

## Kamafugite From the Alto Paranaíba Province as a Multi-nutrient Fertilizer

Bárbara Campos Ferreira<sup>1</sup>, Camila de Andrade Carvalho Gualberto<sup>1</sup>, Georgy Faroutine<sup>1</sup>,  
Hamilton Seron Pereira<sup>1</sup>, Gaspar Henrique Korndörfer<sup>1</sup>, Eduardo Spolidorio<sup>2</sup> & Luiz Carlos Clerot<sup>3</sup>

<sup>1</sup> Institute of Agricultural Sciences, Federal University of Uberlândia, Uberlândia, Brazil

<sup>2</sup> Piracicaba, São Paulo, Brazil

<sup>3</sup> São Leopoldo, Rio Grande do Sul, Brazil

Correspondence: Bárbara Campos Ferreira, Institute of Agricultural Sciences, Federal University of Uberlândia, Amazonas Avenue, Building 4C, Room 123, P.O. Box 38400-902, Uberlândia, MG, Brazil. Tel: 55-34-99991-3123. E-mail: barbaracampos11@hotmail.com

Received: July 13, 2020

Accepted: August 24, 2020

Online Published: September 15, 2020

doi:10.5539/jas.v12n10p213

URL: <https://doi.org/10.5539/jas.v12n10p213>

### Abstract

The study evaluated the potential agricultural use of kamafugite as a multi-nutrient fertilizer in the cultivation of *Urochloa brizantha*. Two experiments were carried out under greenhouse conditions, one using a Ferralsol and the other an Arenosol. The experimental design was a randomized block with four replicates, in a factorial scheme  $4 \times 2 + 2$ , comprising four doses of kamafugite (1667, 3334, 6668, and 13336 mg dm<sup>-3</sup>), two product forms (filler and powder), and two additional treatments, TSF + KCl and a control treatment without K<sub>2</sub>O and P<sub>2</sub>O<sub>5</sub> application. The sources were incubated for 60 days on two soil types and, after the incubation period, *Urochloa brizantha* plants were grown and two consecutive cuts were performed. The kamafugite was efficient in increasing plant dry mass and the levels of P, K, Ca, and Mg accumulated in plants, mainly in the 2nd *Urochloa brizantha* crop. The granulometry filler was more efficient in the sandy soil and the form powder in the clayey soil. Kamafugite can be used as an alternative source of nutrients for the *Urochloa brizantha* crop, being a low-cost and a potential source to improve tropical soil fertility over time.

**Keywords:** agronomic efficiency, natural fertilizer, rock dust, *Urochloa brizantha*

### 1. Introduction

Brazilian soils, especially in the Cerrado biome, have low fertility and availability of macronutrients such as phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) due to climatic conditions prevailing in the country that resulted in weathering. The soil properties, which predominate the high acidity (pH < 4-5), low cation exchange capacity, low base saturation, high levels of Al<sup>3+</sup> and ions of Fe and Mn are obstacles to agricultural practices. Only after practices like liming and application of mineral fertilizers, which can supply the amount of macro and micronutrients, these soils become suitable for continuous planting of grains, oilseeds, and other crops (Prado, Benites, Polidoro, Gonçalves, & Naumov, 2012).

Among the nutrients, P is one of the major constraints of agricultural production in tropical soils since it presents a complex dynamic in these soils. Under acidic conditions, Fe and Al oxides are preferably positively charged, being able to retain phosphate ions on their surface. Therefore, more phosphate fertilizers than those required by plants are used in order to saturate the components responsible for nutrient fixation. In this context, more than 5 million tons of phosphate fertilizers were delivered to the final consumer in Brazil in 2017 (ANDA, 2017). As observed for P, soil K levels must also be supplied with the use of fertilizers. From the total potassic fertilizers used in Brazil, 95% is imported in the form of potassium chloride (KCl) (IPNI, 2016), representing a big impact on the country's trade balance.

The search for low-cost sources of nutrients associated to the scarcity of fertilizers applicable to agroecological farming systems and the increase dependence on fertilizer imports make the use of agrominerals in agriculture an important alternative to Brazilian soil fertilization. Thus, some specific rocks are nutrient low-release sources, which reduce losses by leaching and fixation, as well as have a long-term action. Kamafugitic rocks are

examples that have significant amounts of nutrients in their composition and may increase soil fertility in the medium to long-term, according to their solubility and soil reaction.

Kamafugites constitute a group of rare rocks found in a few locations in the world, *e.g.*, Uganda, Italy, Brazil, and China. According to Junqueira-Brod et al. (2002), these rocks occur in Brazil as extensive spills and deposits, forming two of the largest kamafugitic provinces of the planet, the Igneous Province of Alto Paranaíba (PIAP)-Mata da Corda Group and the Alkaline Province of Goiás (PAGO). Nascimento et al. (2008) affirm that these rocks are potential sources of macronutrients (P, K, Ca and Mg) and can be considered as “multi-nutrient” sources.

In this sense, the use of alternative sources of nutrients, such as kamafugite, is a practice with potential to promote benefits in areas cultivated with *Urochloa brizantha* cv. Piatã (Syn. *Brachiaria brizantha*). In general, approximately 80% of the Brazilian tropical pastures are in some degree of degradation, so, the proper management of the fertility of soils cultivated under pasture is a fundamental practice to recover degraded areas. In addition, livestock farming is developed with low investments and the use of agrominerals can be a viable, economical and ecological alternative, given its availability, low production cost and long-term nutrient release.

In this context, the objective of this study was to evaluate the potential of agricultural use of kamafugite, in filler and powder forms, as a source of P, K, Ca, and Mg for *Urochloa brizantha* cv. Piatã (Syn. *Brachiaria brizantha*).

## 2. Materials and Methods

### 2.1 Product Characterization

The kamafugitic rock is originated in the region of Alto Paranaíba, county of Lagoa Formosa, Minas Gerais, Brazil (18°53'11" S; 46°19'30" W). These rocks are classified as mafic to ultramafic, with ultrapotassic affinity ( $K_2O/Na_2O$  molar ratio > 3), whose occurrence is commonly associated with the continental rifts. Such condition allows the crystallization of K-rich minerals such as phlogopite, leucite, and kalsilite (Le Maitre, 2002; Brod et al., 2000; Sahama, 1974). Due to the phosphate mineralization in practically the entire region of occurrence of the material rock, 1.5 to 2.5% of  $P_2O_5$  are found, with occasional occurrences that can reach contents of up to 25%  $P_2O_5$ .

The kamafugite used in the present study is an alkaline volcanic rock, containing leucite, kalsilite, pyroxene, olivine, perovskite, and rarely phlogopite. The highest levels of phosphate occur associated with facies with swarms of white venules of calcite and apatite that give a breached aspect to the rock. The powder and filler kamafugite forms were obtained by crushing and milling processes. Thus, the product in filler form is obtained by passing 100% of particles in 0.3 mm sieve, containing 4.0 and 1.2% of total and available  $K_2O$ , respectively, as well as 3.1% of total  $P_2O_5$ , 1.94% of available  $P_2O_5$ , 1.4% of  $CaO$ , and 0.7% of  $MgO$ . The product was also applied as a powder, obtained by passing 100% of particles in 2.0 mm sieve, presenting 4.0% of total  $K_2O$ , 1.2% of available  $K_2O$ , 3.3% of total  $P_2O_5$ , 1.97% of available  $P_2O_5$ , 1.7% of  $CaO$ , and 0.5% of  $MgO$ .

Both product forms were characterized according to macronutrient contents, determined on a flame photometer according to the method described by MAPA (2017). In addition to kamafugite, triple superphosphate (TSF) and potassium chloride (KCl), containing 45% of total  $P_2O_5$  and 60% of total  $K_2O$ , respectively, were used as standard sources. The chemical characteristics of nutrient sources used in this study were determined according to methodology described in Silva (2009).

### 2.2 Experiment Conduction

Two experiments were conducted in the period of 12/22/2017 to 10/19/2018, under greenhouse conditions, at the Institute of Agricultural Science at Federal University of Uberlândia, Umuarama Campus, Minas Gerais, Brazil, at the geographical coordinates 18°52'40" S; 48°15'20" W. Each experiment was conducted using samples of two soil types collected at 0-20 cm depth in the state of Minas Gerais. These soils were classified according to World Reference Base (WRB) for Soil Resources (FAO, 2015) as Ferralsol (clayey soil) and as Arenosol (sandy soil) with 84% and 14% of clay, respectively. The clayey soil presented pH equal to 4.5 (1:2.5 soil sample/water ratio), 0.2 mg  $dm^{-3}$  of P, 19.6 mg  $dm^{-3}$  of K (both P and K were measured by Mehlich-1 method), 0.2 cmol<sub>c</sub>  $dm^{-3}$  of  $Ca^{2+}$ , and 0.1 cmol<sub>c</sub>  $dm^{-3}$  of  $Mg^{2+}$  ( $Ca^{2+}$  and  $Mg^{2+}$  were measured by AAS on 1.0 mol  $L^{-1}$  KCl extracts added with lanthanum oxide). The sandy soil presented pH equal to 4.4, 3.1 mg  $dm^{-3}$  of P, 11.7 mg  $dm^{-3}$  of K, 0.2 cmol<sub>c</sub>  $dm^{-3}$  of  $Ca^{2+}$ , and 0.1 cmol<sub>c</sub>  $dm^{-3}$  of  $Mg^{2+}$ , measured using the same methods as used for clayey soil.

The experiment followed a completely randomized design with four replicates, comprising 96 total plots in factorial scheme  $4 \times 2 + 2$ . Four doses of kamafugite (1667, 3334, 6668, and 13336 mg  $dm^{-3}$ ) were applied resulting in four  $P_2O_5$  doses (63, 126, 252, and 504 mg  $dm^{-3}$  of  $P_2O_5$ ) and four  $K_2O$  doses (20, 40, 80, and 160 mg  $dm^{-3}$  of  $K_2O$ ) in two product forms (filler and powder), calculated as a function of the total  $K_2O$  and  $P_2O_5$

contents present in the kamafugite. In addition, a treatment including TSF + KCl (252 mg dm<sup>-3</sup> of P<sub>2</sub>O<sub>5</sub> and 80 mg dm<sup>-3</sup> of K<sub>2</sub>O) was used as standard treatment, as well as a control treatment without P<sub>2</sub>O<sub>5</sub> and K<sub>2</sub>O application. In order to maintain humidity, around 80% of the field capacity value for each soil, deionized water was added to pots. Soil moisture was rigorously controlled by daily weighing of the plastic containers, replacing the volume lost through evapotranspiration with deionized water.

The treatments were incubated for 60 days in 5 dm<sup>-3</sup> of the two soil types (clayey and sandy soils). The soil moisture was controlled by daily weighing of the plastic containers, replacing the volume lost through evapotranspiration with deionized water to maintain humidity around 80% of the field capacity value for each soil. All treatments received equal doses of CaCO<sub>3</sub> and MgCO<sub>3</sub> to correct the soil acidity and increase the bases saturation to 70%. After the incubation period, 200 mg kg<sup>-1</sup> of N were added to samples through the ammonium sulfate ((NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>). Micronutrients were also supplied adding 1.5, 5.0, 0.5, and 0.05 mg dm<sup>-3</sup> of Cu, Zn, B, and Mo through CuSO<sub>4</sub>·5H<sub>2</sub>O, ZnSO<sub>4</sub>·7H<sub>2</sub>O, H<sub>3</sub>BO<sub>3</sub> and (NH<sub>4</sub>)<sub>6</sub>Mo<sub>7</sub>O<sub>24</sub>·4H<sub>2</sub>O, respectively. Ten seeds of *Urochloa brizantha* cv. Piatã (Syn. *Brachiaria brizantha*) were sown per pot, at a depth of 2 cm. After the emergence of the seedlings, thinning was carried out, maintaining six plants per pot.

At 15 and 30 DAS (days after sowing), ammonium sulfate was applied providing 50 mg dm<sup>-3</sup> of N. Daily irrigation was done as well as periodic observations to evaluate the possible incidence of pests and plant diseases in *Urochloa brizantha* cultivation.

### 2.3 Plant and Soil Analysis

Two *Urochloa brizantha* plant cuts were performed approximately at 4 cm above ground level at 40 and 80 DAS. After the second plant cut, soil samples were also collected. The plant samples were dried in an oven at 65 °C until reaching constant weight and weighed to obtain dry matter of the aerial part (DM). Afterwards, the samples were ground and submitted to nitric-perchloric digestion (Sarruge & Haag, 1974). After that, the nutrients concentrations in the plant were analysed according to Silva (2009). Soil chemical analyses were performed according to Teixeira, Donagemma, Fontana, and Teixeira (2017) (soil available P, K, Ca and Mg).

The contents of nutrients in the aerial part were converted to accumulated values using DM values, obtaining values in mg pot<sup>-1</sup>. Using the nutrient accumulated values, agronomic efficiency index (AEI) of the kamafugite relative to TSF + KCl was calculated using the equation proposed by Fageria, Santos, and Moraes (2010):

$$AEI (\%) = (\text{kamafugiteDM} - \text{controlDM}) / (\text{TSF} + \text{KClDM} - \text{controlDM}) \times 100 \quad (1)$$

The kamafugite DM refers to the plant DM with the application of the kamafugite (80 mg dm<sup>-3</sup> of K<sub>2</sub>O and 252 mg dm<sup>-3</sup> of P<sub>2</sub>O<sub>5</sub>), TSF + KCl DM refers to the plant DM with the application of TSF + KCl (252 mg dm<sup>-3</sup> of P<sub>2</sub>O<sub>5</sub> + 80 mg dm<sup>-3</sup> of K<sub>2</sub>O) and the control DM refers to the plant DM in the additional control treatment without P<sub>2</sub>O<sub>5</sub> and K<sub>2</sub>O application.

### 2.3 Statistical Analysis

Results of each variable were submitted to variance analysis according to Tukey's test at 0.05 of significance, as well as polynomial regression analysis using the SISVAR statistical program (Ferreira, 2014). The treatments were compared to control treatment and to standard treatment (TSF + KCl) using the Dunnett's test at 0.05 of significance (Silva & Azevedo, 2009).

## 3. Results and Discussion

The effects of kamafugite on *Urochloa brizantha* plant DM after consecutive cuts, as compared with TSF + KCl, are shown in Figure 1. In general, the application of both kamafugite forms resulted in higher DM values than the control treatment, mainly after the application of the highest doses (Figure 1). At 40 DAS, the application of 6668 mg dm<sup>-3</sup> of the product in the filler form in sandy soil provided the highest DM values, which were close to the DM values of the standard treatment TSF + KCl (Figure 1b). At 80 DAS in clayey soil, at the highest doses of kamafugite, the dry mass values were higher than the standard treatment TSF + KCl, regardless the product form (Figure 1c). After the second growth, these values ranged, on average for both kamafugite forms, from 10 to 18 g pot<sup>-1</sup> in clayey soil and from 11 to 16 g pot<sup>-1</sup> in sandy soil. This result demonstrates the good residual effect of the product when compared to the first cut, increasing the plant dry matter production over time.

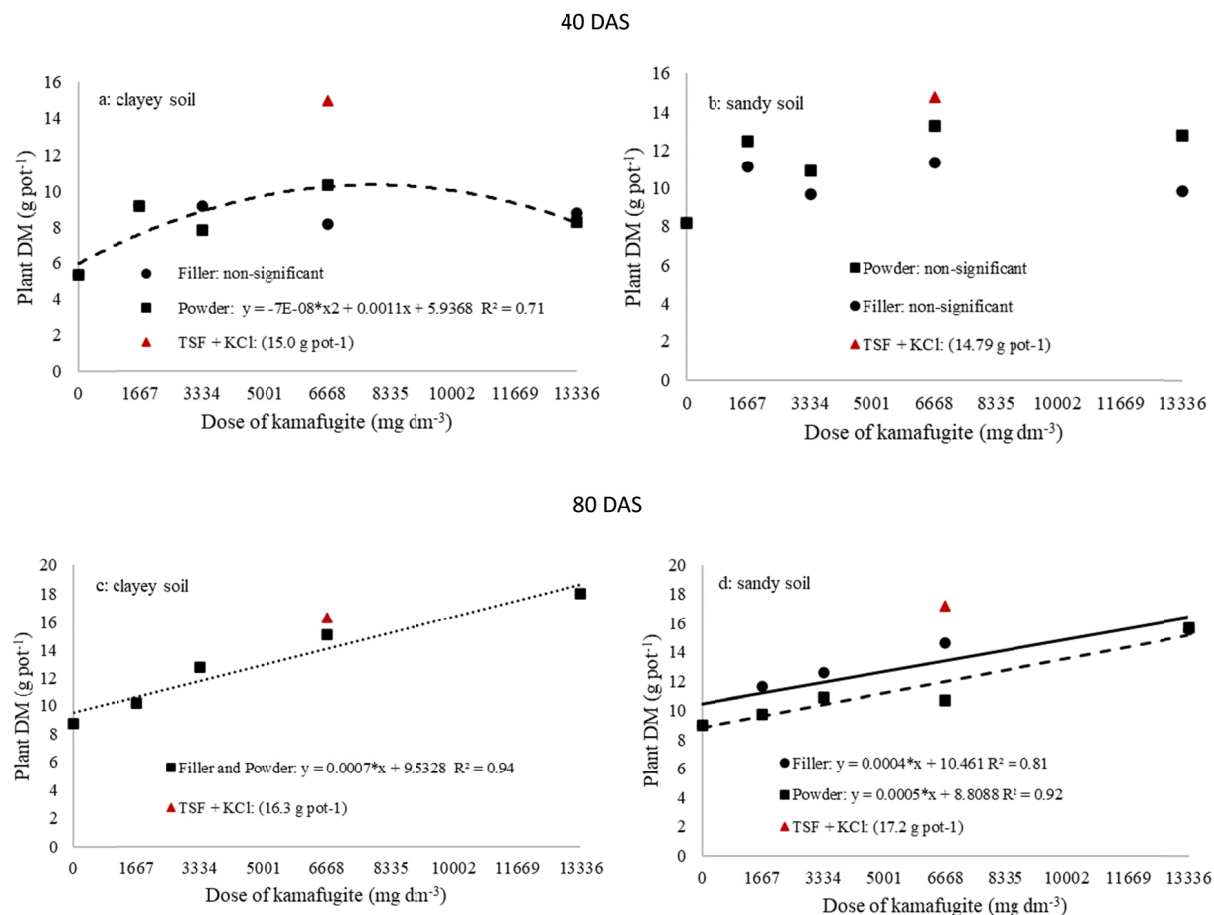


Figure 1. *Urochloa brizantha* plant dry matter (DM) at 40 days after sowing in clayey soil (a) and in sandy soil (b) and 80 days after sowing in clayey soil (c) and in sandy soil (d) as function of increasing doses of kamafugite. Triangles symbols refer to the TSF + KCl treatment applied at the dose of 252 mg dm<sup>-3</sup> of P<sub>2</sub>O<sub>5</sub> and 80 mg dm<sup>-3</sup> of K<sub>2</sub>O

Both TSF and KCl are soluble sources with high availability. In addition, the TSF supplies P faster than the agromineral, favoring the first crop production, despite the kamafugite has shown to be more efficient in increasing plants dry matter over time. The application of slow-releasing fertilizers, such as the kamafugite, can supply crop demand for nutrients after consecutive cycles (Resende et al., 2006). Thus, the nutrient release from rocks is slow and gradual, which reduces nutrient losses by leaching, such as K, and results in a long-term release (Martins, Gonçalves, Marchi, Guilherme, & Martins, 2015). In addition, according to Novais and Smyth (1999), fertilizers with lower reactivity increase P availability slowly, minimizing the fixation processes and improving nutrient use by crops.

The effect of kamafugite application on plant development can also be noted analyzing agronomic efficiency index (AEI) values (Figure 2). Comparing AEI values from kamafugite treatments with the TSF + KCl, the product showed lower values (< 100%) at 40 DAS, since the TSF and KCl have higher solubility and provide P and K immediately to plants. At 80 DAS, both forms of kamafugite presented higher AEI values, mainly in the clay soil, reaching almost 90% of agronomic efficiency (Figure 2A). In general, higher AEI values were observed at 80 DAS, evidencing the good residual power of the product, providing the nutrients to the plants gradually and avoiding losses by fixation and leaching as previously discussed.

The use of slow-release fertilizers is especially relevant in tropical areas where nutrient contents are generally low and plant deficiency frequently occurs after a few years of cropping on such highly developed soils (Darunsonntaya, Suddhiprakarn, Kheoruenromne, Prakongkep, & Gilkes, 2012).

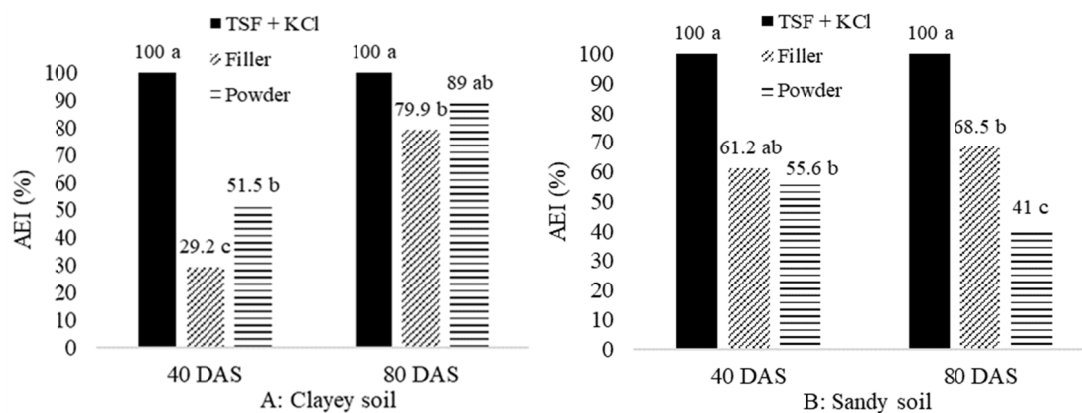


Figure 2. Agronomic efficiency index (AEI) of the kamafugite relative to TSF + KCl in clayey (A) and sandy (B) soils at 40 and 80 days after sowing. Different letters within each column group denote significant difference between treatments ( $p < 0.05$ )

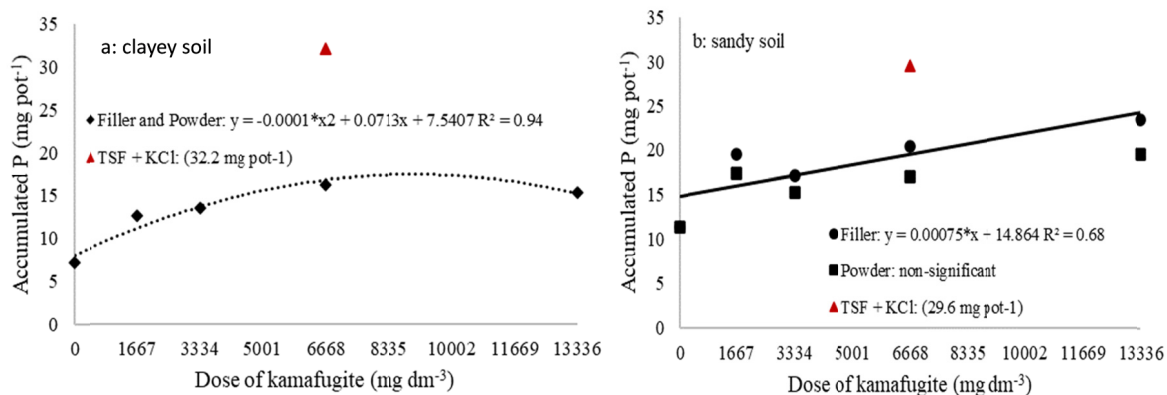
In the clayey soil, unlike in sandy soil, there is a better kamafugite performance in the powder form (Figure 2a). This is due to the finer grain size of the filler product form, favoring the fixation of the P in clayey soils, which has, preferably, positive charges, retaining several types of anions on their surfaces, as P ions. In the sandy soil, the filler form of kamafugite promoted better results in relation to powder form (Figure 2b), since this soil presents less potential to fix the P released by the source, increasing the P content in soil solution and the nutrient availability to plants.

At 40 DAS, the application of the highest kamafugite doses in both soil types increased accumulated P values, yet the effects are not comparable with the ones obtained in the TSF + KCl treatment (Figures 3a and 3b). This result was expected since conventional sources of P have greater solubility, releasing the nutrient faster and showing better results in the first crop cycle. Kamafugite is a less soluble product, with gradual release of nutrients, thus better results are expected in consecutive crops.

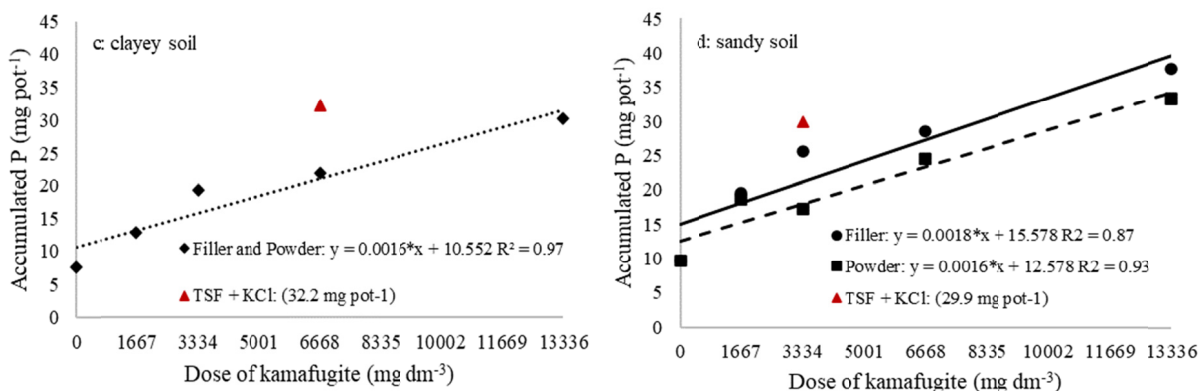
It was observed that, in general, the application of kamafugite in both soils linearly increased the accumulated P values in the aerial part of *Urochloa brizantha* plants harvested at 80 DAS (Figures 3c and 3d). In the clayey soil, regardless the product form, an increment of  $20 \text{ mg pot}^{-1}$  of accumulated P was observed with the highest dose of kamafugite ( $13336 \text{ mg dm}^{-3}$ ) (Figure 3c). In the sandy soil, the application of the highest dose of the product resulted in higher accumulated P values than the standard TSF + KCl treatment, as well as the finer form of the product (filler) was more efficient in promoting the accumulation of P in *Urochloa brizantha* plants than the powder form (Figure 3d).

There was a tendency of the product to increase the availability of P to plants in consecutive crops. This fact demonstrates that the application of the highest agromineral doses can result in a production equivalent to more soluble sources, revealing the potential of kamafugite to provide P to plants and its good residual effect. In this sense, Guedes, Fernandes, Lima, Gama, and Silva (2009), reported that low solubility P sources have lower efficiency in a short-term than soluble phosphates, but their residual effect is generally higher over time.

40 DAS



80 DAS



Soil

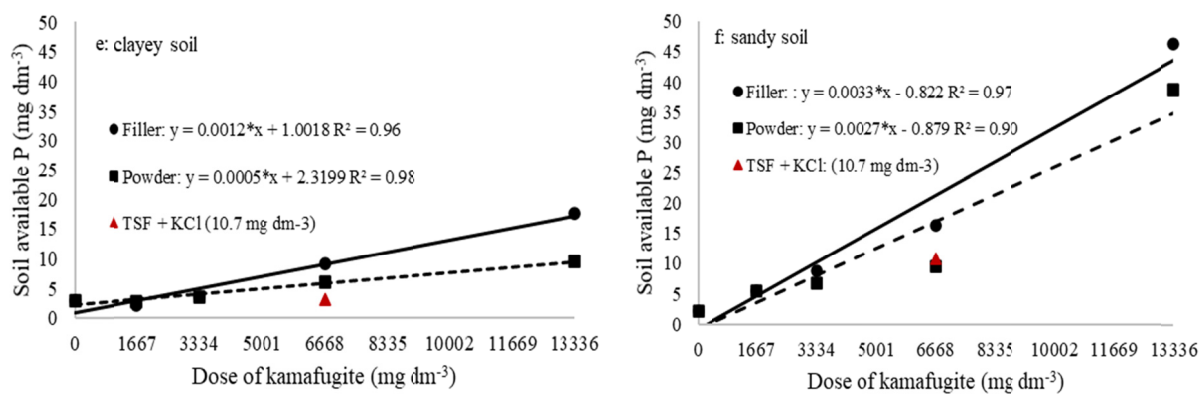


Figure 3. P accumulated in *Urochloa brizantha* plants at 40 days after sowing in clayey (a) and sandy (b) soils, 80 days after sowing in clayey (c) and sandy (d) soils and soil available P in clayey (e) and sandy (f) soils as function of increasing doses of kamafugite. Triangles symbols refer to the TSF + KCl treatment applied at the dose of 252 mg dm<sup>-3</sup> of P<sub>2</sub>O<sub>5</sub> and 80 mg dm<sup>-3</sup> of K<sub>2</sub>O

The product showed a great potential to increase soil P contents in both soils, especially at the highest dose (13336 mg dm<sup>-3</sup> of kamafugite), resulting in increases of 3-fold and 40-fold when compared to control treatment in clayey soil and sandy soil, respectively (Figures 3e and 3f). When applied at the same doses, the kamafugite showed to be more efficient in increasing P contents than the standard treatment TSF + KCl in both soils (Figures 3e and 3f). Caione, Lange, Benett, and Fernandes (2011) affirm that phosphate fertilizers with low

solubility in water and good solubility in weak acids present slower release of P to soil, decreasing their soil fixation potential. The use of slow-release nutrient source is especially important to grasses of the genus *Urochloa*, which can promote soil acidification and, consequently, a higher reactivity of natural fertilizer during its development (Dias et al., 2015).

In clayey soil, the application of kamafugite at doses of 6668 and 13336 mg dm<sup>-3</sup> of P<sub>2</sub>O<sub>5</sub> resulted in soil P contents considered appropriated and high, respectively, according to Sousa and Lobato (2002) (Figure 3e). In sandy soil, the P content increased from very low to adequate and high following the application of increases doses of kamafugite in the powder and filler form, respectively (Sousa & Lobato, 2002) (Figure 3f). These results are especially important in tropical agroecosystems where *Urochloa brizantha* plants are largely grown, since the low soil P availability is a major constraint to agricultural production in acid soils of tropical and subtropical regions (Ramos, Faquin, Rodrigues, Silva, & Boldrin, 2009).

In clayey soil, both forms of kamafugite applied increased the accumulated K values in the aerial part of *Urochloa brizantha* plants harvested at 40 DAS in relation to the control, yet lower than the standard treatment TSF + KCl. Only on this soil, the product in the filler form was more efficient than the powder form (Figure 4a). At 40 DAS, as the dose of kamafugite applied to sandy soil through both product forms soil was increased, increase in accumulated K values were also obtained (Figures 4a and 4b). At 80 DAS, the application of the highest dose of kamafugite (13336 mg dm<sup>-3</sup>) increased plant accumulated K values in both soils (Figures 4c and 4d). At the highest K<sub>2</sub>O dose applied through kamafugite in clayey soil, accumulated K values were higher than the standard treatment TSF + KCl (Figure 4c). At the same dose (13336 mg dm<sup>-3</sup> of kamafugite) in sandy soil, accumulated K values do not differ statistically from the standard treatment (Figure 4d). Those results show the efficacy of kamafugite in providing K to plants when compared to more soluble sources, with higher nutrient concentration.

The application of soluble K-sources, as KCl, results in a low K retention in soil's cation-exchange capacity since the element presents a small hydrated ion load and size (Takahashi, Dahlgren, Kanno, Nanzyo, & Takahashi, 2018). The K present in the kamafugite is released to soil in a gradual form, avoiding leaching losses and, consequently, being better utilized by plants. Thus, the kamafugite can be used as a sustainable and low-cost source of K for long term crops, as this rock releases K<sub>2</sub>O slowly and reduces the demand for more expensive chemical fertilizers after consecutive growth cycles. Martins et al. (2014) also highlighted the potential of ultrapotassic rocks as alternative sources of K for agriculture in addition to conventional sources (KCl).

The observed increases in plant K contents following the application of the kamafugite are related to the chemical composition of this source, since it has 4 dag dm<sup>-3</sup> of K<sub>2</sub>O. The kamafugite K-content can be attributed to the ultrapotassic nature of these rocks, which is related to the excess of K<sub>2</sub>O in relation to Na<sub>2</sub>O. Such condition allows the crystallization of potassium rich minerals such as phlogopite, leucite, and kalsilite.

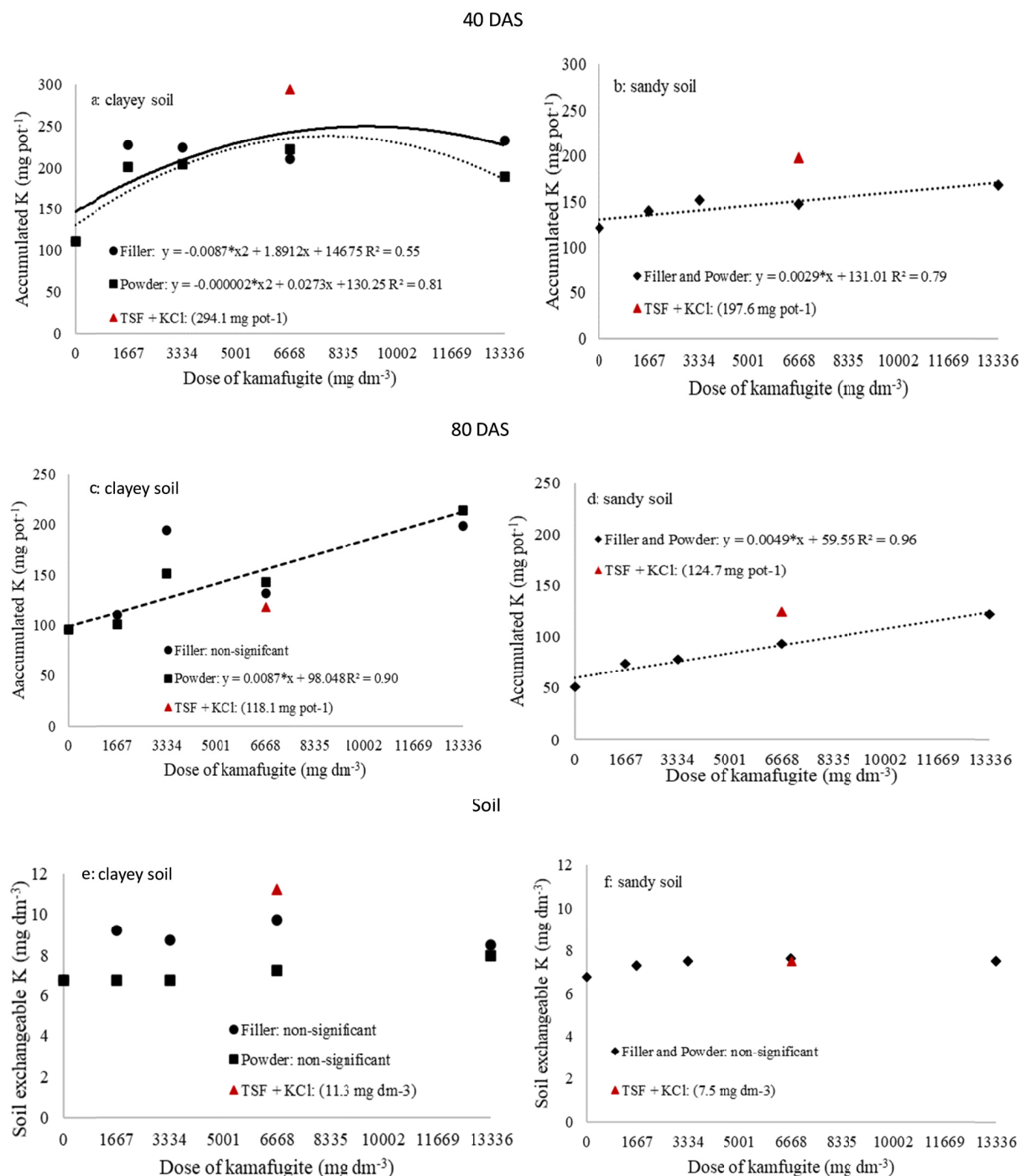


Figure 4. K accumulate in *Urochloa brizantha* plants at 40 days after sowing in clayey (a) and sandy (b) soils, at 80 days after sowing in clayey (c) and sandy (d) soils and soil exchangeable K in clayey (e) and sandy (f) soils as functions of increasing doses of kamafugite. Triangles symbols refer to the TSF + KCl treatment applied at the dose of 252 mg dm<sup>-3</sup> of P<sub>2</sub>O<sub>5</sub> and 80 mg dm<sup>-3</sup> of K<sub>2</sub>O

The kamafugite did not increase soil K contents when compared to the control. In the clayey soil, the filler form was more efficient in increasing soil K contents than the powder form (Figure 4e). In the sandy soil, soil K contents following the application of kamafugite did not differ from the same dose applied by the KCl source in the standard treatment (TSF + KCl), which suggests that the K found in the soil after the incubation period was available to the plants (Figure 4f). Ribeiro, Santos, L. F. S. Souza, and J. S. Souza (2016) observed a reduction in



the exchangeable soil K contents after soybean planting, for both ultramafic alkaline rock and pyroclastic breccia, suggesting that the nutrient was absorbed by the plants.

Due to the high K mobility in soil, the exchangeable K content does not efficiently represent the availability of this nutrient in soils with different mineralogical, physical, and chemical characteristics (Meurer & Anghinoni, 1993). In addition, because they are rocks with a gradual release of nutrients, it is expected that with a longer incubation time than the one used in this study, greater K-release to soil would occur.

Bakken, Gautneb, Sveistrup, and Myhr (2000), studying the use of biotite and carbonatite as sources of K over three years in pasture cultivation, observed that in the last year of the study, without the addition of any K fertilizer, the effects of carbonatite and biotite were comparable to the KCl. These authors concluded that increasing the evaluation period may result in gains comparable to those obtained with conventional sources of nutrients.

In general, the application of the highest kamafugite doses resulted in increases in the accumulated Ca and Mg values in *Urochloa brizantha* plants harvested at 40 DAS and 80 DAS, with better results observed in clayey soil (Table 1). The finer grain size of the product (filler) showed to be more efficient in increasing Ca and Mg contents in plants than the powder form (Table 1).

This fact may be associated to the higher specific surface of the particles, providing greater soil contact and, consequently, greater release of the nutrients. These results show that, in addition to K and P, kamafugite can supply Ca and Mg to plants, since equal amounts of nutrients were applied to all treatments at the beginning of the experiment. Thus, the higher Ca and Mg values observed are due to product application. Kamafugites are important sources of 2:1 clays, such as vermiculite, smectite and montmorillonite. These clays, when available, may increase the soil's cation-exchange capacity and the soil water retention capacity. These factors are important in the maintenance and retention of soluble cations, such as  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^{+}$  and other micronutrients that are adsorbed by 2:1 clays (Martins et al., 2014).

It was observed that soil Ca contents did not increase with the application of kamafugite in both filler and powder forms after consecutive *Urochloa brizantha* crops (Table 1). Soil Ca contents are considered as medium and low to medium in clayey and sandy soil, respectively (Souza & Lobato, 2002). Mg contents in the clayey soil following the application of kamafugite were superior to control treatment, changing from below ( $< 0.5 \text{ cmol}_c \text{ dm}^{-3}$ ) to medium ( $0.5 \text{ to } 2.0 \text{ cmol}_c \text{ dm}^{-3}$ ) according to Souza and Lobato (2002) (Table 1). On the other hand, the dose of  $3334 \text{ mg dm}^{-3}$  of the rock dust in the sandy soil increased the soil nutrient content in relation to control treatment (Table 1).

As previously discussed, the low soil Ca and Mg contents may be associated to the accumulation of nutrients by plants, as observed in both *Urochloa brizantha* crops. Since tropical soils presents low available Ca and Mg levels, resulting in a reduction on plant growth and root development, the use of slow-release nutrient sources may increase the content of these nutrients in plant tissues over time, as well as improve forage quality.

Table 1. Ca and Mg values accumulated in the aerial part of the *Urochloa brizantha* plants and their contents on the soil due to the application of doses of kamafugite filler and powder

<b>Calcium</b>						
<i>Clayey soil</i>						
Kamafugite doses	Soil		Accumulated (40 DAS)		Accumulated (80 DAS)	
	Filler	Powder	Filler	Powder	Filler	Powder
----- mg dm <sup>-3</sup> -----	----- cmol dm <sup>-3</sup> -----					----- mg pot <sup>-1</sup> -----
1667	2.51	2.30	50.64 a*	55.90 a*	38.44	50.9 *
3334	2.42	2.55	56.21 a*	43.83 b*	58.70 *	59.00 *
6668	2.62	2.63	45.45 a*	53.83 a*	59.95 *	68.34 *
13336	2.87	2.54	47.90 a*	41.48 a*	78.35 *	74.73 *
Means	2.60 a	2.50 a	50.05	48.76	58.86 a	63.11 a
Control	2.06		23.44		31.81	
<i>Sandy soil</i>						
Kamafugite doses	Soil		Accumulated (40 DAS)		Accumulated (80 DAS)	
	Filler	Powder	Filler	Powder	Filler	Powder
----- mg dm <sup>-3</sup> -----	----- cmol dm <sup>-3</sup> -----					----- mg pot <sup>-1</sup> -----
1667	1.15 b	1.69 a	55.71	56.16	75.02	61.70
3334	1.56 a	1.41 a	56.94	39.14	80.34 *	54.73
6668	1.72 a	1.12 b	62.56 *	49.45	87.16 *	66.81
13336	1.65 a	1.04 b	59.03	43.46	94.34 *	95.48 *
Means	1.52	1.32	58.56 a	47.05 b	84.21 a	69.68 b
Control	1.46		34.08		44.30	
<b>Magnesium</b>						
<i>Clayey soil</i>						
Kamafugite doses	Soil		Accumulated (40 DAS)		Accumulated (80 DAS)	
	Filler	Powder	Filler	Powder	Filler	Powder
----- mg dm <sup>-3</sup> -----	----- cmol dm <sup>-3</sup> -----					----- mg pot <sup>-1</sup> -----
1667	0.74	0.62	92.2 *	97.5 *	97.9	138.8
3334	0.69	0.71	97.8 *	79.4 *	177.8 *	157.8 *
6668	0.64	0.60	88.8 *	116.4 *	194.4 *	253.3 *
13336	0.63	0.61	92.8 *	96.3 *	282.7 *	281.2 *
Means	0.68 a	0.63 a	92.9 a	97.4 a	188.2 a	207.8 a
Control	0.47		42.2		73.1	
<i>Sandy soil</i>						
Kamafugite doses	Soil		Accumulated (40 DAS)		Accumulated (80 DAS)	
	Filler	Powder	Filler	Powder	Filler	Powder
----- mg dm <sup>-3</sup> -----	----- cmol dm <sup>-3</sup> -----					----- mg pot <sup>-1</sup> -----
1667	0.29	0.37	55.71	56.16	140.6 a	148.6 a
3334	0.40	0.43 *	56.94	39.14	186.0 a*	93.5 b
6668	0.36	0.26	62.56 *	49.45	218.2 a*	71.8 b
13336	0.38	0.25	59.03	43.46	183.7 a*	219.1 a*
Means	0.36 a	0.33 a	58.56 a	47.05 b	182.1	133.3
Control	0.25		34.1		93.7	

Note. Means followed by distinct letters in the line differ from each other by the Tukey test at 0.05 of significance. \* differs from the control by the Dunnett test at 0.05 significance.

#### 4. Conclusions

- (1) Kamafugite is efficient in increasing dry matter of *Urochloa brizantha* plants, especially in the filler form in sandy soils and in the powder form in clayey soils.
- (2) The application of the highest doses of kamafugite increase the accumulation of P, K, Ca, and Mg in plants, as well as soil P, Ca, and Mg contents, showing a good residual effect.
- (3) The kamafugite presents agronomic efficiency value similar to the standard treatment TSF + KCl, mainly for the 2<sup>nd</sup> crop of *Urochloa brizantha* plants.
- (4) Kamafugite can be used as an alternative source of nutrients for *Urochloa brizantha*.

## Acknowledgments

The authors are grateful to the Brazilian National Council for Scientific and Technological Development (CNPq), the Coordination of Improvement of Higher Level Personnel (CAPES) and the Foundation of Support Research of the State of Minas Gerais (FAPEMIG) for financial support and scholarships.

## References

- ANDA (Associação Nacional para Difusão de Adubos). (2017). *Anuário do setor de fertilizantes 2016* (p. 76). Estatísticas. São Paulo: ANDA. Retrieved from <http://www.anda.org.br/index.php?mpg=03.01.00&ver=por>
- Anghinoni, I., & Barber, S. A. (1980). Phosphorus influx and growth characteristics of corn roots as influenced by phosphorus supply. *Agronomy Journal*, *72*, 682-688. <https://doi.org/10.2134/agronj1980.00021962007200040028x>
- Bakken, A. K., Gautneb, H., Sveistrup, T., & Myhr, K. (2000) Crushed rocks and mine tailings applied as K fertilizers on grassland. *Nutrient Cycling in Agroecosystems*, *56*, 53-57. <https://doi.org/10.1023/A:1009709914578>
- Brod, J. A., Gibson, S. A., Thompson, R. N., Junqueira-Brod, T. C., Seer, H. J., Moraes, L. C., & Boaventura, G. R. (2008). The Kamafugite–Carbonatite association in the Alto Paranaíba igneous province (APIP), Southeastern Brazil. *Revista Brasileira de Geociências*, *30*, 408-412. <https://doi.org/10.25249/0375-7536.2000303408412>
- Caione, G., Lange, A., Benett, C. G. S., & Fernandes, F. M. (2011). Fontes de fósforo para adubação de cana-de-açúcar forrageira no cerrado. *Pesquisa Agropecuária Tropical*, *41*, 66-73. <http://dx.doi.org/10.5216/pat.v41i1.8497>
- Cerri, C. C., Moreira, C. S., Alves, P. A., Raucci, G. S., Castigioni, B. A., Mello, F. F. C., ... Cerri, C. E. P. (2016). Assessing the carbon footprint of beef cattle in Brazil: a case study with 22 farms in the State of Mato Grosso. *Journal of Cleaner Production*, *112*, 2593-2600. <https://doi.org/10.1016/j.jclepro.2015.10.072>
- Darunsontaya, T., Suddhiprakarn, A., Kheoruenromne, I., Prakongkep, N., & Gilkes, R. J. (2012). The forms and availability to plants of soil potassium as related to mineralogy for upland Oxisols and Ultisols from Thailand. *Geoderma*, *170*, 11-24. <https://doi.org/10.1016/j.geoderma.2011.10.002>
- Dias, D. G., Pegoraro, R. F., Alves, D. D., Porto, E. M. V., Santos Neto, J. A. dos, & Aspiázú, I. (2015). Produção do capim piatã submetido a diferentes fontes de fósforo. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *19*, 330-335. <https://doi.org/10.1002/9781118827352>
- Fageria, N. K., Santos, A. B., & Moraes, M. F. (2010). Yield, potassium uptake, and use efficiency in upland rice genotypes. *Communications in Soil Science and Plant Analysis*, *41*, 2676-2684. <https://doi.org/10.1080/00103624.2010.517882>
- FAO (Food and Agriculture Organization of United Nations). (2015). *World Reference Base (WRB) for Soil Resources 2014: International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*. FAO, Rome, Italy. Retrieved from <http://www.fao.org/3/i3794en/i3794en.pdf>
- Ferreira, D. F. (2014). SISVAR: um programa para análises e ensino de estatística. *Revista Symposium*, *6*, 36-41.
- Geman, H. (2015). *Agricultural finance: From crops to land, water and infrastructure*. New Jersey: Wiley. <https://doi.org/10.1002/9781118827352>
- Guedes, E. M. S., Fernandes, A. R., Lima, E. do V., Gama, M. A. P., & Silva, A. L. P. da. (2009). Fosfato natural de Arad e calagem e o crescimento de *Brachiaria brizanta* em Latossolo Amarelo sob pastagem degradada na Amazônia. *Revista Ciências Agrárias*, *52*, 117-129. Retrieved from <http://periodicos.ufra.edu.br/index.php/ajaes/article/view/129/24>
- IPNI (International Plant Nutrition Institute). (2016). *Fertilizantes*. Retrieved from <http://brasil.ipni.net/article/BRS-3132>
- Junqueira-Brod, T. C., Llacer, H. L., Gaspar, J. C., Brod, J. A., & Meneses, P. R. (2002). A província alcalina de goiás e a extensão do seu vulcanismo kamafugítico. *Revista Brasileira de Geociências*, *32*(4), 559-566. <https://doi.org/10.25249/0375-7536.2002324559566>
- Le Maitre, R. W. (2002). *Igneous Rocks: A Classification and Glossary of Terms: Recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Igneous Rocks* (2nd ed.). Cambridge, NY: Cambridge University Press. <https://doi.org/10.1017/S001675680388028>

- MAPA (Ministério da Agricultura, Pecuária e Abastecimento). (2017). *Manual de métodos analíticos oficiais para fertilizantes minerais, orgânicos, organominerais e corretivos* (p. 141). Brasília, MAPA/DAS/CGAL. Retrieved from [http://www.agricultura.gov.br/assuntos/laboratorios/arquivos-publicacoes-laboratorio/manual\\_in-5\\_analiticos-oficiais-para-fertilizantes-e-corretivos\\_com\\_capa\\_final\\_03.pdf](http://www.agricultura.gov.br/assuntos/laboratorios/arquivos-publicacoes-laboratorio/manual_in-5_analiticos-oficiais-para-fertilizantes-e-corretivos_com_capa_final_03.pdf)
- Martins, E. de S., Silveira, C. A. P., Bamberg, A. L., Martinazzo, R., Bergmann, M., & Angélica, R. S. (2014). *Silicate agrominerals as nutrient sources and as soil conditioners for tropical agriculture* (Paper presented at the 16<sup>th</sup> World Fertilizer Congress of CIEC: Technological Innovation for a Sustainable Tropical Agriculture, Rio de Janeiro, Rio de Janeiro). Retrieved from <http://ainfo.cnptia.embrapa.br/digital/bitstream/item/114028/1/silicate.pdf>
- Martins, V., Gonçalves, A. S. F., Marchi, G., Guilherme, L. R. G., & Martins, E. D. S. (2015). Potassium solubilization in verdete and limestone mixtures treated thermochemically. *Pesquisa Agropecuária Tropical*, 45, 66-72. <https://doi.org/10.1590/1983-40632015v4527917>
- Meurer, E. J., & Anghinoni, I. (1993). Disponibilidade de potássio e sua relação com parâmetros de solo. *Revista Brasileira de Ciência do Solo*, 17, 377-382.
- Novais, R. F., & Smyth, T. J. (1999). *Fósforo em solo e planta em condições tropicais*. Universidade Federal de Viçosa, Viçosa.
- Prado, R. B., Benites, V. de M., Polidoro, J. C., Gonçalves, C. E., & Naumov, A. (2012). Mapping Soil Fertility at Different Scales to Support Sustainable Brazilian Agriculture. *World Academy of Science, Engineering and Technology International Journal of Agricultural and Biosystems Engineering*, 6, 844-852. Retrieved from <https://publications.waset.org/11111/pdf>
- Ramos, S. J., Faquin, V., Rodrigues, C. R., Silva, C. A., & Boldrin, P. F. (2009). Biomass production and phosphorus use of forage grasses fertilized with two phosphorus sources. *Revista Brasileira de Ciência do Solo*, 33, 335-343. <https://doi.org/10.1590/S0100-06832009000200011>
- Resende, A. V., Martins, E. S., Oliveira, C. G., Sena, M. C., Machado, C. T. T., Kinpara, D. I., & Oliveira Filho, E. C. (2006). Suprimento de potássio e pesquisa de uso de rochas “in natura” na agricultura brasileira. *Espaço e Geografia*, 9, 19-42. Retrieved from <http://lsie.unb.br/espacoegografia/index.php/espacoegografia/article/download/52/51>
- Ribeiro, L. S., Santos, A. R., Souza, L. F. S., & Souza, J. S. (2016). Rochas silicáticas portadoras de potássio como fontes do nutriente para as plantas solo. *Revista Brasileira de Ciência do Solo*, 34, 891-897. <https://doi.org/10.1590/S0100-06832010000300030>
- Sahama, T. G. (1974). Potassium-rich alkaline rocks. In H. Sorensen (Ed.), *The Alkaline Rocks*. London: Wiley.
- Sarruge, J. R., & Haag, H. P. (1974). *Análises químicas em plantas*. Piracicaba, SP: ESALQ.
- Silva, F. C. (2009). *Manual de análises químicas de solos, plantas e fertilizantes* (2<sup>n</sup> ed). Embrapa, Brasília, DF.
- Silva, F. de A. S. E., & Azevedo, C. A. V. de. (2002). Versão do programa computacional Assistat para o sistema operacional Windows. *Revista Brasileira de Produtos Agroindustriais*, 4, 71-78. <https://doi.org/10.15871/1517-8595/rbpa.v4n1p71-78>
- Sousa, D. M. G., & Lobato, E. (2002). *Cerrado: Correção do solo e adubação*. Embrapa Cerrados, Planaltina, DF.
- Takahashi, Y., Dahlgren, R. A., Kanno, H., Nanzyo, M., & Takahashi, T. (2018). Mechanisms for high potassium selectivity of soils dominated by halloysite from northern California, USA. *Soil Science and Plant Nutrition*, 64, 90-99. <https://doi.org/10.1080/00380768.2017.1411167>
- Teixeira, P. C., Donagemma, G. K., Fontana, A., & Teixeira, W. G. (2017). *Manual de métodos de análise de solo* (3<sup>rd</sup> ed.). Embrapa, Brasília, DF.

### Copyrights

Copyright for this article is retained by the author(s), with first publication rights granted to the journal.

This is an open-access article distributed under the terms and conditions of the Creative Commons Attribution license (<http://creativecommons.org/licenses/by/4.0/>).