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Agricultural use of phonolite and verdete rocks as a source of k for corn crop[1]

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ABSTRACT

This study aimed to evaluate the effect of the application of Siliceous Rocks Powder as a source of K (phonolite and verdete) *in natura* and calcined at temperatures of 300, 600, 800 and 1000° C, pure and in consortium with dolomitic limestone and coffee husk to corn crop (*Zea mays* L.). The analyses of the phenological variables, stem diameter, number of shoots, leaves, plants height, weight of dry biomass of the aerial part and the contents of N, P and K, accumulated in the aerial part of the plants were performed. The range of calcination temperature between 300 °C and 600 °C, being the treatments that become K more available to the plants. The treatment that produced the highest biomass was the rocks in mixture (m/m) with coffee husk. The calcination temperatures influenced the biomass production and the content of macronutrients accumulated in the dry biomass of the aerial part. The least efficient treatment in the production of biomass was associated with the rocks in mixture with dolomitic limestone.

Keywords: alternative potassium sources; calcination; *Zea mays*.

INTRODUCTION

Corn is the largest agricultural crop in the world, thus exceeding the mark of 1 billion tons and being fundamental to national agriculture, mainly in commercial growth combined with subsistence culture of small producers (Miranda, 2018).

To ensure high productivity, Brazilian agriculture consumes large quantities of fertilizers. This high consumption is related to the characteristics of the soils, which are mostly acidic and with low soil nutrient availability. Among the elements required by plants, the K content is essential, seeing that it is a nutrient that has limited and non-renewable reserves in Brazil (Boldrin *et al.*, 2019).

Thus, to meet the needs of K content and recover the productivity of Brazilian soils, high amounts of fertilizers are used and K is the most commonly plant nutrient applied in Brazilian agriculture, mainly as potassium chloride (KCl), in which Brazil stands out as one of the largest importers worldwide, due to its low national production being able to supply only 2% of domestic agricultural consumption (Tavares *et al.*, 2018).

Despite the high K_2O content and high solubility of the main potassium fertilizer used in Brazilian agriculture, the KCl content can increase the uptake of other cations such as Ca and Mg owing to the concentration of Cl-. With the high concentration of K in the soil, there may be a reduction in the uptake of other cations by plants, in addition to increasing losses by leaching (Clement *et al.*, 2013; Mancuso *et al.*, 2014).

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The ratio of Ca and Mg influences processes within the soil as well as in the plant, including the absorption of elements. In plant nutrition, this fact is related to the similar chemical properties of cations, such as the degree of valence and mobility, causing competition for the same sites of adsorption in the soil and absorption by the roots. In other words, the excessive presence of one can impair the adsorption and absorption processes of the other, as occurs with excess Ca inhibiting the assimilation of Mg by plants (Orlando Filho *et al.*, 1996). In view of being an imported product, this effect increases the cost of agricultural production.

The use of rocks as fertilizers arises as an option to reduce the dependence on potassium fertilizers, and the slow-release fertilizer being directly applied directly to the soil or in the production of K salts (Silva *et al.*, 2012; Santos *et al.*, 2016). However, there are challenges related to the use of rocks as potassium fertilizers, such as low solubility or even low K_2O content compared to KCl, as well as the supply of nutrients in the right amounts and at the right time for each crop (Boldrin *et al.*, 2019; Nogueira *et al.*, 2021).

Studies over the years have shown that the vast majority of silicate rocks with considerable K content, such as phonolite and verdete rocks have low capacity, or even are not capable of providing K content to plants *in natura* without prior treatment, or even are not capable of providing K content to crops (Mancuso *et al.*, 2014; Santos *et al.*, 2016).

Phonolite is a rock of volcanic origin, composed mainly of microcline, orthoclase, andesine and nepheline, distributed throughout the world and with 8.1% of K_2O (Mancuso *et al.*, 2014; Toledo *et al.*, 2019). Verdete is a fine-grained metasedimentary rock with a K_2O content of 11.1%. Its mineralogy is composed by 37% of glauconite, a hydrated lamellar silicate of iron rich in K, 24% of recrystallized quartz, in size that varies between 0.5 and 7 mm, usually subleased, 14% of light brown clay matrix; 11% of kaolinite, 7% of other micas, such as muscovite, chlorite and biotite, both rocks with large reserves throughout the national territory (Silva *et al.*, 2012).

To optimize the efficiency of the use of these rocks and take advantage of their potential to supply K content to plants (Violatti *et al.*, 2019; Arrieta *et al.*, 2020), processes such as grinding to increase the contact surface with the soil, calcined at different temperatures with or without the addition of flux such as CaO that alters the crystalline structure of the minerals, the acidification with acids of low molecular weight associated with incubation times or even the mixture of rocks with organic matrices rich in K_2O such as coffee husk, could demonstrate positive results in the solubility and K_2O release capacity from the mineral matrices (Martins *et al.*, 2015; Pessoa *et al.*, 2015; Santos *et al.*, 2015).

In this context, this study aimed to evaluate the effect of the application of Siliceous Rocks Powder as a source of K (phonolite and verdete) *in natura* and calcined at temperatures of 300, 600, 800 and 1000 °C, pure and in consortium with dolomitic limestone and coffee husk to corn crop (*Zea mays* L.).

MATERIAL AND METHODS

For the study, the phonolite (Pho), was extracted from the Plateau of Poços de Caldas and obtained by Mineração Corimbaba, whereas the verdete (V) was extracted from Cedro do Abaeté (MG).

The mineral matrices were submitted to grinding in rotary ball mill, for 20 minutes and the material was separated in a 150 mesh sieve (Brasil, 2013). The material that did not pass through the sieve returned to the mill and the procedure was repeated until the entire sample reached the desired granulometry.

After the preparation and homogenization of both rocks, samples of phonolite and verdete with a total weight of 50g were placed in porcelain crucible and calcined in muffle furnace at four different levels of temperature (300, 600, 800 and 1000 °C). The calcination was carried out in a muffle furnace, in which the rocks were kept at the desired temperature for two hours and cooled slowly to room temperature inside the muffle furnace.

The mixtures were prepared in the proportion of 50% of phonolite rock and 50% of dolomitic limestone (m/m), the same proportion was used for the treatment of the mixture of verdete with dolomitic limestone. After setting the mixtures, 50g of the mixtures were weighed in porcelain crucible and calcined in muffle furnace for two hours until reaching the desired temperatures of 300, 600, 800 and 1000 °C.

The treatment aimed to enrich the rocks with K content from organic origin, i.e., in which the shell of coffee was used as organic matrix, consisting of a content of 5% of K_2O, for both rocks. The mixtures of 50% of the mineral matrices (phonolite and verdete) and 50% of the organic matrix coffee husk (m/m) were prepared, in which 50g of the mixtures were weighed and taken in porcelain crucible for calcination in muffle furnace for two hours until reaching the desired temperatures of 300 and 600 °C. As mentioned, only two calcination temperatures were used in the treatment of the mixture of the rocks with the coffee husk, seeing that in the temperatures of 800 and 1000 °C, the coffee husk was totally incinerated without leaving any trace.

According to the total K_2O content of the 8.1% phonolite rocks and the verdete rock about 11.1%, the amount of the mixture to be applied per pot of 2 kg was calculated, for a K proportion of 300 kg ha^{-1}, as shown in table 1. To perform this calculation, the recommendation of K_2O/ha for corn, which varies from 20 to 90 kg of K_2O/ha, was taken into account. However, it is worth mentioning that the K_2O of these rocks is much lower than that used commercially and that K_2O also has low solubility (Pessoa *et al.*, 2015). The soil used in the experiment was a typical Latossolo vermelho distrófico (Oxisols). The soil was air dried and passed through a 2 mm mesh sieve.

To elevate the base saturation (V2) to 70% (Tomé Júnior, 1997), the soil was corrected with dolomitic limestone, moistened and left to rest for 45 days. To facilitate the reaction, water was added to the soil maintaining adequate humidity at about 80% of field capacity inside each pot with a capacity of 2 kg.

The dolomitic limestone was analysed at the Chemistry Department of the UFLA, for Ca and Mg contents (CaO = 33.72; MgO = 9.5; Neutralizing Power - NP = 98; Relative Efficiency - RE = 98; Total Relative Neutralizing Power - TRNP = 95).

The organic matrix coffee husk, in which the rocks phonolite (Pho) and verdete (V) were mixed, was chemically analysed by digestion of the material, what consists of decomposition of organic and inorganic compounds into their elements constituents employing mineral acids and heating (N = 20.1 $mgkg^{-1}$; P = 1.3 $mgkg^{-1}$; K = 21.1 $mgkg^{-1}$; Ca = 7.8 $mgkg^{-1}$; Mg = 1.7 $mgkg^{-1}$; Mn = 60.2 $mgkg^{-1}$; Zn = 15.2 $mgkg^{-1}$; B = 31.8 $mgkg^{-1}$; Cu = 23.8 $mgkg^{-1}$; Fe = 96.6 $mgkg^{-1}$). In this technique, 0.5 g of coffee husks were used, which were dried at 70 °C and ground to pass through a 20-mesh sieve. Subsequently, 4 ml of Nitric acid and 2 ml of Perechloric acid were added. After two hours of rest, the mixture was taken to the controlled digester block with a gradual temperature increase of 60, 90, 110, 200 °C. distilled water was added to the already cold tubes and the mixture was filtered into a "snap-cap" flask. The determination was made in ICP OES, Spectro brand, Blue model (Malavolta *et al*., 1997).

The experiments were conducted in the greenhouse in a factorial scheme (2x5), with three repetitions, involving KCl as reference source, in a randomized block design. The first factor corresponds to the two silicate rocks: phonolite and verdete. The second factor corresponds to the evaluated treatments of the *in natura* and calcined rocks (*in natura*, at 300, 600, 800 and 1000 °C) pure and in mixture with the matrices dolomitic limestone and coffee husk in a single dose equivalent to 300 kg ha^{-1} K_2O.

As a source of K content, in which three different treatments are constituted, for each rock and for each culture, the first treatment evaluated the rocks *in natura* and calcined at temperatures of 300 °C, 600 °C, 800 °C and 1000 °C, thus totaling 18 pots for each rock. The second treatment with the rocks phonolite and verdete in mixture with dolomitic limestone consisted of 50% of each rock and 50% of dolomitic limestone *in natura* and calcined at temperatures mentioned above, aiming at evaluating the dolomitic limestone as a solubilizer in the solubilization of rocks totaling 18 pots for each rock under study and for each crop assessed.

The third treatment consisted in the enrichment of the rocks with K of organic origin, coffee husk with 5% of K_2O, in which the mixture of 50% of the rocks and 50% of the coffee husk *in natura* and calcined at temperatures of 300 °C and 600 °C was evaluated, totaling 12 pots for each rock (Table 1). In this treatment, the temperatures of 800 °C and 1000 °C for both rocks were not evaluated, because at these temperatures the coffee husk was completely incinerated.

The supply of N, P, S, B, Cu, Fe, Mo, Zn and Mn contents was done according to Malavolta (1980), who modified for the dosages 300; 280; 50; 0.5; 1.5; 5.0; 0.1; 5.0 and 3.6 $mgdm^{-3}$, respectively. The K application were exclusively applied through rocks. Ca and Mg contents were supplied solely via the correctives and the other nutrients were supplied according to the recommendation of Malavolta (1980), in which ammonium sulphate ($(NH_4)_2SO_4$) in the form of white granules contains 20% of nitrogen (N) and 22% of sulphur (S) in its composition, the monoammonium phosphate (MAP) with a 54% phosphorus (P_2O_5) content of 11% nitrogen, were used in a single dose at planting in mixture with the soil.

Table 1: Doses of phonolite as a source of potassium (K) content, applied to the soil and consisting of a volume of 2kg of soil per pot

Treatments	**Total K_2O content**	**Applied K_2O dose**	**Mineral and organic matrix mixture of K_2O content**	**Mass of rock and mixtures applied to the soil**
	%	**Kg há$^{-1}$**	**%**	**g 2000g^{-1} soil/pot**
Phonolite (unmixed)				
KCl witness treatment	60.0	300	-	0.6
Phonolite *in natura*	8.10	300	-	8.6
Phonolite at 300 °C	8.10	300	-	8.6
Phonolite at 600 °C	8.30	300	-	8.6
Phonolite at 800 °C	8.20	300	-	8.6
Phonolite at 1000 °C	8.20	300	-	8.6
Phonolite (Calcined Phonolite)		**Calcined Phonolite**		
KCl witness treatment	60.0	300	-	7.2
Phonolite CP *in natura*	8.42	300	0.32	17.2
Phonolite CP 300 °C	8.42	300	0.32	17.2
Phonolite CP 600 °C	8.62	300	0.32	17.2
Phonolite CP 800 °C	8.52	300	0.32	17.2
Phonolite CP 1000 °C	8.52	300	0.32	17.2
Phonolite (Coffee Husk)		**Coffee Husk**		
KCl witness treatment	60.0	300	-	0.6
Phonolite CH *in natura*	29.2	300	21.1	6.0
Phonolite CH at 300 °C	29.2	300	21.1	6.0
Phonolite CH at 600 °C	29.4	300	2.1	6.0
Verdete (unmixed)				
KCl witness treatment	60.0	300	-	0.6
Verdete *in natura*	11.10	300	-	10.4
Verdete at 300 °C	11.00	300	-	10.4
Verdete at 600 °C	11.30	300	-	10.4
Verdete at 800 °C	11.20	300	-	10.4
Verdete at 1000 °C	11.20	300	-	10.4
,0-Verdete Calcined Phonolite		**Calcined Verdete**		
KCl witness treatment	60.0	300	-	0.6
Verdete CP *in natura*	11.42	300	0.32	20.4
Verdete CP at 300 °C	11.32	300	0.32	20.4
Verdete CP at 600 °C	11.62	300	0.32	20.4
Verdete CP at 800 °C	11.52	300	0.32	20.4
Verdete CP at 1000 °C	11.52	300	0.32	20.4
Verdete Coffee Husk		**Coffee Husk**		
KCl witness treatment	60.0	300	-	0.6
Verdete CH *in natura*	32.20	300	21.1	7.2
Verdete CH at 300 °C	32.10	300	21.1	7.2
Verdete CH at 600 °C	32.40	300	21.1	7.2

Three seeds were sown per pot, with maintenance of one plant per pot, daily irrigations were performed with deionized water, maintaining the humidity of 60% of the Total Pore Volume. Growth assessments were initially performed at the time of germination and sprouting (when the leaves come out). The evaluations were made weekly, starting on June 11, 2019 and were evaluated until the beginning of flowering of the plants, which occurred on October 7, 2019, totaling 118 days. The phenological factors as growth, by means of the height of the plant, measured from the insertion of the cotyledons to the apical bud, the diameter of the stem measured at the base of the plants close to the substrate, by using for this a ruler graduated in centimeters and a pachymeter graduated in millimeters, respectively.

At the end of the evaluation period, the plants were cut at the base of the root close to the substrate, in which the mass of fresh matter of the aerial part, and the relation of height/stem diameter were obtained by direct weighing of the referred parts, in analytical scales. The definitive height of the plants was measured from the base close to the substrate up to the apical bud and the diameter of the stem. The plants were first washed in running water to remove all solid residues and washed again in distilled water and placed in paper bags with a capacity of 3 kg for drying in a forced air oven at 60 °C, (for three days), until reaching constant weight in order to determine the production of dry matter, and then the mass of dry matter was obtained by direct weighing on an analytical balance.

After the described procedures, the plant material was ground in a Willey mill and sent for leaf chemical analysis to quantify the contents of N, K and P according to the methods described by Malavolta *et al.* (1997). The data were subjected to weighted mean analysis when significant, the Skott Knott test of means was performed at 5% probability level (Ferreira, 2011).

RESULTS AND DISCUSSIONS

With respect to the analysis of variance, significance was observed ($p < 0.05$) between the treatments and sources, as well as the interaction between the phenological factors observed in this study such as stem diameter, number of leaves, shoots, plant height, dry biomass of the aerial part and the content and accumulation of N, K and P.

For the height of the plant, it was observed that for the treatments of matrices with verdete (V), verdete in mixture with dolomitic limestone (VDL) and verdete with coffee husk (VCH), the treatments calcined at 600 ºC presented higher height. The one with coffee husk provided relevant growth in height (Figure 1A). The plants in which the potassium chloride treatment was provided showed larger diameter (Figure 1B).

In the treatment with pure phonolite (Calcined phonolite), the samples calcined at 1000 ºC provided substantial growth, thus decreasing growth in the treatments of lower calcination temperature and with the KCl witness with the lowest growth at the end (Figure 1C). On the other hand, regarding the diameter, for the treatments with pure phonolite, the plants in which KCl was provided presented the largest diameter, whereas the smallest diameter was observed in the plants with calcined phonolite at 1000 °C (Figure 1D).

In the treatments consisting of the mixture of the phonolite with coffee husk and calcined at 600 °C provided the greatest growth in height, followed by the treatment calcined at 300 °C and with less growth for the treatments with phonolite without calcination (natural) and with KCl.

The dry matter is one of the growth parameters that may meet the development of the plant seeing that it is related to all the factors that act on the growth of the plant. For the plants consisting of calcined verdete (calcined verdete) and calcined verdete with coffee husk (CV and VCH), there was no statistical difference between the dry matter of the plants within each matrix. This result can be considered relevant, because they were equated with the treatments that contained the product KCl as a source of K.

For the plants with calcined phonolite (Calcined phonolite), it was observed that the greatest results were found in the treatments that contained KCl and calcined phonolite at 600 °C. It could be possible to verify in this treatment a clearer tendency of the effect of the possible increase of solubility with calcination, where the increase of temperature provided higher production of dry matter until the temperature could reach 600 °C and after this temperature, the plants presented less production of dry matter.

The treatment where the matrix was associated with the verdete in mixture with dolomitic limestone, it could be noted a differentiation between them. Regarding this matrix, the plants that contained the potassium chloride as a source of K, showed greater production of dry matter, then the treatments with the natural verdete, calcined at 300 °C and calcined at 600 °C showed higher dry matter production than the treatments where calcination was 800 °C and 1000 °C, respectively.

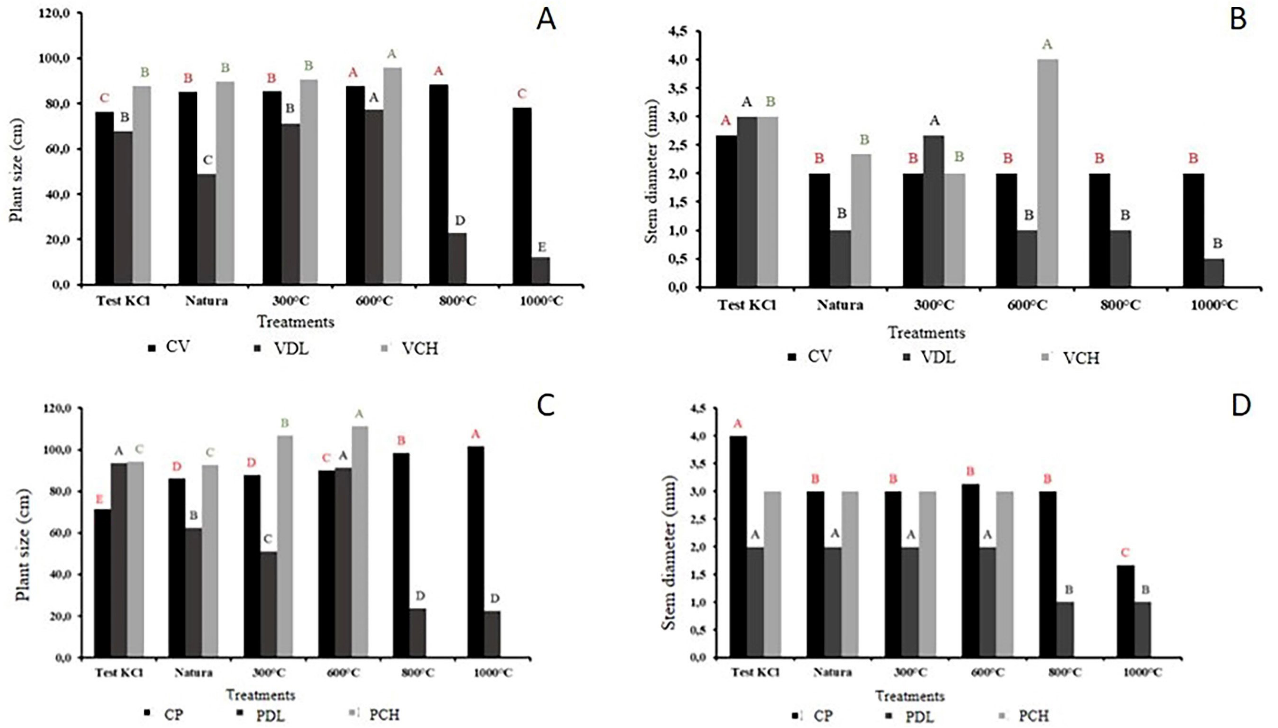

Figure 1: A and C. Height; B and D. diameter of maize grown with verdete and phonolite rock. Calcined verdete (V), verdete in mixture with dolomitic limestone (VDL) and verdete with coffee husk (VCH), Calcined Phonolite (CP), Phonolite in mixture with dolomitic limestone (PDL) and Phonolite with coffee husk (PCH).

The plants that contained the calcined phonolite in mixture with dolomitic limestone showed a dry matter production response quite similar to that observed in the same treatment with verdete, with the lowest dry matter production rates in the plants that contained the rock calcined above 800 °C. Teixeira *et al.* (2015) verified through calcination tests and X-ray analysis that phonolite calcined at 600 °C did not significantly alter its crystalline structure, but the authors verified major structural changes in calcination at 900 and 1200 °C.

The visual analysis (Figure 2A and B) also allows inferring that the phonolite rock, in the treatments to which they were submitted, provided a more favourable conditioning for the development of the plant in general, the overall average dry matter of all the phonolite treatment (excluding the KCl witness treatments) being 11.3g and the verdete 8.9g, i.e. about 27% higher dry matter production of the maize plants with phonolite treatments.

The N content in the aerial part of the corn plants cultivated in the treatments that contained only the verdete rock, presented higher N foliar content in the treatments that contained KCl, natural verdete and calcined verdete at 300 °C, whereas the lowest content was obtained in the treatment with calcined verdete at 1000 °C. As for the treatment whose source of K was associated with the mixture of coffee husk and verdete rocks, the treatments with the mixture calcined at 300 °C and 600 °C showed a higher content of this nutrient (Figure 2C).

The treatments provided N accumulation, thus generating a greater differentiation of the effect among them. For the treatments composed of the three sources of K, the highest accumulations were observed in the control treatment (KCl) and an increase in total N content was observed in the plants of the treatments with increasing calcination and decreasing in the treatments with calcination above 800 °C (Figure 2D).

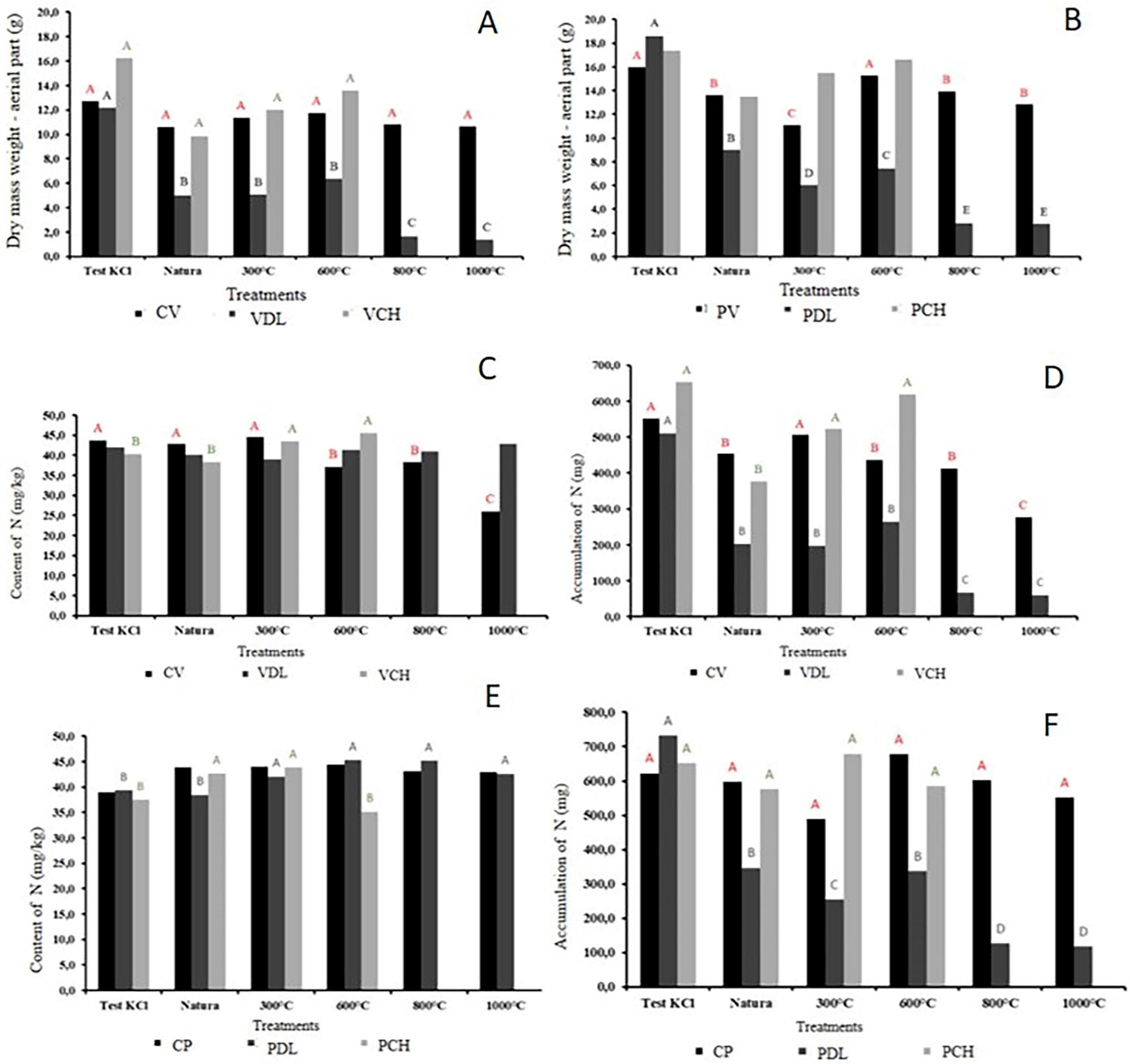

Figure 2: Dry matter of maize plant grown with A. verdete and B. phonolite rocks. C. Content and D. accumulation of N in the dry matter of maize plants cultivated with verdete soil. E. Content and F. accumulation of N in the dry matter of maize plants grown with phonolite rocks. Calcined Phonolite (CP), Phonolite in mixture with dolomitic limestone (PDL), Phonolite with coffee husk (PCH), Calcined verdete (V), verdete in mixture with dolomitic limestone (VDL) and verdete with coffee husk (VCH).

Overall, the responses in N content in maize plants were similar for both rocks (Figure 2E). For accumulation, the plants that contained the phonolite with coffee husk showed no statistical difference between them, and the same was observed for the plants that contained pure phonolite (Figure 2F).

For the plants that contained the phonolite in mixture with dolomitic limestone, there was a relevant differentiation in the accumulation of N content, with the control treatment with KCl could provide higher accumulation of this nutrient, which can be justified by the greater significant production of dry matter in this treatment. The lower production of dry matter also explains the lower accumulation of N content in the treatments with calcined phonolite at 800 and 1000 °C.

Limestone comes from a sedimentary rock composed mainly of calcium carbonate and acts as a neutralizer of soil acidity. Different types of limestone have enough calcium carbonate to correct the soil, and its use makes a big difference in crop productivity. With the addition of dolomitic limestone in the soil, there is an increase in the pH and the availability of K+ for the plants (Bamberg *et al.*, 2023). Soil Fertilization and Maize-Wheat Grain Production with Alternative Sources of Nutrients.). Regarding the use of coffee husk, because it is readily soluble.

Both for the content and accumulation, in the treatments that contained the verdete in mixture with dolomitic limestone, it could be noted that the plants showed higher content and accumulation of P when compared to other treatments (Figure 3A and B). For the treatment that the source of K was verdete with coffee husk (VCH), the highest amounts of P contents were observed in the control treatments with KCl and the treatment with the verdete in mixture with coffee husk calcined at 600 °C. KCl is used as a standard source of K, thus, treatments that present results similar to its application are considered as an alternative source of K (Arrieta *et al.*, 2020).

Research shows that in the presence of magnesium (Mg), there is a significant absorption of P content (Mendoza & Borie, 1998), seeing that the Mg is an element that "carries" the P. This effect is very beneficial, since Brazilian soils are very weathered and naturally poor in P content. Thus, a possible product composed of this mixture could also have a conditioning effect on the soil, which would increase the viability of the product.

Similar to the response observed in the treatments with verdete, the calcined phonolite with dolomitic limestone provided the highest leaf P content for the plants, probably due to the synergism of Mg with P, in addition, the partial calcination of limestone may also have initiated the calcination process of limestone, partially transforming the carbonate of calcium and magnesium and calcium and magnesium oxide. However, it is known that this complete transformation of carbonate into oxide occurs at higher temperatures, usually between 900 and 1200 °C (Miyamoto *et al.*, 2019).

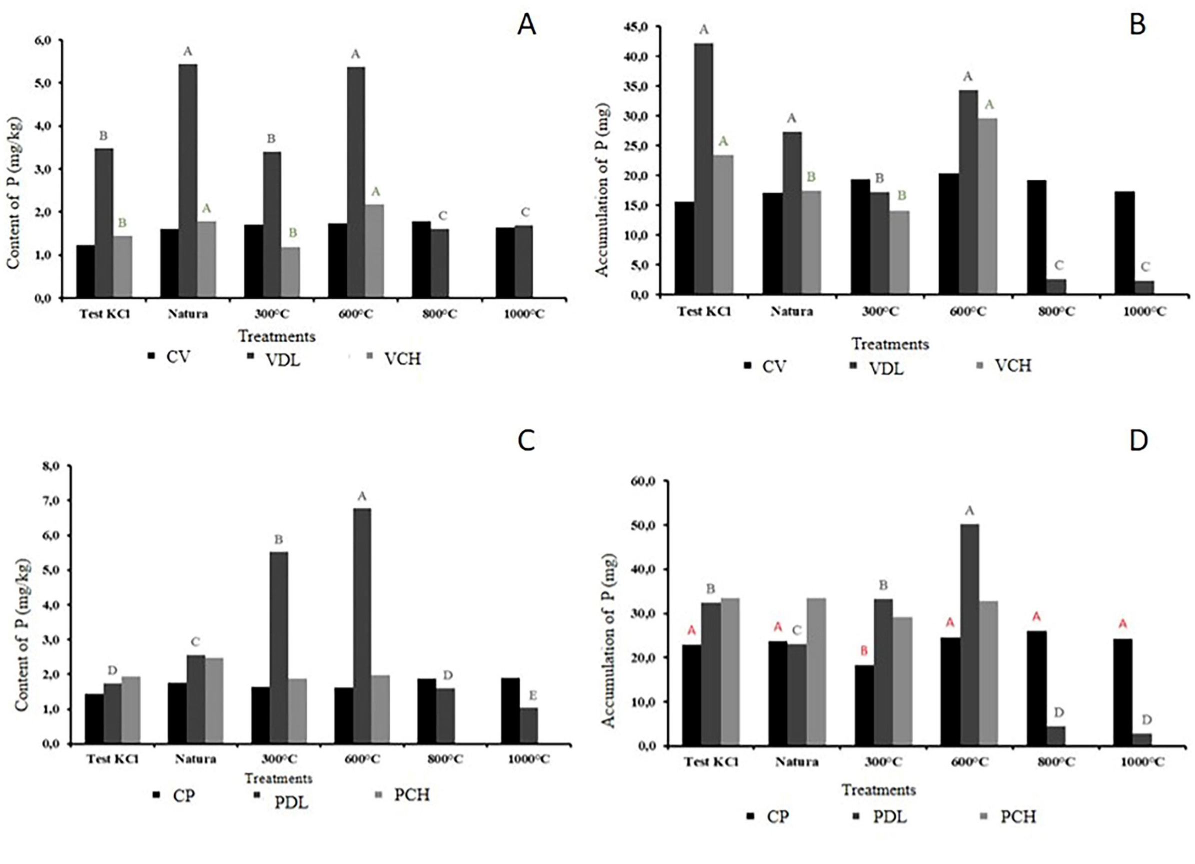

Figure 3: A. Content and B. accumulation of P in the dry matter of maize plant grown with verdete rock. C. Content and D. accumulation of P in the dry matter of maize plants grown with phonolite rocks. Calcined verdete (CV), verdete in mixture with dolomitic limestone (VDL) and verdete with coffee husk (VCH). Calcined Phonolite (CP), Phonolite in mixture with dolomitic limestone (PDL) and Phonolite with coffee husk (PCH).

The highest content of P in the treatment regarding dolomitic limestone with phonolite calcined at 600 °C also reflected the accumulation of this nutrient, followed by calcination at 300 °C which was equal to the control treatment.

For the treatment with pure phonolite, calcination did not provide statistical difference for the contente (Figure 3C), but for the accumulation (Figure 3D), the treatment with calcination at 300 °C showed the lowest average of P content, due to its lower production of dry matter.

Regarding the K contente, the dilution/concentration effect was the most evident. For the treatments containing the mixture matrix of verdete with dolomitic limestone, the content of K in the treatments of calcination at 800 °C and 1000 °C were the highest (Figure 4A), whereas for the accumulation of this element, the treatment with KCl provided the highest accumulation (Figure 4B). This was expected because the KCl is the main commercial product source of K in Brazil, it has high solubility and concentration between 58 and 60%.

It is highlighted in this graph that the treatments with coffee husk, especially for the treatments calcined at 600 ºC. It is known that natural coffee husk has about 5% of K content (Zoca *et al.*, 2014), however, when calcined, the residual material is an ash that has a high concentration of K, since this element is not volatile at this temperature.

For the treatments that contained pure phonolite, there was no difference between the contents observed, however, for the accumulation, it was observed that the treatments with calcination at 300 and 1000 ºC presented the lowest accumulations of this treatment.

Nogueira *et al.* (2021) used phonolite as a source of K in corn and found an increase in K in corn plants. Furthermore, different phonolite doses did not influence leaf chlorophyll index, but increased plant height, stem diameter and shoot dry matter. These results indicate the efficiency of phonolite as alternative sources of K for corn.

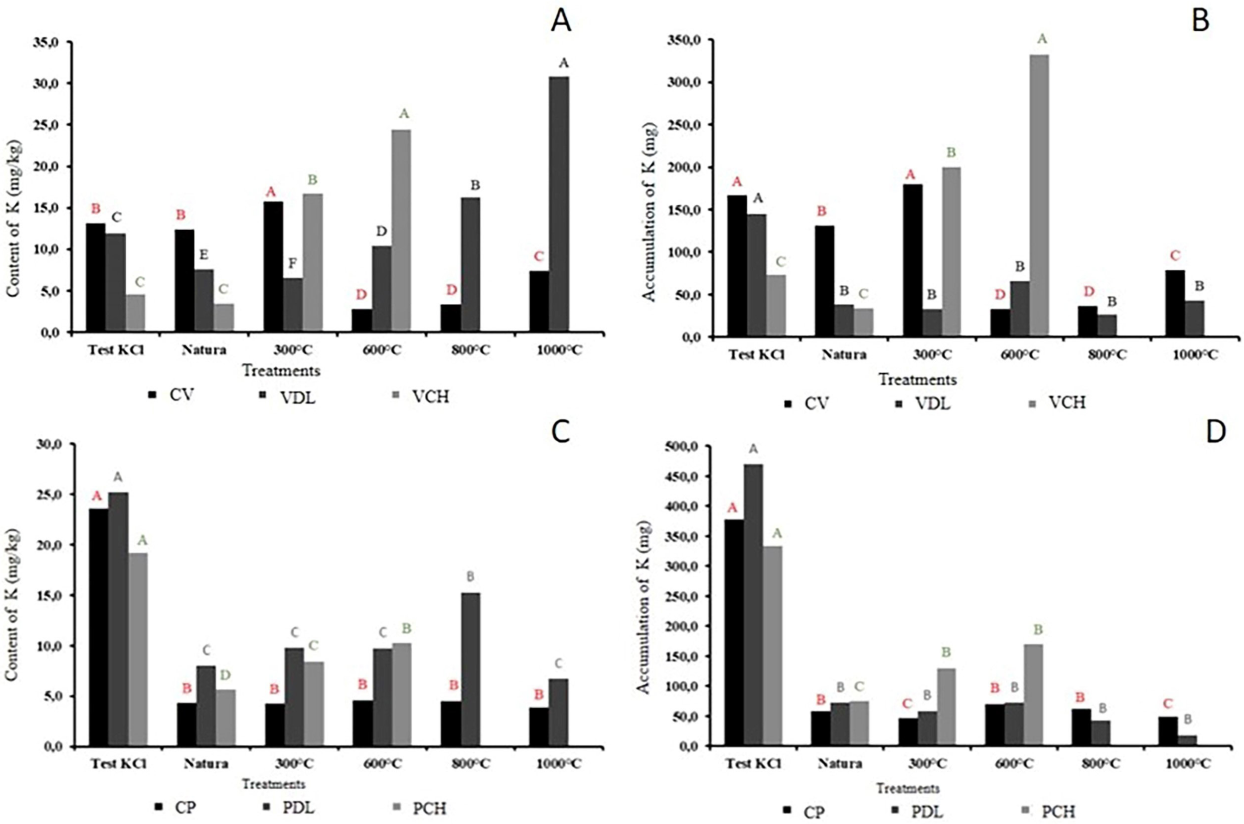

Figure 4: A. Content and B. accumulation of P in the dry matter of maize plant grown with verdete rock. C. Content and D. accumulation of P in the dry matter of maize plants grown with phonolite rocks. Calcined verdete (CV), verdete in mixture with dolomitic limestone (VDL) and verdete with coffee husk (VCH). Calcined Phonolite (CP), Phonolite in mixture with dolomitic limestone (PDL) and Phonolite with coffee husk (PCH).

The treatments that contained calcined phonolite with coffee husk showed an increase in the K content with increasing calcination (Figure 4C), a trend that was also observed for the accumulation of this nutriente (Figure 4D).

With respect to the treatment with dolomitic limestone, it could be noted an increase in the K content in the dry matter of corn plants until the treatment with samples calcined at 800 °C and reduction at 1000 °C. For the accumulation, although there is no statistical difference, a similar trend is observed, with a reduction in the accumulation of the nutrient in the plant in the treatment with samples calcined at 1000 °C.

Mancuso *et al.* (2014) could reinforce the premise that the use of alternative sources of low solubility should be considered mainly as a partial replacement or complement to conventional fertilizer. On the other hand, the previous treatment of these sources can increase the solubility of the rocks, as well as increasing their potential for agricultural use. However, there is the fact that fertilisation is often carried out in doses that are much higher than plant demands and this occurs because soluble sources of high concentration present remarkable losses, for instance, potassium by leaching. Thus, there is still a lack of studies with these alternative sources that associate the solubilities determined in the laboratory with the results obtained in crops.

Concernig a temperature near 600 ºC, there is a break in the crystalline structure of the verdete rocks, which should increase the solubility of the rock with a consequent increase in the availability of nutrients. At a temperature near 1000 ºC there is another change in the structure of the rock, seeing that at this temperature the solubility apparently decreases, a condition that may be different depending on the material being calcined or ground.

At temperatures above 600 ºC the rock changes colour from greenish to light brown and above about 1000 ºC the colour becomes dark, and above this temperature a melting process begins and when cooled the rocks become black amorphous, thus indicating a severe alteration in the original crystalline structure of the rock. Despite being originally different, metamorphic and sedimentary verdete rock and phonolite rock of volcanic origin, it is noted that both rocks have feldspars as the main source of K.

However, the study has some limitations, such as the short agronomic evaluation time without evaluation of the residual effect and the small useful volume of the vessels (2 kg), which may influence the results and their interpretation. However, it was the conditions that the researchers had for carrying out the experiment. Thus, future studies should be carried out to eliminate this possible influence of vessel volume on the results obtained.

CONCLUSION

Under the conditions in which the experiment was carried out, calcination altered the solubility of the evaluated rocks, and the calcination temperature range between 300 °C and 600 °C made K more available. The highest biomass was obtained from rocks mixed with coffee husks, influenced by temperatures. The least efficient treatment in the production of biomass was the mixing of rocks with dolomitic limestone.

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REFERENCES

Arrieta RG, Gualberto CAC, Prudente TS, Santos GA, Silveira LH & Pereira HS (2020) Glauconitic Siltstone as a Source of Potassium, Silicon and Manganese for Flooded Rice. Journal of Agricultural Science, 12:96-104.

Bamberg AL, Martinazzo R, Silveira CAP, Pillon CN, Stumpf L, Bergmann M & de Souza ME (2023) Soil fertilization and maize-wheat grain production with alternative sources of nutrients. Research Article, In Press.

Boldrin KVF, Paiva PDO, Boldrin PF, Neto AEF & Almeida BR (2019) Alternative sources of potassium in the growth of calla lily. Scientia Horticulturae, 255:96-102.

Brasil - Departamento Nacional da Produção Mineral (2013) Potássio. Available at: <https://sistemas.dnpm.gov.br/publicacao/mostra_imagem.asp?IDBancoArquivArquivo=7404>. Accessed on: January 29th, 2019.

Clemente JM, Martinez HEP, Alves LC & Lara MCR (2013) Effect of N and K doses in nutritive solution on growth, production and coffee bean size. Revista Ceres, 60:279-285.

De Toledo FHSF, de Moraes Gonçalves JL, Mariño YA, de Vicente Ferraz A, de Oliveira Ferreira EV, Moreira GG, Hakamada R & Arthur Júnior JC (2019) Aboveground biomass, transpiration and water use efficiency in eucalypt plantation fertilized with KCl, NaCl and phonolite rock powder. New Forests, 51:469-488.

Ferreira DF (2011) Sisvar: A computer statistical analysis system. Ciência e Agrotecnologia, 35:1039-1042.

Malavolta E (1980) Elementos de nutrição mineral de plantas. Piracicaba, Agronômica Ceres. 251p.

Malavolta E, Vitti GC & Oliveira AS (1997) Avaliação do estado nutricional de plantas: princípios e aplicações. 2ª ed. Piracicaba, Potafos. 308p.

Mancuso MAC, Oratto RP, Crusciol CAC & Castro GSA (2014) Effect of potassium sources and rates on Arabica coffee yield, nutrition, and macronutrient export. Revista Brasileira de Ciência do Solo, 38:1448-1456.

Martins V, Gonçalves ASF, Marchi G, Guilherme LRG & Martins EDS

(2015) Solubilização de potássio em misturas de verdete e calcário tratadas termoquimicamente. Pesquisa Agropecuária Tropical, 45:66-72.

Mendoza J & Borie F (1998) Effect of Glomus etunicatum inoculation on aluminum, phosphorus, calcium, and magnesium uptake of two barley genotypes with different aluminum tolerance. Communications in Soil Science and Plant Analysis, 29:681-695.

Miranda RA (2018) Uma história de sucesso da civilização. A Granja, 74:24-27.

Miyamoto W, Kosai S & Hashimoto S (2019) Evaluating metal criticality for low-carbon power generation technologies in Japan. Minerals, 9:95-111.

Nogueira TAR, Miranda BG, Jalal A, Lessa LGF, Filho MCMT, Marcante NC, Abreu-Junior CH, Jani AD, Capra GF, Moreira A & Martins ES (2021) Nepheline Syenite and Phonolite as Alternative Potassium Sources for Maize. Agronomy, 11:1385-1392.

Orlando Filho JO, Bittencourt VC, Carmello QAC & Beauclair EF (1996) Relações K, Ca e Mg de solo areia quartzosa e produtividade da cana-de-açúcar. Sociedade dos Técnicos Açucareiros e Alcooleiros do Brasil, 14:13-17.

Pessoa RS, Silva CA, Moretti BS, Furtini Neto AE, Inda AV & Curi N (2015) Solubilization of potassium from alternative rocks by humic and citric acids and coffee husk. Ciência e Agrotecnologia, 39:553-564.

Santos WO, Mattiello EM, Vergutz L & Costa RF (2016) Production and evaluation of potassium fertilizers from silicate rock. Journal of Plant Nutrition and Soil Science, 179:547-556.

Santos WO, Mattiello EM, Costa LM, Abrahão WAP, Novais RF & Cantarutti RB (2015) Thermal and chemical solubilization of verdete for use as potassium fertilizer. International Journal Of Mineral Processing, 140:72-78.

Silva AAS, Medeiros ME, Sampaio JÁ & Garrido FMS (2012) Caracterização do verdete de Cedro do Abaeté para o desenvolvimento de um material com liberação controlada de potássio. Holos, 28:42-51.

Tavares LF, Carvalho AMX, Camargo LGB, Pereira SGDF & Cardoso IM (2018) Nutrients release from powder phonolite mediated by bioweathering actions. International Journal of Recycling of Organic Waste in Agriculture, 7:89-98.

Teixeira AMS, Garrido FMS, Medeiros ME & Sampaio JA (2015) Estudo do comportamento térmico da rocha fonolito com fins à produção de fertilizantes. Holos, 31:52-64.

Tomé Júnior JB (1997) Manual para interpretação de análise de solo. São Paulo, Agropecuária Guaíba. 247p.

Violatti ICA, Gualberto CAC, Silveira LH, Santos GA, Ferreira BC, Machado PMM & Pereira HS (2019) Glauconitic siltstone as a multi-nutrient fertilizer for *Urochloa brizantha* cv. Marandú. Australian Journal of Crop Science, 13:1280-1287.

Zoca SM, Penn CJ, Rosolem CA, Alves AR, Neto LO & Martins MM (2014) Coffee processing residues as a soil potassium amendment. International Journal of Recycling of Organic Waste in Agriculture, 3:155-165.