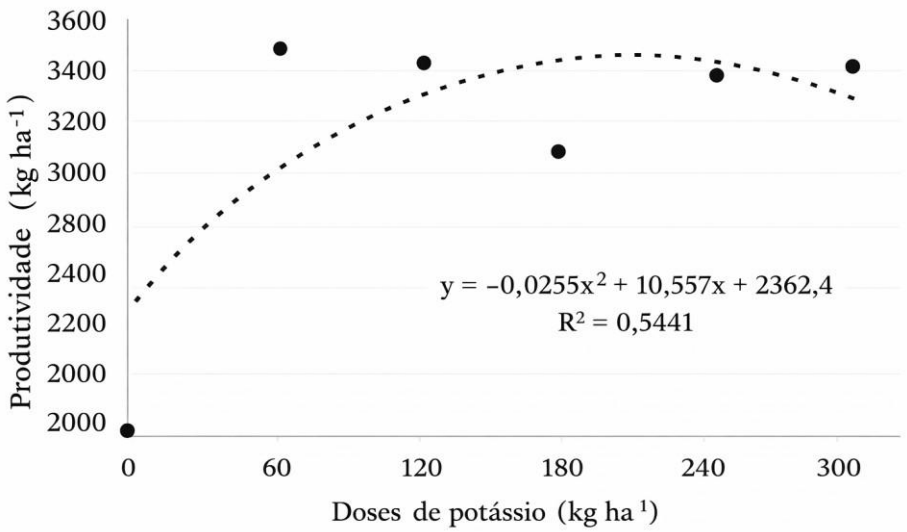
K sources	Leaf K g kg^{-1}	Soil K mg dm^{-3}	Grain yield kg ha^{-1}
Control (no application)	14.20 c	64.55 a	2.027.25 b
Soil remineralizer (Silicalcio)	15.88 c	21.50 b	3.469.50 a
Soil remineralizer (FMX)	21.60 b	20.00 b	3.253.50 a
Potassium chloride (KCl)	25.10 a	63.00 a	3.022.50 a

Source: Authors. Silicalcio remineralizer was applied at increasing rates (equivalent to 60, 120, 180, 240, and 300 kg ha^{-1} of K_2O); FMX remineralizer and soluble potassium chloride were applied at 60 kg ha^{-1} of K_2O. Means followed by the same letter in a column do not differ significantly according to Tukey's test at the 5% level.

K occurs as K^+ both in the soil solution and in the plant; therefore, its availability is regulated by cation exchange capacity (CEC), with low-CEC soils being more prone to leaching losses. The dynamics of this nutrient are complex, which prevents straightforward interpretations without proper understanding of the system, including quantification of losses to estimate the amount required for compensation (Semler *et al*., 2022).

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Figure 2. Grain yield of soybean plants grown in a sandy soil as affected by increasing rates of the Silicalcio remineralizer (equivalent to kg ha^{-1} of K_2O). Goiânia, Goiás, Brazil.



Source: Authors.

Grain yield did not differ significantly among treatments with K sources in the sandy soil, with values ranging from 3.022,50 kg ha^{-1} (KCl) to 3.469,50 kg ha^{-1} (Silicalcio); the lowest yield was recorded for the control (2.027,25 kg ha^{-1}) (Table 10).

A grain yield of 3,405 kg ha^{-1} was obtained with Silicalcio rates equivalent to 120 and 300 kg ha^{-1} of K_2O (Figure 2).

According to Pereira (2016), the average soybean yield in Brazil has increased significantly over the the last three decades owing to the generation, adaptation, and transfer of technologies. Soybean yield depends on the genetic characteristics of the cultivar, management practices, environmental conditions, and the interactions among these factors.

5 CONCLUSIONS

Application of increasing rates of the Silicalcio remineralizer, derived from ground sedimentary carbonate rock powder, increased pH in both the sandy clay loam

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and sandy soils evaluated, along with increases in Ca and Mg contents, cation exchange capacity, and base saturation.

The Silicalcio remineralizer significantly increased stem diameter in both soils. This remineralizer promoted higher grain yields than the control and did not differ significantly from the FMX remineralizer.

The results confirm that the Silicalcio remineralizer improves soil chemical attributes and the agronomic performance of soybean crops.

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REFERENCES

ALMEIDA JÚNIOR, J. J.; LAZARINI, E.; SMILJANIC, K. B. A.; SIMON, G. A.; MATOS, F. S. A.; BARBOSA, U. R.; SILVA, V. J. A.; MIRANDA, B. C.; SILVA, A. R. Análise das variáveis tecnológicas na cultura da soja (*Glycine max*) com utilização de remineralizador de solo como fertilizante. **Brazilian Journal of Development**, Curitiba, v. 6, n. 8, p. 56835–56847, ago. 2020. Disponível em: https://www.brazilianjournals.com/index.php/BRJD/article/view/14784. Acesso em: 15 nov. 2020.

ALMEIDA, F. *et al*. Avaliação da fertilidade do solo sob sistemas de produção agrícola no Cerrado brasileiro. **Revista Brasileira de Ciência do Solo**, v. 46, e022023004, 2022. DOI: 10.36783/18069657rbcs.v46.10247.

ALMEIDA, L. S. *et al*. Remineralizadores de solo: eficiência agronômica em ambientes tropicais. **Revista Brasileira de Ciência do Solo**, 2022. DOI: https://doi.org/10.36783/18069657rbcs20210155.

ALOVISI, A. M. T. *et al*. Remineralizers and soil health in tropical agriculture. **Sustainability**, v. 16, 2024. DOI: https://doi.org/10.3390/su16010045.

BEERLING, D. J. *et al*. Potential for large-scale CO_2 removal via enhanced rock weathering with croplands. **Nature**, 2022. DOI: https://doi.org/10.1038/s41586-020-2448-9.

BORIN, A. L. C. **Rochagem como fonte alternativa de nutrientes para culturas agrícolas**. 2017. Dissertação (Mestrado em Agronomia) – Universidade Federal de Uberlândia, Uberlândia, 2017. Disponível em: https://repositorio.ufu.br/handle/123456789/19834.

BRASIL, E. C. *et al*. Potassium fertilization with rock powders in soybean. **Pesquisa Agropecuária Brasileira**, 2023. DOI: https://doi.org/10.1590/S1678-3921.pab2023.v58.02811.

BRASIL, E. C. *et al*. Uso de remineralizadores na cultura da soja: produtividade e atributos do solo. **Revista de Ciências Agrárias**, 2025. Disponível em: https://seer.sct.embrapa.br/index.php/rca.

BRASIL. Instrução Normativa MAPA nº 5, de 10 de março de 2016. Estabelece critérios para registro, comercialização e características mínimas dos remineralizadores de solo. Brasília, DF: Ministério da Agricultura, Pecuária e Abastecimento, 2016.

COMPANHIA NACIONAL DE ABASTECIMENTO (CONAB). **1º Levantamento da Safra de Grãos 2025/26**. Portal Gov.br, 14 out. 2025. Disponível em: https://www.gov.br/conab/pt-br/assuntos/noticias/primeiro-levantamento-da-conabaponta-para-uma-colheita-de-354-7-milhoes-de-toneladas-de-graos-na-safra-2025-26. Acesso em: 26 fev. 2026.

ISSN: 1696-8352

DUARTE, A. P.; PEREIRA FILHO, I. A. Effect of guano-based fertilizers on soil nutrient dynamics and crop yield. **Agriculture, Ecosystems & Environment**, v. 287, 106671, 2019. DOI: 10.1016/j.agee.2019.106671.

EMBRAPA. **Análise de solo**. Agência de Informação Tecnológica, 2025. Disponível em: https://www.embrapa.br/agencia-de-informacao-tecnologica. Acesso em: 15 abr. 2024.

FERREIRA, M. **Efeito residual de remineralizador como fonte de potássio na cultura da soja**. 2024. 31 p. Trabalho de Conclusão de Curso (Graduação em Agronomia) – Universidade Federal de Uberlândia, Monte Carmelo, MG, 2024.

GABRIEL, J. L. *et al*. Impact of tillage and crop residue on soil physical and chemical properties. **Soil & Tillage Research**, v. 160, p. 23–32, 2016. DOI: 10.1016/j.still.2016.02.010.

GUELFI-SILVA, D. R. *et al*. Enhanced weathering and carbon sequestration in tropical soils. **Geoderma**, 2024. DOI: https://doi.org/10.1016/j.geoderma.2023.116870.

JULIO, L. F. *et al*. Temporal changes in soil acidity and exchangeable Al under liming treatments. **Geoderma**, v. 276, p. 85–94, 2016. DOI: 10.1016/j.geoderma.2016.03.014.

LIMA, R. C. M.; STAMFORD, N. P.; ROSÁLIA, C. E.; SANTOS, S.; DIAS, S. H. L. R. Rendimento da alface e atributos químicos de um Latossolo em função da aplicação de biofertilizantes de rochas com fósforo e potássio. **Horticultura Brasileira**, v. 25, n. 2, p. 224–229, 2007.

LOBATO, E.; SOUSA, D. M. G. **Cerrado: correção do solo e adubação**. 2. ed. Brasília, DF: Embrapa Informação Tecnológica; Planaltina, DF: Embrapa Cerrados, 2004.

MACHADO, R. V. *et al*. Soil remineralizers: agronomic and environmental perspectives. **Agronomy**, 2023. DOI: https://doi.org/10.3390/agronomy13020567.

MANNING, D. A. C. *et al*. Global potential of enhanced weathering in agriculture. **Philosophical Transactions of the Royal Society A**, 2022. DOI: https://doi.org/10.1098/rsta.2021.0149.

MANNING, D. A. C.; THEODORO, S. H. Enabling food security through use of local rocks and minerals. **The Extractive Industries and Society**, 2023. DOI: https://doi.org/10.1016/j.exis.2022.101065.

MEDEIROS, D. S.; SANCHOTENE, D. M.; RAMOS, C. G.; OLIVEIRA, L. F. S.; SAMPAIO, C. H.; KAUTZMANN, R. M. Soybean crops cultivated with dacite rock by-product: a proof of a cleaner technology to soil remineralization. **Journal of Environmental Chemical Engineering**, v. 9, 106742, 2021. DOI: https://doi.org/10.1016/j.jece.2021.106742.

ISSN: 1696-8352

MEDEIROS, J. C. *et al*. Soil remineralization and its effects on chemical attributes. **Revista Brasileira de Engenharia Agrícola e Ambiental**, 2021. DOI: https://doi.org/10.1590/1807-1929/agriambi.v25n3p193-199.

NOVAIS, R. F. *et al*. **Fertilidade do solo**. Viçosa: Sociedade Brasileira de Ciência do Solo, 2007. Disponível em: https://www.sbcs.org.br.

SANTOS, L. A. *et al*. Remineralizers in tropical soils: agronomic responses and challenges. **Agriculture**, 2023. DOI: https://doi.org/10.3390/agriculture13050987.

SILVA, A. P.; LOPES, S. F. Estratégias de manejo da fertilidade com remineralizadores: economia agrícola e sustentabilidade. **Journal of Cleaner Production**, v. 312, art. 127845, 2024.

SILVA, F. C. *et al*. Soil chemical changes with remineralizer application. **Revista Brasileira de Ciência do Solo**, 2022. DOI: https://doi.org/10.36783/18069657rbcs20210120.

SOUZA, R. C. *et al*. Rochagem como alternativa sustentável para fertilização do solo. **Revista Brasileira de Ciência do Solo**, 2022. DOI: https://doi.org/10.36783/18069657rbcs20210102.

SOUZA, V. L. *et al*. Remineralizers in Cerrado soils: agronomic performance. **Pesquisa Agropecuária Tropical**, 2023. DOI: https://doi.org/10.1590/1983-40632023v5376521.

TAIZ, L.; ZEIGER, E.; MOLLER, I.; MURPHY, A. **Fisiologia e desenvolvimento vegetal**. 6. ed. Porto Alegre: Artmed, 2017.

VAN STRAATEN, P. **Farming with rocks and minerals: challenges and opportunities**. Guelph: University of Guelph, 2023. Disponível em: https://www.uoguelph.ca/~pvanstra/farmingwithrocks.pdf.