

## Feasibility evaluation of the use of mud residue from marble shop as soil remineralizer

*Avaliação da viabilidade de utilização do resíduo fino de marmoraria  
como remineralizador de solo*

Flávia Cristina Silveira Braga<sup>1</sup> , Tainara Arthuso de Oliveira<sup>2</sup> ,  
Débora Silvano Moreira<sup>3</sup> , Pedro Valle Salles<sup>2</sup> , Igor Vasconcelos Santana<sup>1</sup> 

<sup>1</sup>Universidade Federal de Minas Gerais, Instituto de Geociências, Centro de Pesquisa Professor Manuel Teixeira da Costa, Avenida Presidente Antônio Carlos, 6.627, Pampulha, CEP: 31270-901, Belo Horizonte, MG, BR (flaviacsbraga@gmail.com; igorunesp@gmail.com)

<sup>2</sup>Universidade do Estado de Minas Gerais, João Monlevade, MG, BR (tainaraa.o@hotmail.com; pedrovallesalles025@gmail.com)

<sup>3</sup>Universidade Federal de Minas Gerais, Instituto de Geociências, Programa de Pós-Graduação em Geologia, Belo Horizonte, MG, BR (geo.debora@yahoo.com.br)

Received on March 23, 2023; accepted on October 6, 2023.

### Abstract

Brazil is a major producer of dimension/ornamental stones, with a great diversity of raw materials. The sawing process transforms 20 to 30% of the extracted block into powder, with the generation of fine waste around 800,000 t/year. An alternative to reusing this waste is its application as a source of nutrients for the soil. This study evaluated the potential use of mud residue from a marble shop located in João Monlevade, Minas Gerais, as a remineralizer, based on fertility, mineralogical and chemical analysis performed by X-ray diffraction and X-ray fluorescence. For fertility, pH in CaCl<sub>2</sub> 0.01 mol L<sup>-1</sup>, organic matter, aluminum saturation, potential acidity, sum of bases, cation-exchange capacity, base saturation, macro and micronutrients were determined. The studied residue has free silica, the sum of basis, and K<sub>2</sub>O content in the range established by MAPA to be certified as a remineralizer. The sample contains 6.7% phyllosilicates, a source of faster K availability, and 19.4% K-feldspar, a slow-release source. Results described in this study indicate that residue can be a promising, efficient, and low-cost alternative to improve soil fertility.

**Keywords:** Agromineral; Remineralizer; Solid residues; Sustainability.

### Resumo

O Brasil é um grande produtor de rochas ornamentais, com grande diversidade de matérias-primas. O processo de serragem transforma de 20 a 30% do bloco extraído em pó, com geração de resíduos finos em torno de 800.000 t/ano. Uma alternativa para o reaproveitamento desses resíduos é a sua utilização como fonte de nutrientes para o solo. Este estudo avaliou o potencial de utilização do resíduo de lama de uma marmoraria localizada em João Monlevade, Minas Gerais, como remineralizador, com base em análises de fertilidade, mineralógicas e químicas realizadas por difração de raios X e fluorescência de raios X. Para a fertilidade, foram determinados pH em CaCl<sub>2</sub> 0,01 mol L<sup>-1</sup>, matéria orgânica, saturação de alumínio, acidez potencial, soma de bases, capacidade de troca catiônica, saturação de bases, macro e micronutrientes. O resíduo estudado possui teor de sílica livre, soma de bases e K<sub>2</sub>O na faixa estabelecida pelo MAPA para ser certificado como remineralizador. A amostra contém 6,7% de filossilicatos, uma fonte de disponibilidade mais rápida de K, e 19,4% de K-feldspato, uma fonte de liberação lenta. Os resultados descritos neste estudo indicam que o resíduo pode ser uma alternativa promissora, eficiente e de baixo custo para melhorar a fertilidade do solo.

**Palavras-chave:** Agromineral; Remineralizador; Resíduos sólidos; Sustentabilidade.

## INTRODUCTION

Brazil is a major producer of dimension/ornamental stones, having reached fourth place in the world in production and exports in 2006 (Chiodi Filho and Chiodi, 2014), having a raw rock total production in 2022 of 10 Mt, being currently the fifth largest exporter, behind China, India, Italy, and Turkey (Chiodi Filho, 2023), with a great diversity of raw materials. Approximately 10,000 companies operate in this sector in Brazil, including marble factories (61%), processing sectors (20%), mining (10%), exporters (4%), services (3%), slab deposits (1%) and machinery, equipment, and input industries (1%) (Chiodi Filho, 2013). The entire production chain of dimension stones generates solid waste, from block extraction, sawing, cutting, and polishing process. The sawing process transforms 20 to 30% of the extracted block into powder (Moura and Leite, 2011). The total processing waste generated in the 2023 production was 3,7 Mt of 10 Mt of raw rock total production (Chiodi Filho, 2023). Several studies have been carried out with a focus on the reuse of these wastes, such as the production of various construction materials (Gonçalves, 2000; Almeida et al., 2007; Moura and Leite, 2011; Araújo, 2019). Another form of reuse that has been explored, and which is the focus of this research, is as a source of nutrients for the soil (Machado et al., 2008; Lichs et al., 2019; Nasser et al., 2022).

The Brazilian territory consists, for the most part, of acidic and nutrient-poor soils. To make them productive, high amounts of fertilizers are used, which comprise about 40% of agricultural production costs (Martins et al., 2008). The most important nutrients are primary macronutrients: nitrogen (N), phosphorus (P), and potassium (K); secondary macronutrients: calcium (Ca), magnesium (Mg), and sulfur (S); and micronutrients: boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), zinc (Zn), cobalt (Co), and silicon (Si). According to Rodrigues (2008), 70% of the total fertilizers used in Brazil are derived from imported conventional nutrient sources (FCN — *Fontes Convencionais de Nutrientes*), essentially composed of variants of nitrogen, phosphorus, and potassium (NPK), of high concentration and high solubility in water. The high solubility in water, especially in tropical and subtropical climate conditions, results in low use efficiency, and therefore, the search for alternative nutrient sources has expanded in recent years (Camara et al., 2021).

In this context, the direct use of rock powder, registered as remineralizers, emerged as a viable, economical, and ecological alternative, improving the physical and chemical quality of soil. The use of remineralizers to totally or partially replace high-solubility fertilizers was regulated by the Brazilian Ministry of Agriculture (MAPA — *Ministério da Agricultura, Pecuária e Abastecimento*), employing Law 12,890, of December 10, 2013 (Brasil, 2013). Remineralizers

are defined in this law as materials of mineral origin that have been reduced by mechanical processes, being capable of generating changes in soil fertility indices, as they provide macro and micronutrients for plants. Normative Instructions (INs) numbers 05 and 06, published by the MAPA (Brasil, 2016), establish the minimum characteristics for product certification, such as a minimum of 9% of sum of bases and 1% of potassium oxide ( $K_2O$ ), maximum of 15 ppm of arsenic (As), 10 ppm of cadmium (Cd), 0.1 ppm of mercury (Hg), and 200 ppm of lead (Pb), and less than 25% of free silica ( $SiO_2$ ), in addition to proven agronomic efficiency (Viana et al., 2021).

The remineralizers promote the improvement of physical-chemical properties and biological activity of the soil and can help to reduce the use of FCN, in addition to enabling the practice of more sustainable and organic agriculture (Leonardos and Theodoro, 1999; Lichs et al., 2019). The use of remineralizers, depending on the material and factors related to the soil and plant cultivated, can correct the soil acidity, provide nutrients, and condition the soil (Luz et al., 2010). The main interest of rock powder is to provide alternative nutrient sources, especially K, through physical and chemical modification processes of different raw materials (Souza, 2014).

Agrogeology aims to understand the weathering processes during soil formation and identify possibilities to increase the release rate of nutrients from minerals (van Straaten, 2002). Research with a focus on the use of silicate materials as sources of K found that this application, in tropical climates, achieves high rates of dissolution and better performance, due to the high temperatures and humidity in the soil, which favor the reaction mechanisms between the minerals and the soil solution (Luz et al., 2010; Angélica et al., 2014a, 2014b; Braga et al., 2014a, 2014b; Oliveira et al., 2014). The agronomic efficiency of the powder rock depends on the rock origin, mineralogy, and chemical composition, as well as factors associated with soil characteristics such as mineral compound incubation time, the previous treatment applied, and the cultivated species (Távora, 1982; Nascimento and Loureiro, 2004).

The fine (2–0.075 mm) and ultrafine (< 0.075 mm) waste generated in the cutting and polishing phase of dimension stones are called abrasive mud or processing mud (Camara et al., 2021). These residues contain a mixture of different rocky materials, which may be able to generate the availability of different nutrients in the short, medium, and long term (Duarte et al., 2013). Despite providing fewer nutrients in the short term, when compared to industrial mineral fertilizers of high solubility (FCN), rock powder can gradually provide nutrients over a long time after application to soil (Martins et al., 2008).

The use of remineralizers is, therefore, a promising technique that can provide a dependence reduction on imports

of high solubility fertilizers, and combined with the process of reuse of solid residue, it is capable of promoting a more sustainable production chain both in the field of agriculture and in the dimension stone extraction and processing sector. This practice is consistent with the so-called Circular Economy, which presents as objectives, according to Camara et al. (2021) the cyclical use of products and materials through maintenance, reuse, remanufacturing, recycling, and regeneration.

The present research evaluated the potential use of mud residue from a marble shop located in the municipality of João Monlevade, Minas Gerais state, as a remineralizer, based on mineralogical, X-ray diffraction (XRD), and fertility analysis.

## MATERIAL AND METHODS

### Sampling and preparation

The samples consist of fine (2–0.075 mm) and ultrafine (< 0.075 mm) waste generated in the cutting and polishing phase of various ornamental rocks, including mainly marbles, granite, gneiss, and gabbro, collected in a marble shop located at João Monlevade, Minas Gerais state. The mud results from the cutting and polishing phase; it is decanted, and the solid material is deposited in a temporary reservoir (Figure 1). When this reservoir is full, the marble shop hires a company for a final disposal of the material. The reservoir has about 2.3 meters of length and width, and is 50 centimeters thick, resulting in a storage of 2.645 m<sup>3</sup>. Three samples were collected making a vertical hole along the 50 cm thick, using a round handle articulated digger.



**Figure 1.** Waste reservoir of the marble shop where the sample studied was collected.

The three samples were dried in the Universidade do Estado de Minas Gerais (UEMG) laboratory oven for 48 hours at 100°C, then homogenized and quartered.

### Analytical procedures

The XRD analysis was carried out in Centro de Pesquisa Professor Manoel Teixeira da Costa (CPMTC) of Universidade Federal de Minas Gerais (UFMG). The sample was passed through a 200 mesh sieve, i.e., granulometry below 0.074 mm. The powder was mounted by back-loading a flat aluminum sample holder. The analysis was carried out in a PANalytical X'Pert PRO diffractometer, with a 240 mm Bragg-Brentano  $\theta/\theta$  geometry, with a copper tube. The instrument set up at the incident beam side was as follows: Soller slit 0.04 rad; fixed divergent slit 1°; beam mask 15 mm. The setup at the diffracted beam side was as follows: antiscatter slit 1°; receiving slit 0.5° opening; Soller slit 0.04 rad; curved graphite monochromator, and xenon/methane-filled proportional detector. The scan was set to range from 5 to 70° (in 2 $\theta$  range), 40 kV, 45 mA, 0.02° step size, and 1 second counting time per step, in continuous mode.

The software HighScore Plus (HSP), published by PANalytical Inc., was used to process the XRD raw data, phase identification, and further calculation of weight fractions, through Rietveld analysis. The observed diffractogram was uploaded in HSP, the Y-axis was set to square root mode in order to facilitate the visualization of noise/peaks, and the background automatically fit. A peak-search function algorithm with high significance was initially applied to allow major peaks detection only; small secondary peaks were manually inserted afterward, by visual inspection of the diffractogram. A default profile fitting cycle was executed (“Flat background”; “More background”; “Peak position”; “Peak height”; “Peak FWHM”; “Peak shape”) in order to extract precise peak information and assign mineral candidates.

From this point forward, major phase identification was based on patterns available in the Crystallographic Open Database (COD), which contains more than 466,000 (year 2021) crystallographic information files (CIF). It is worth mentioning that the sample was collected from a “marble” shop’s waste material, so possible misfits and misinterpretations can arise due to the heterogeneity of the materials that made up the sample — granite, gneiss, marble — i.e., a mixture of natural phases that are not formed from pure solutions; impurities, substitution, and weathering can occur to various extents, affecting peak positions and intensities. This is especially problematic at the 20–30°(2 $\theta$ ), due to the convolution of Bragg peaks derived from plagioclase feldspars. Furthermore, plagioclase with variable amounts of anorthite component can occur in the sample, leading to peak complexity. The major mineral phases identified were quartz, orthoclase, oligoclase, biotite, and calcite — the latter as a

minor phase. Kaolinite might be present in trace amounts as well, but only its  $d \sim 7.1 \text{ \AA}$  (001) reflection at  $12.4^\circ(2\theta)$  is barely seen above the background, and therefore it was not considered during the Rietveld refinement; small secondary kaolinite peaks, not considered in the analysis, can contribute to some extent to the overall misfit of the calculated pattern. References of assigned phases are:

- Quartz (reference code: 96-900-9667, COD ID: 9009666), Gualtieri (2000);
- Orthoclase (reference code: 96-101-1206, COD ID: 1011205), Chao et al. (1940);
- Oligoclase (reference code: 96-901-1424, COD ID: 9011423), Phillips et al. (1971);
- Biotite (reference code: 96-900-2302, COD ID: 9002301), Brigatti et al. (2000);
- Calcite (reference code: 96-900-0096, COD ID: 9000095), Graf (1961).

For the Rietveld refinement, the peak shape was represented by the pseudo-Voigt function and crystal structure data were obtained from the cited references above. The refinement strategy was applied over the entire scan range, i.e.,  $5\text{--}70^\circ(2\theta)$  but three regions were omitted because they exhibited reflections from the aluminum sample holder, not accounted for in the refinement. The excluded regions were at  $\sim 38.0\text{--}39.0^\circ$ ,  $44.2\text{--}44.9^\circ$  and  $64.8\text{--}65.5^\circ(2\theta)$ , which correspond to the most intense aluminum Bragg reflections below  $70^\circ(2\theta)$  (COD ID: 9008460). The kaolinite (001) reflection at  $12.4^\circ(2\theta)$  was omitted from the analysis as well.

The background and scale factor were the initial refined parameters, followed by specimen displacement, Caglioti peak shape parameters W, V, U (one at a time), and Peak Shape parameter 1's. An asymmetry function was applied in general, but probably with a stronger effect on the low-angle Bragg reflections. Sample texture (preferred orientation) was refined for biotite (March-Dollase function) only. Peak positions slightly off the "ideal ( $2\theta$ )" were corrected by refining the lattice parameters a, b, and c. The main misfit at this point corresponded to the calculated intensities at the feldspars "critical" region, around  $27.5^\circ(2\theta)$ . Refining the atomic coordinates x, y, z for oligoclase and orthoclase reduced the misfit and, at the end of this process, the convergence between the measured and calculated data — agreement indices (R-factors) — were: Rwp (weighted profile) = 11.21%; Rexp (expected) = 6.59%;  $X^2$  Goodness of Fit (GOF) = 2.89.

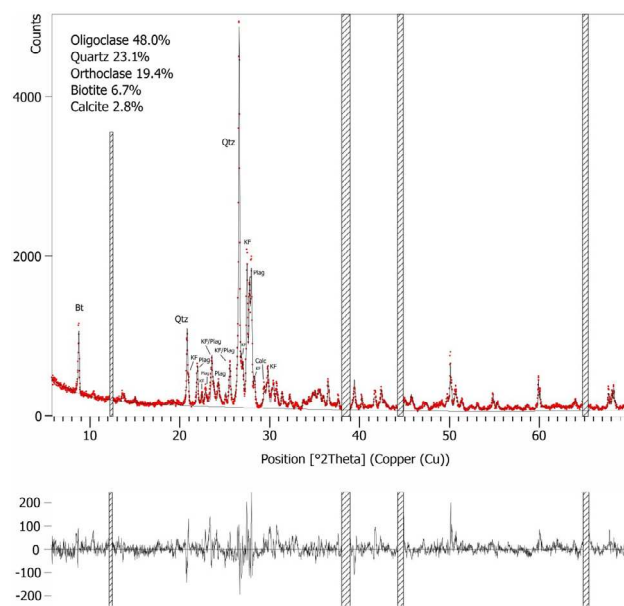
The X-ray fluorescence (XRF) analysis was performed at Centro Federal de Educao Tecnolgica de Minas Gerais (CEFET-MG), using a SHIMADZU EDX-720. Sixteen oxides were analyzed:  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{CaO}$ ,  $\text{K}_2\text{O}$ ,  $\text{TiO}_2$ ,  $\text{MgO}$ ,  $\text{P}_2\text{O}_5$ ,  $\text{BaO}$ ,  $\text{SrO}$ ,  $\text{SO}_3$ ,  $\text{MnO}$ ,  $\text{ZrO}_2$ ,  $\text{Rb}_2\text{O}$ ,  $\text{As}_2\text{O}_3$ , and  $\text{Y}_2\text{O}_3$ .

Fertility analysis was conducted at Escola Superior de Agricultura Luiz Queiroz from Universidade de So Paulo

(ESALQ-USP). The following parameters were determined: pH in  $\text{CaCl}_2$   $0.01 \text{ mol L}^{-1}$ ; organic matter (MO) extracted with sodium dichromate, determined by colorimetry; aluminum saturation (m); potential acidity (H+Al) composed of exchangeable and non-exchangeable acidity by the pH SMP method; sum of bases (SB); cation-exchange capacity (CEC), base saturation (V), macronutrients (P, K, Ca, Mg, Al, S), and micronutrients (B, Cu, Fe, Mn, Zn, Na, Si). P and K were extracted by ion-exchange resin procedure; Al, Ca, and Mg were extracted with  $\text{KCl}$   $1 \text{ mol L}^{-1}$ ; S with calcium phosphate  $0.01 \text{ mol L}^{-1}$ ; B with hot water; Cu, Fe, Mn, and Zn with diethylenetriamine pentaacetic acid (Raij et al., 2001); Na with Mehlich-1 (Silva, 2009); and Si with calcium chloride  $0.01 \text{ mol L}^{-1}$  (Korndrfer et al., 2004).

## RESULTS AND DISCUSSION

The XRD analysis indicated that the sample was composed mainly of oligoclase (48.0%), quartz (23.1%), orthoclase (19.4%), biotite (6.7%), and calcite (2.8%), as shown in Figure 2. Traces of kaolinite were estimated. The biotite identified could be a mix of various phyllosilicates such as muscovite and illite, very common in granite and gneiss.



**Figure 2.** X-ray diffractogram of the residue sample, indicating the minerals quantified. The figure illustrates the assigned phases, where Bt stands for biotite; Plag for oligoclase; KF for orthoclase; Qtz for quartz, and Calc for calcite. The figure also exhibits the weight fraction for each phase, the measured data (red dots), the calculated profile (black solid line), and the difference plot, which displays the difference between the anchor scan and the calculated profile. The dashed areas depict omitted regions. Only major peaks below  $30^\circ(2\theta)$  were labeled for simplicity.

The total chemical analysis (Table 1) indicated that the sample was mainly composed of  $\text{SiO}_2$  (58.03%),  $\text{Al}_2\text{O}_3$  (14.04%),  $\text{Fe}_2\text{O}_3$  (9.11%),  $\text{CaO}$  (7.72%),  $\text{K}_2\text{O}$  (6.96%),  $\text{TiO}_2$  (1.35%),  $\text{MgO}$  (0.92%),  $\text{P}_2\text{O}_5$  (0.63%), and  $\text{BaO}$  (0.55%). The other oxides analyzed had a concentration below 0.5%. The  $\text{BaO}$  content was probably associated with alkali feldspar, once it substitutes K in a simple-solid solution (Roy, 1967). The sum of bases obtained was 15.6%, and together with the K value of 6.96%, they were in the range established by the IN as the minimum to certify a product as a soil remineralizer, which need to be at least 9% and 1%, respectively. The free silica established by the IN was below 25%, and the quartz content obtained by XRD analysis was 21%, indicating a compatible percentage.

The XRD results (Table 2) showed other parameters of the residue. The pH was 6.94, the Al was  $< 0.1$  mmolc.dm<sup>-3</sup>, and the potential acidity was 6.9 mmolc.dm<sup>-3</sup>, which indicates low values of interchangeable Al. The sum of basis value obtained was 39 mmolc.dm<sup>-3</sup>, which indicates the number of exchangeable bases Ca, Mg, K, and Na. In soil, this value points to the degree of weathering, since in younger soil that suffered less weathering, the contents of the four elements are higher than in old soil (Sobral et al., 2015).

The parameter V is the proportion of the cation exchange capacity occupied by the bases, and soils with values above 70% do not need liming (Sobral et al., 2015). The V value obtained was 85%, indicating that there were no charges occupied by acidity components H or Al. The

**Table 1.** The X-ray fluorescence results.

Oxide	Result (%)
$\text{SiO}_2$	58.03
$\text{Al}_2\text{O}_3$	14.04
$\text{Fe}_2\text{O}_3$	9.11
$\text{CaO}$	7.72
$\text{K}_2\text{O}$	6.96
$\text{TiO}_2$	1.35
$\text{MgO}$	0.92
$\text{P}_2\text{O}_5$	0.63
$\text{BaO}$	0.55
$\text{SrO}$	0.18
$\text{SO}_3$	0.18
$\text{MnO}$	0.15
$\text{ZrO}_2$	0.10
$\text{Rb}_2\text{O}$	0.04
$\text{As}_2\text{O}_3$	0.03
$\text{Y}_2\text{O}_3$	0.01

CEC obtained was 45.9 mmolc.dm<sup>-3</sup>, indicating a low content of clay minerals according to Sobral et al. (2005), which is congruent with the XRD results. In soils, CEC values above 40.0 mmolc.dm<sup>-3</sup> are considered high values (Sobral et al., 2015).

Comparing the XRF results for K, Mg, and Ca, with the exchangeable values obtained using ion-exchange resin procedure for K and KCl 1 mol L<sup>-1</sup> for Mg and Ca, it is possible to calculate that 0.33%, 0.86%, and 1.10% of total K, Mg, and Ca, respectively, of the sample are considered “exchangeable”. Most soil K is found in the structure of primary and secondary minerals, and the smallest part (about 2% of the total) is readily available to plants, which are those bound to soil colloids (exchangeable K), or present in the soil solution (Gama et al., 2020). The K in feldspars and feldspathoids is structural type, found inside the three-dimensional network of silicon tetrahedral and, to be used by plants, these minerals need to be dissolved through the natural reactions of chemical weathering that occur during soil formation and development (Villa et al., 2004; Araújo and Sampaio, 2010). Using fine granulometry of residue, the contact surface area of the exposed material will be larger, and consequently, there will be a greater release of ions (Martins et al., 2010; Camara et al., 2021).

**Table 2.** Fertility parameters.

Parameter	Unit	Result
B (hot water)	mg.dm <sup>-3</sup>	< 0.10
Cu (DTPA)	mg.dm <sup>-3</sup>	59.1
Fe (DTPA)	mg.dm <sup>-3</sup>	32.1
Mn (DTPA)	mg.dm <sup>-3</sup>	4.5
Zn (DTPA)	mg.dm <sup>-3</sup>	6.4
Na (Mehlich-1)	mg.dm <sup>-3</sup>	352
Si (CaCl <sub>2</sub> 0.01 mol L <sup>-1</sup> )	mg.kg <sup>-1</sup>	21.5
pH (CaCl <sub>2</sub> )	-	6.94
MO	g.dm <sup>-3</sup>	4.6
P (resin)	mg.dm <sup>-3</sup>	18.8
S (calcium phosphate 0.01 mol L <sup>-1</sup> )	mg.dm <sup>-3</sup>	17
Ca (KCl 1 mol/L)	mmolc.dm <sup>-3</sup>	30.2
Mg (KCl 1 mol/L)	mmolc.dm <sup>-3</sup>	3.9
K (resin)	mmolc.dm <sup>-3</sup>	4.93
Al (KCl 1 mol/L)	mmolc.dm <sup>-3</sup>	< 0.1
H+Al (SMP)	mmolc.dm <sup>-3</sup>	6.9
SB	mmolc.dm <sup>-3</sup>	39
CEC	mmolc.dm <sup>-3</sup>	45.9
V	%	85
M	%	0

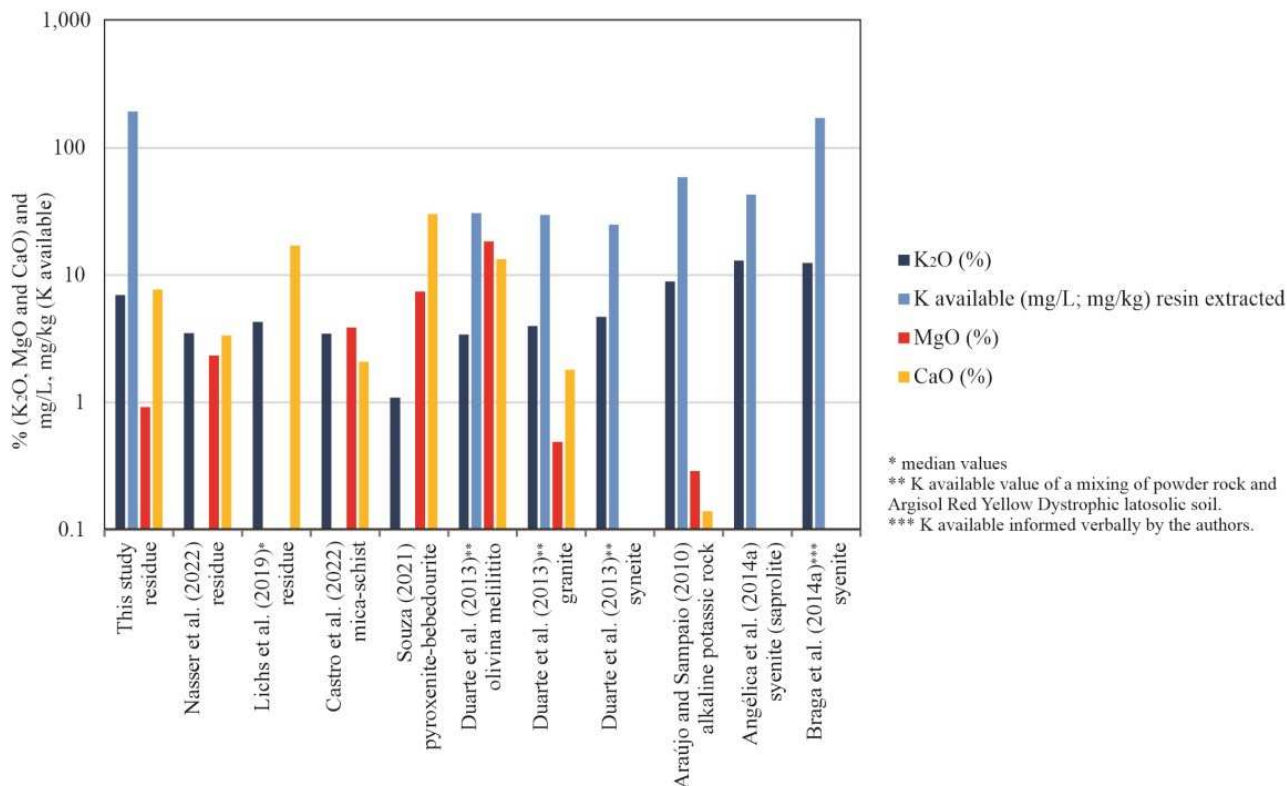
The Ca and Mg contents measured in the residue are considered medium and low, respectively, and are similar to those found in alternative fertilizers such as coffee and rice straw, cattle manure, and sewage sludge, which have been widely used in agriculture (Prezotti et al., 2007).

### Comparison with previous studies

Nasser et al. (2022) studied ornamental rock-cutting waste from Adamantina, São Paulo state, and concluded, based on chemical analysis of the residue, that it could not be commercialized as a remineralizer, due to its high  $\text{SiO}_2$  content (57.43%); still, the authors considered the residue presented a good potential as an alternative source of  $\text{K}_2\text{O}$  (3.50%), CaO (3.36%), MgO (2.34%), and S (2.26%) (Figure 3). However, the authors did not analyze the mineralogical composition, therefore, it was not possible to affirm that all  $\text{SiO}_2$  content obtained was in the form of free silica once the residue was probably also composed of other silicates. Si is naturally abundant in the soil in an inert form and consequently is unavailable for plant uptake (Tubaña and Heckman, 2015). It is considered a non-essential element for plants; however, it is beneficial to plant growth, mainly as nanoparticles (Rajput et al., 2021). Therefore, the abundance of Si in soils is not an indication that appropriate supplies of soluble Si are available.

Lichts et al. (2019) evaluated the mud residue of ornamental rock processing to verify the effects of variation in waste results due to variation in the processed material. The sum of bases presented a variation between 21.98 and 27.43%,  $\text{K}_2\text{O}$  between 3.71 and 4.87%, and CaO between 14.29 and 19.09% (Figure 3). According to the authors, the residue added to the soil regulated its pH, since the soil in natura had a pH of 5.4. In the rejects, the pH value was around 8, and with the addition of residue, the soil reached 6.7. The residue also stimulated the development of soil microbiota in bean crops. The variance in CaO content between our study (7.72%) and the findings reported by Lichts et al. (2019) may be a crucial factor influencing the extent of pH correction achieved in the soil, as higher CaO levels are typically associated with more pronounced alkaline effects, which can significantly impact the soil's pH correction capabilities.

Bertossi et al. (2012) studied the influence of fine waste from processing silicate ornamental rocks on soil and water quality. According to the authors, fine-grained waste could induce waterproofing of soil and deteriorate groundwater quality if used incorrectly. The authors observed that the hydraulic conductivity measured on mixtures of soil and waste was decreased in relation to pure soil and the mix of increasing quantities of fine waste on soil induced rising on electric conductivity, pH, and Ca, Mg, K, Na, and Mn



**Figure 3.** Comparison of  $\text{K}_2\text{O}$ , K available, MgO, and CaO content of the residue studied with other published researches, which analyzed the same residue, and various powder rocks.

concentrations of percolated water. However, all measured water quality parameters were under allowable limits established by CONAMA (Brasil, 2008) Resolution nº 396/2008. Considering the application of the studied residue in João Monlevade and region, red and red-yellow oxisols occur — the same class analyzed by Bertossi et al. (2012), which generally shows high hydraulic conductivity and elevated effective porosity, with a significant decrease in hydraulic conductivity at depth (Fiori et al., 2010). Therefore, it is expected that the application of residue could generate a slight reduction in water percolation velocity.

Castro et al. (2022) evaluated the agronomic efficiency of mica-schist as a soil remineralizer in millet and soya. The authors showed that in sandy soil the mica-schist performed better in millet than in KCl, however, in clay soils it is necessary to increase the mica-schist doses in the first year of cultivation, indicating that the powder rock use partially substitutes the KCl. The XRF indicates that the mica-schist is composed of 3.47%  $K_2O$  and 2.09% CaO, lower values than those of our studied sample (Figure 3). The mica-schist is composed mainly of oligoclase (23.8%), quartz (23.6%), muscovite (22.1%), biotite (14.5%), and chlorite (11.3%).

Souza (2021) analyzed the pyroxenite-bebedourite rock from the Catalão I Carbonatite Alkaline Complex as a potassium remineralizer for the nutrition of Marandu grass (*Brachiaria brizantha*) culture. The rock had a total of 1.09%  $K_2O$ , 30.24% CaO, 7.42% MgO, and 5.26%  $P_2O_5$  (Figure 3). The author verified that the treatment of 5t/ha obtained the best result for plant height growth.

The availability of K in soil using an application of melilitite, granite, and syenite powder was evaluated by Duarte et al. (2013), which have a total  $K_2O$  content of 3.42, 3.99, and 4.70%, respectively (Figure 3). The content of K in the soil was determined using extraction with Mehlich-1 and ion exchange resin. The authors concluded that olivine melilitite did not differ from KCl in relation to K availability in the soil and its uptake by plants. However, granite and syenite powder did not respond to the variables tested, which points out that they are materials with slow K availability to plants. The high K availability of melilitite could be related, according to Duarte et al. (2013), to the presence of easily weathered minerals in its composition, such as phlogopite. The mineralogy of the residue presented herein indicates that the phyllosilicates could be a source for faster K availability, and feldspar a slower source. It is important to emphasize that another important factor that influences slow or fast availability is the granulometry.

Araújo and Sampaio (2010) studied the K extraction of an alkaline potassic rock from Poços de Caldas, Minas Gerais state, using nitric acid, citric acid, and Mehlich-1. The studied sample was composed mainly of microcline, muscovite, and gibbsite, and had a total of 8.9%  $K_2O$ , 54.8%  $SiO_2$ , 19.7%  $Al_2O_3$ , 0.14% CaO, and 0.29% MgO (Figure

3). The highest K extraction was obtained using Mehlich-1, with 58.9 mg/L extracted along 120 hours, with no release increase when extending the time of extraction.

Angélica et al. (2014a) studied weathering profiles overlying syenite rocks in the Triunfo region, Pernambuco state, to understand the K behavior from the primary microcline in the bedrock up to the soils. The authors observed kaolinite formation after K-feldspar hydrolysis, with the total  $K_2O$  decreasing to the upper part of the profiles, and increasing the available K (obtained by cation exchange resin) and total  $Fe_2O_3$  to the top of the profiles. According to the authors, since no new K-bearing mineral is formed in the soil analyzed, K availability is related to the K-feldspar structure, which becomes looser due to upward weathering. This is the expected behavior of the weathering of the studied residue when applied in soil, once a great part of the  $K_2O$  content of the residue is related to K-feldspar.

Braga et al. (2014b) showed the main characteristics of a syenite deposit with a mineral potential of 67.8 Mt using a cut-off grade of 12.50%  $K_2O$ , located in the municipality of Guanambi, Bahia state. According to XRD and petrographic analysis, the syenite was mainly composed of alkali feldspar (microcline — 77.0%), biotite (11%), and clinopyroxene (11%). Agronomic tests using this rock applied the recommended dose to corn crops based on total K rock content (100 mg of K per kg of soil, equivalent to 240 t ha<sup>-1</sup> of  $K_2O$ ) (Gabos et al., 2014; Oliveira et al., 2014). The authors verified that the plant dry mass in the treatment presented an increment 41.5% higher than the control treatment. The great results in the agronomic tests are attributed by Braga et al. (2014b) mainly to the high potash content, the feldspar “fingerprint” texture, and the considerable amount of biotite.

## Possibilities of application

The main application considered for the residue studied is to local small producers (familiar agriculture), considering the limited volume and transportation costs. The application of remineralizer is important for small farmers, mainly because they have limited access to resources, financial incentives, and technology, and often face challenges in acquiring conventional fertilizers. Furthermore, it caters to producers who tend to seek healthier food production with less impact on the environment. Theodoro et al. (2006) found that the use of rock fertilization maintained corn, rice, cassava, sugarcane, and horticultural yields comparable to conventional fertilization, providing more sustainable soil fertility for small family producers in the state of Minas Gerais.

The main challenges for the use of remineralizers are the timing and intensity of nutrient supply, and the capacity to provide nutrients in the right quantities and at the appropriate times for each incorporated crop. Therefore, large doses with fine granulometry need to be applied in order to

achieve better incorporation. The solubilization and liberation of nutrients from rock powder depend on many factors besides mineralogy, chemical composition, and granulometry, such as leaching conditions, soil pH, biological activity, temperature, precipitation, redox potential, exposure time to the environment, soil-plant relationship, among others (Camara et al., 2021). Thus, applied studies to determine the agronomic efficiency under greenhouse using local oxisol are essential to better determine the possibilities of application.

## CONCLUSIONS

The studied residue, based on the parameters analyzed, has a good potential to be used as a soil remineralizer, once its free silica, the sum of basis, and  $K_2O$  content are in the range established by MAPA to be certified as a remineralizer. However, MAPA also establishes the maximum content of some metals (As, Cd, Hg, Pb), consequently, these elements still need to be analyzed, using the Inductively Coupled Plasma (ICP) methodology, to verify if the studied residue has less than the limit determined as safe.

The results also indicated that the residue has a good potential to provide micronutrients and help to regulate the pH of acidic soils, due to its long-term release. The mineralogical composition of the residue indicates that phyllosilicates, which constitute 6.7% of the sample, could be a source for faster K availability, and the K-feldspar, which forms 19.4% of the sample, is a slow-release source.

Results described in this study provide an important insight into the use of residue as a promising efficient and low-cost alternative to improve soil fertility. After this analysis, it is necessary to verify the agronomic efficiency under greenhouse and field conditions.

Considering a dose of 240 t ha<sup>-1</sup> for the application of powder rock in corn crops (Gabos et al., 2014; Oliveira et al., 2014) of a small rural producer, defined as someone who holds possession of a rural tract of land not exceeding 50 hectares, the use of rock powder could avoid the disposal of at least 12,000 t of material in nature. The use of remineralizers is a promising technique capable of promoting a more sustainable production chain in both agriculture and the extraction and processing of ornamental rock sectors.

## ACKNOWLEDGMENTS

This research was supported by the Universidade do Estado de Minas Gerais with a scholarship to Tainara Arthuso de Oliveira [Programa Institucional de Apoio à Pesquisa (PAPq) – UEMG – 2022]. The authors thank Centro de Pesquisa Professor Manuel Teixeira da Costa (CPMTC) of UFMG for the XRD analysis.

## REFERENCES

- Almeida, N., Branco, F., Santos, J. R. (2007). Recycling of stone slurry in industrial activities: application to concrete mixtures. *Building and Environment*, 42(2), 810-819. <https://doi.org/10.1016/j.buildenv.2005.09.018>
- Angélica, R. S., Leite, A. A. S., Braga, F. C. S., Oliveira, M. A., Oliveira, K. S., Martins, E. S. (2014a). Feldspar crystallinity and potassium behaviour in soils overlying syenites: agromineral application. In: *16<sup>th</sup> World Fertilizer Congress of CIEC*. Rio de Janeiro, p. 161-163. Available at: <https://ainfo.cnptia.embrapa.br/digital/bitstream/item/117754/1/S1872.pdf>. Accessed on: Jul 31, 2023.
- Angélica, R. S., Leite, A. A. S., Braga, F. C. S., Oliveira, M. A., Oliveira, K. S., Martins, E. S. (2014b). X-ray powder diffraction analysis as a tool in mineral exploration for agromineral evaluation. *16<sup>th</sup> World Fertilizer Congress of CIEC*. Rio de Janeiro, p. 214-216. Available at: <https://www.alice.cnptia.embrapa.br/alice/bitstream/doc/1008456/1/s1878.pdf>. Accessed on: Jul 31, 2023.
- Araújo, F. M. (2019). *Análise da influência do resíduo da lama de marmoraria como elemento de substituição parcial do cimento nas propriedades do concreto*. Dissertation (Master). Belo Horizonte: Departamento de Engenharia dos Materiais e da Construção Civil, Escola de Engenharia, Universidade Federal de Minas Gerais, 145 p. Available at: <http://hdl.handle.net/1843/30127>. Accessed on: Out 5, 2023.
- Araújo, S. C., Sampaio, J. A. (2010). Estudo do Uso de Rocha Potássica como Fertilizante de Liberação Lenta. In: Luz, A. B., Baltar, C. A. M., Bertolino, L. C. (eds.). *II Simpósio de Minerais Industriais do Nordeste*. Anais... Campina Grande: CETEM, p. 145-152. Available at: [http://mineralis.cetem.gov.br/bitstream/cetem/1263/1/Part%203.5%20anais\\_segundo\\_simposio\\_minerais\\_industriais\\_do\\_nordeste%20.pdf](http://mineralis.cetem.gov.br/bitstream/cetem/1263/1/Part%203.5%20anais_segundo_simposio_minerais_industriais_do_nordeste%20.pdf). Accessed on: Jul 31, 2023.
- Bertossi, A. P. A., Neves, M. A., Cardoso, M. S. N., Prado, A. C. A., Damasceno, C. A., Polidoro, J. C. (2012). Influência da utilização do resíduo fino de beneficiamento de rochas ornamentais silicáticas na qualidade do solo e da água. *Geociências, UNESP*, 31(2), 185-195. Available at: [https://www.revistageociencias.com.br/geociencias-arquivos/31\\_2/Art04\\_Bertossi\\_et\\_al.pdf](https://www.revistageociencias.com.br/geociencias-arquivos/31_2/Art04_Bertossi_et_al.pdf). Accessed on: Jul 31, 2023.
- Braga, F. C. S., Leite, A. A. S., Angélica, R. S., Martins, E. S., Oliveira, M. I. L., Wender, I. G. (2014a). K-alternative fertilizer Project: ultrapotassic syenite deposit in Pernambuco state. *16<sup>th</sup> World Fertilizer Congress of CIEC*. Rio de Janeiro, p. 167-169. Available at: <https://www.alice.cnptia.embrapa>.



- br/alice/bitstream/doc/1008428/1/S1874.pdf. Accessed on: Jul 31, 2023.
- Braga, F. C. S., Leite, A. A. S., Oliveira, M. A., Martins, E. S., Gabos, M. B., Angélica, R. S. (2014b). K-alternative fertilizer Project: biotite-bearing ultrapotassic deposit in Bahia state. *16<sup>th</sup> World Fertilizer Congress of CIEC*. Rio de Janeiro, p. 164-166. Available at: <https://www.alice.cnptia.embrapa.br/alice/bitstream/doc/1008386/1/S1873.pdf>. Accessed on: Jul 31, 2023.
- Brasil (2008). Resolução CONAMA nº 396, de 3 de abril de 2008. Dispõe sobre a classificação e diretrizes ambientais para o enquadramento das águas subterrâneas e dá outras providências. *Diário Oficial da União*, Seção I, p. 66-68. Available at: <https://pesquisa.in.gov.br/imprensa/jsp/visualiza/index.jsp?data=07/04/2008&jornal=1&pagina=66&totalArquivos=68>. Accessed on: Aug 1, 2023.
- Brasil (2013). *Lei nº 12.890, de 10 de dezembro de 2013*. Altera a lei nº 6.894, de 16 de dezembro de 1980, para incluir os remineralizadores como uma categoria de insumo destinado à agricultura, e dá outras providências. Brasília. Available at: [http://www.planalto.gov.br/ccivil\\_03/\\_ato2011-2014/2013/lei/112890.htm](http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2013/lei/112890.htm). Accessed on: Feb 20, 2023.
- Brasil (2016). Ministério da Agricultura, Pecuária e Abastecimento. Instrução Normativa nº 05 de 10 de março de 2016. Estabelece as regras sobre definições, classificação, especificações e garantias, tolerâncias, registro, embalagem, rotulagem e propaganda dos remineralizadores e substratos para plantas, destinados à agricultura. *Diário Oficial da União*. Available at: [https://www.in.gov.br/materia/asset\\_publisher/Kujrw0TZC2Mb/content/id/21393137/do1-2016-03-14-instrucao-normativa-n-5-de-10-de-marco-de-2016-21393106](https://www.in.gov.br/materia/asset_publisher/Kujrw0TZC2Mb/content/id/21393137/do1-2016-03-14-instrucao-normativa-n-5-de-10-de-marco-de-2016-21393106). Accessed on: Feb 20, 2023.
- Brigatti, M. F., Frigieri, P., Ghezzi, C., Poppi, L. (2000). Crystal chemistry of Al-rich biotites coexisting with muscovites in peraluminous granites Sample: A4. *American Mineralogist*, 85(3-4), 436-448. <https://doi.org/10.2138/am-2000-0405>
- Camara, G. R., Faitanin, B. X., Silveira, L. L. L., Chiodi Filho, C., Santos, E. S. (2021). *Utilização de rochas ornamentais ricas em minerais potássicos como fonte alternativa de insumo agrícola via rochagem – Parte I*. Rio de Janeiro: CETEM/MCTI, 71 p. Série Rochas e Minerais Industriais. Available at: <http://mineralis.cetem.gov.br/handle/cetem/2423>. Accessed on: Jul 31, 2023.
- Castro, J. P. V., Leandro, W. M., Brail, E. P. F., Ferreira, K. R. S., Oliveira, C. B. A., Passos, P. B. (2022). Eficiência agrônômica de remineralizados de solo de micaxisto na sucessão milheto-soja. *Research, Society and Development*, 11(14), e76111435864. <https://doi.org/10.33448/rsd-v11i14.35864>
- Chao, S. H., Hargreaves, A., Taylor, W. H. (1940). The structure of orthoclase. *Mineralogical Magazine and Journal of the Mineralogical Society*, 25(168), 498-512. <https://doi.org/10.1180/minmag.1940.025.168.05>
- Chiodi Filho, C. (2013). *Balanço das Exportações e Importações Brasileiras de Rochas Ornamentais no Período de Janeiro a Setembro de 2013*. Informe 01/2013. São Paulo: Associação Brasileira da Indústria de Rochas Ornamentais, 15 p. Available at: [http://www.ivolution.com.br/mais/fotos/6/17/1161/Informe\\_01\\_2013.pdf](http://www.ivolution.com.br/mais/fotos/6/17/1161/Informe_01_2013.pdf). Accessed on: Feb 20, 2023.
- Chiodi Filho, C. (2023). *Balanço das exportações e importações brasileiras de materiais rochosos naturais e artificiais de ornamentação e revestimento em 2022*. Informe 05/2023. Belo Horizonte: Associação Brasileira da Indústria de Rochas Ornamentais, 17 p. Available at: [https://abirochas.com.br/wp-content/uploads/2022/01/Informe-05\\_2023-Balanco-2022.pdf](https://abirochas.com.br/wp-content/uploads/2022/01/Informe-05_2023-Balanco-2022.pdf). Accessed on: Aug 4, 2023.
- Chiodi Filho, C., Chiodi, D. K. (2014). O setor de rochas ornamentais no Brasil. In: Vidal, F. V., Azevedo, H. C. A., Castro, N. F. (eds.). *Tecnologia de rochas ornamentais: pesquisa, lavra e beneficiamento*. Rio de Janeiro: CETEM/MCTI, p. 492-526. Available at: <http://mineralis.cetem.gov.br:8080/bitstream/cetem/1739/1/CCL00180014Cap10LivroRochas.pdf>. Accessed on: Jul 31, 2023.
- Duarte, W. M., Mafra, A. L., Foresti, M. M., Piccola, C. D., Almeida, J. A. (2013). Potencial de olivina melilitito, granito e sienito na disponibilização de potássio em solos. *Revista de Ciências Agroveterinária*, 12(1), 68-77. Available at: <https://www.revistas.udesc.br/index.php/agroveterinaria/article/view/5200>. Accessed on: Aug 1, 2023.
- Fiori, J. P. O., Campos, J. E. G., Almeida, L. (2010). Variabilidade da condutividade hidráulica das principais classes de solos do estado de Goiás. *Revista Geociências UNESP*, 29(2), 229-235.
- Gabos, M. B., Martins, E. S., Mendes, D. R., Santos, L. F., Oliveira, M. I. L., Leite, A. A. S. (2014). Evaluation of extractants for characterization of K silicate agrominerals. *16<sup>th</sup> World Fertilizer Congress of CIEC*. Rio de Janeiro: CIEC, p. 211-213. Available at: <https://ainfo.cnptia.embrapa.br/digital/bitstream/item/117810/1/S1877.pdf>. Accessed on: Aug 1, 2023.

- Gama, M. A. P., Matos, G. S. B., Silva, G. P., Macedo Neto, A. A. L. (2020). *Especialização em Rochagem e Remineralização dos Solos*. Apostila de Fertilidade do Solo. Módulo III. Belém: Universidade Federal Rural da Amazônia, 14 p.
- Gonçalves, J. P. (2000). *Utilização do resíduo de corte de granito (RCG) como adição para a produção de concreto*. Dissertation (Master). Porto Alegre: Escola de Engenharia, Universidade Federal do Rio Grande do Sul, 135 p. Available at: <http://hdl.handle.net/10183/1676>. Accessed on: Aug 1, 2023.
- Graf, D. L. (1961). Crystallographic tables for the rhombohedral carbonates. *American Mineralogist*, 46(11-12), 1283-1316. Available at: <https://pubs.geoscienceworld.org/msa/ammin/article/46/11-12/1283/541851/Crystallographic-tables-for-the-rhombohedral>. Accessed on: Jul 5, 2023.
- Gualtieri, A. F. (2000). Accuracy of XRPD QPA using the combined Rietveld-RIR method. *Journal of Applied Crystallography*, 33, 267-278. <https://doi.org/10.1107/S002188989901643X>
- Korndörfer, G. H., Pereira, H. S., Nolla, A. (2004). *Análise de silício no solo, planta e fertilizante*. GPSi-ICIAG-UFU. Boletim técnico nº 02. Uberlândia: Instituto de Ciências Agrárias, Universidade Federal de Uberlândia, 50 p.
- Leonardos, O. H., Theodoro, S. H. (1999). Fertilizer tropical soils for sustainable development. *International workshop on Science for Sustainable development in Latin America and Caribe*. Proceedings... Rio de Janeiro: Academia Brasileira de Ciência, p. 143-153.
- Lichts, T., Sander, A., Caraméz, M. G. S., Daubermann, B. B., Decker, J. T., Modolo, R. C. E. (2019). Utilização de resíduos do beneficiamento de rochas ornamentais de uma marmoraria de São Leopoldo com a finalidade de remineralização de solos. *XI Simpósio Sul-brasileiro de Geologia*. Anais... Bento Gonçalves: SBG-Núcleos Sul, p. 278. Available at: [http://sbgeo.org.br/assets/admin/imgCk/files/Anais/ANAIS-XVIISNET-XISSBG-2019\(1\).pdf](http://sbgeo.org.br/assets/admin/imgCk/files/Anais/ANAIS-XVIISNET-XISSBG-2019(1).pdf). Accessed on: Aug 1, 2023.
- Luz, A. B., Lapido-Loureiro, F. E., Sampaio, J. A., Castilhos, Z. C., Bezerra, M. S. (2010). Rochas, minerais e rotas tecnológicas para produção de fertilizantes alternativos. In: Fernandes, F. R. C., Luz, A. B. da, Castilhos, Z. C. (eds.). *Agrominerais para o Brasil*. Rio de Janeiro: CETEM/MCT, p. 61-88. Available at: <http://mineralis.cetem.gov.br/handle/cetem/906>. Accessed on: Aug 1, 2023.
- Machado, R. V., Ribeiro, R. C. C., Andrade, F. V. (2008). Nutrição Mineral e a Utilização de resíduos de Rochas Ornamentais. *XVII Jornada de Iniciação Científica*. Anais... Vitória: UFES-CETEM, p. 130-136. Available at: <http://mineralis.cetem.gov.br/handle/cetem/490>. Accessed on: Aug 1, 2023.
- Martins, E. S., Oliveira, C. G., Resende, A. V., Matos, M. S. F. (2008). Agrominerais – rochas silicáticas como fontes minerais alternativas de potássio para a agricultura. In: Luz, A. B., Lins, A. F. (eds.). *Rochas & Minerais Industriais*. 2. ed. Rio de Janeiro: CETEM/MCT, p. 205-222. Available at: <https://www.cetem.gov.br/antigo/images/publicacoes/livros/rmi/09-AGROMINERAIS-ROCHAS-SILICATICAS.pdf>. Accessed on: Aug 1, 2023.
- Martins, E. S., Resende, A. V., Oliveira, C. G., Furtini Neto, A. E. (2010). Materiais silicáticos como fontes regionais de nutrientes e condicionadores de solo. In: Fernandes, F. R. C., Luz, A. B., Castilhos, Z. C. (eds.). *Agrominerais para o Brasil*. Rio de Janeiro: CETEM/MCT, p. 89-104. Available at: <http://mineralis.cetem.gov.br:8080/bitstream/cetem/907/1/cap5.pdf>. Accessed on: Aug 1, 2023.
- Moura, W. A., Leite, M. B. (2011). Estudo da viabilidade da produção de blocos com utilização de resíduo de serragem de rochas ornamentais para alvenaria de vedação. *Rem: Revista Escola de Minas*, 64(2), 147-154. <https://doi.org/10.1590/S0370-44672011000200003>
- Nascimento, M., Loureiro, F. E. L. (2004). *Fertilizantes e sustentabilidade: o potássio na agricultura brasileira, fontes e rotas alternativas*. Rio de Janeiro: CETEM/MCT, 66 p. Série Estudos e Documentos. Available at: <http://mineralis.cetem.gov.br/handle/cetem/579>. Accessed on: Aug 1, 2023.
- Nasser, M. D., Guarçoni, A., Carneiro, V. A., Burket, D., Tavares, M. B. (2022). Caracterização química do resíduo gerado por beneficiamento de rochas ornamentais do município de Adamantina (SP). *Cientific@ Multidisciplinary Journal*, 9(1), 1-7. <https://doi.org/10.37951/2358-260X.2022v9i1.6000>
- Oliveira, M. I., Martins, E. S., Gabos, M. B., Braga, F. C. S., Almeida, J. P. A., Leite, A. A. S. (2014). Performance of K silicate agrominerais for corn crop. *16<sup>th</sup> World Fertilizer Congress of CIEC*. Rio de Janeiro: CIEC, p. 158-160. Available at: <http://www.alice.cnptia.embrapa.br/alice/handle/doc/1008384>. Accessed on: Aug 1, 2023.
- Phillips, M. W., Colville, A. A., Ribbe, P. H. (1971). The crystal structures of two oligoclases: a comparison with low and high albite Locality: Camedo, Switzerland Sample: An28. *Zeitschrift fur Kristallographie*, 133, 43-65.

- Prezotti, L. C., Gomes, J. A., Dadato, G. G., Oliveira, J. A. (2007). *Manual de recomendação de calagem e adubação para o Espírito Santo – 5a aproximação*. Vitória: SEEA/ INCAPER/CEDAGRO, 305 p. Available at: <http://biblioteca.incaper.es.gov.br/digital/handle/123456789/3242>. Accessed on: Aug 1, 2023.
- Raij, B. van, Andrade, J. C., Cantarella, H., Quaggio, J. A. (2001). *Análise Química para Avaliação da Fertilidade de Solos Tropicais*. Campinas: Instituto Agronômico, 285 p. Available at: [http://lab.iac.sp.gov.br/Publicacao/Raij\\_et\\_al\\_2001\\_Metod\\_Anal\\_IAC.pdf](http://lab.iac.sp.gov.br/Publicacao/Raij_et_al_2001_Metod_Anal_IAC.pdf). Accessed on: Aug 1, 2023.
- Rajput, V. D., Minkina, T., Feizi, M., Kumari, A., Khan, M., Mandzheva, S., Sushkova, S., El-Ramady, H., Verma, K. K., Singh, A., van Hullebusch, E. D., Singh, R. K., Jatav, H. S., Choudhary, R. (2021). Effects of Silicon and Silicon-Based Nanoparticles on Rhizosphere Microbiome, Plant Stress and Growth. *Biology*, 10(8), 791. <https://doi.org/10.3390/biology10080791>
- Rodrigues, A. F. S. (2008). Agronegócio e Mineralnegócio: relações de dependência e sustentabilidade. In: Diretoria de Desenvolvimento e Economia Mineral (ed.). *Informe mineral: desenvolvimento e economia mineral*. Brasília: DNPM, p. 28-47. Available at: <https://www.gov.br/anm/pt-br/centrais-de-conteudo/dnpm/informes/informe-mineral-2008-2o-semester>. Accessed on: Aug 1, 2023.
- Roy, N. N. (1967). The mineralogy of the potassium-barium feldspar series. II. Studies on hydrothermally synthesized members. *Mineralogical Magazine and Journal of the Mineralogical Society*, 36(277), 43-49. <https://doi.org/10.1180/minmag.1967.036.277.06>
- Silva, F. C. (2009). *Manual de análises químicas de solos, plantas e fertilizantes*. 2. ed. Brasília: Embrapa Informação Tecnológica, 627 p. Available at: <http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/330496>. Accessed on: Aug 1, 2023.
- Sobral, L. F., Barretto, M. C. V., Silva, A. J., Anjos, J. L. (2015). *Guia prático para interpretação de resultados de análises de solos*. Aracaju: Embrapa Tabuleiros Costeiros, 15 p. Available at: <http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1042994>. Accessed on: Aug 1, 2023.
- Souza, E. K. B. (2021). *Desempenho da rocha piroxenito-bebedourito como remineralizador de solos*. Final Graduation Work. Catalão: Universidade Federal de Goiás, Engenharia de Minas. 46 p. Available at: [https://files.cercomp.ufg.br/weby/up/710/o/EDIANA\\_KATJA\\_BERTOLDO\\_SOUZA.pdf](https://files.cercomp.ufg.br/weby/up/710/o/EDIANA_KATJA_BERTOLDO_SOUZA.pdf). Accessed on: Aug 1, 2023.
- Souza, F. N. S. (2014). *O potencial de agrominerais silicáticos como fonte de nutrientes na agricultura tropical*. Thesis (PhD) Brasília: Universidade de Brasília, 107 p. <https://doi.org/10.26512/2014.12.T.18064>
- Távora, J. E. M. (1982). Reservas minerais de potássio e suas explorações. In: Yamada, T., Igue, K., Muzilli, O., Usherwood, N. R. (eds.). *Potássio na agricultura brasileira*. Piracicaba: Instituto de Potassa Fosfato, p. 37-50.
- Theodoro, S. H., Leonardos, O., Rocha, E. L., Rego, K. G. (2006). Experiências de uso de rochas silicáticas como fonte de nutrientes. *Espaço e Geografia*, 9(2), 263-292. Available at: <https://periodicos.unb.br/index.php/espacoegografia/article/view/39794>. Accessed on: Oct 9, 2023.
- Tubaña, B. S., Heckman, J. R. (2015). Silicon in Soils and Plants. In: Rodrigues, F. A., Datnoff, L. E. (eds.). *Silicon and Plant Diseases*. Cham: Springer, p. 7-51. [https://doi.org/10.1007/978-3-319-22930-0\\_2](https://doi.org/10.1007/978-3-319-22930-0_2)
- van Straaten, P. (2002). *Rocks for crops: Agrominerals of Sub-Saharan Africa*. Nairobi: ICRAF, 338 p. Available at: [https://apps.worldagroforestry.org/Units/Library/Books/PDFs/11\\_Rocks\\_for\\_crops.pdf](https://apps.worldagroforestry.org/Units/Library/Books/PDFs/11_Rocks_for_crops.pdf). Accessed on: Aug 1, 2023.
- Viana, L. S. B., Caitano, T. B. S., Pontes, A. N. (2021). A remineralização de solos como iniciativa ao desenvolvimento sustentável. *Research, Society and Development*, 10(14), e45101421516. <https://doi.org/10.33448/rsd-v10i14.21516>
- Villa, M. R., Fernandes, L. A., Faquin, V. (2004). Formas de potássio em solos de várzea e sua disponibilidade para o feijoeiro. *Revista Brasileira de Ciência do Solo*, 28(4), 649-658. <https://doi.org/10.1590/S0100-06832004000400007>