Journal of Sustainable Development; Vol. 16, No. 5; 2023
ISSN 1913-9063 E-ISSN 1913-9071
Published by Canadian Center of Science and Education

# Evaluation of Agronomic Efficiency with Regional Source of Natural Potassium in the Brazilian Midwest

Carolina Brom Aki de Oliveira[1], Wilson Mozena Leandro[1], João Paulo Vilela de Castro[1], Priscyla Batista Passos[1], Manoel Lucas da Silva[1] & Mariane Porto Muniz[1]

[1] School of Agronomy, Goias Federal University, Goiania, Brazil

Correspondence: Carolina Brom Aki de Oliveira, School of Agronomy, Goias Federal University, Goiania, GO., Av. Esperança s/n, Campus Samambaia, Brazil. Tel: 55-62-3521-1530. E-mail: bromaki@ufg.br

Received: July 9, 2023 Accepted: August 19, 2023 Online Published: August 21, 2023
doi:10.5539/jsd.v16n5p20 URL: https://doi.org/10.5539/jsd.v16n5p20

## Abstract

Brazil plays an important role in global food production, but faces challenges due to its dependence on imported fertilizers. To reduce this vulnerability of the agricultural sector, the use of natural sources such as agrominerals, also known as rock dust, is gaining ground. The objective of this study was to characterize and evaluate a new source of natural potassium, extracted from a deposit located in the Brazilian Midwest, through geological characterization and agronomic evaluation through yield tests, soil and foliar potassium content. The tests were conducted in a greenhouse with seven treatments, two soil types and four replications, with millet, soybeans and beans in succession to evaluate the residual effect of the product. The agromineral was classified as a nepheline syenite saprolite with an average $K_2O$ content of 11.6%. The effects of the agromineral were promising, especially in the medium term. In the case of beans, at the standard dose of 60 $K_2O$, yields in clay soils were 3.6 Mg ha$^{-1}$ higher than in the 60 KCl treatment, which obtained only 2.3 Mg ha$^{-1}$, probably due to absorption or leaching losses, since the effect evaluated was residual in nature. For all the crops evaluated, the agromineral showed an increase in potassium levels in both the soil and the leaves compared to the control group, indicating that it is a potential alternative to gradually reduce the use of traditional chemical fertilizers. Field trials are recommended to validate these benefits, taking into account more realistic environmental variations.

**Keywords:** agrominerals, potassium, sustainability, natural fertilizer

## 1. Introduction

Brazil plays an extremely important role in the context of food security, as it is recognized as a significant global food producer, being the world's largest exporter of liquids, responsible for over half of the world's soy consumption, and the second-largest producer of beef (Food and Agriculture Organization of the United Nations [FAO], 2022; Mores et al., 2022; United States Department of Agriculture [USDA], 2022). However, it is important to note that the growth of the Brazilian agricultural sector in the last two decades has been accompanied by a remarkable dependence on fertilizer imports, thus revealing the vulnerability of the national agricultural system (Osaki, 2022). In terms of global fertilizer consumption, Brazil represents approximately 17,3% of the total, occupying the fourth position, behind only China, India, and the United States (USDA, 2022). Among the nutrients used, potassium stands out, which corresponds to 38% of the total consumption, followed by calcium, with a share of 33%. It is important to note that the most significant agricultural crop in Brazil is soybeans, requiring more than 40% of the fertilizers used (Secretariat for Strategic Affairs [SAE], 2020).

Agriculture in Brazil is a sector that still presents vulnerabilities, especially due to the dependence on the import of inputs necessary for the composition of NPK fertilizers, which are indispensable for the supply of nutrients (Theodoro & Leonardos, 2011). According to Fonseca (2016), although the country has enough phosphorus deposits to meet its demands, the same cannot be said about potassium, sulfur, and nitrogen deposits. This results in an absolute import dependency. In this context, it is relevant to note that although Brazil is the fourth largest consumer of fertilizers, its production represents only 2% of world production (Ribeiro & Leite, 2017). This disparity between the consumption and national production of fertilizers puts the country in an unfavorable position in terms of autonomy and security in the agricultural sector.

In the year 2020, Brazil recorded a record in the import of fertilizers, which represents an increase of 11% compared to the 26.4 million tons imported in 2019 potassium chloride presented an increase of 12% compared to the previous year, corresponding to 39% of the total volume of imported fertilizers. It is worth mentioning that potassium chloride is one of the products with the greatest dependence on the international market due to low domestic production (Globalfert, 2021). Potassium chloride (KCl) is imported from Russia, Canada, Belarus, and Germany. The potassium deposits with the highest volume are mainly found in vast epicontinental basins, such as those located in Russia, Belarus, North America, and Central Europe (Van Straaten, 2017; Ribeiro & Leite 2022).

An alternative that has been gaining prominence to help reduce this import dependence is the use of silicate agrominerals in agriculture, also known as rock powder. Agrominerals are finely ground volcanic rocks for direct application, such as basalts, phonolites, Kamafugites, and other nutrient-rich volcanic rocks that can improve soil productivity (Van Straaten, 2022). The scientific basis for the use of crushed silicate rocks as sources of nutrients in agriculture is constantly expanding, with different conclusions reported by studies conducted in different regions of the world. The Brazilian experience culminated in the formal recognition by the government of farmers' interest in using these materials and the establishment of an appropriate regulatory framework (Manning & Theodoro, 2020; Theodoro & Leonardos, 2006).

A relevant aspect also in the adoption of the use of agrominerals is the environmental issue because they are ground rocks are highly sustainable products after all, they are natural, and part of the agrominerals used come from sources such as waste and by-products of mining, reducing the negative impact on the environment of these industries. According to Van Straaten, (2006), with the proper choice of locally available rock materials for the correct soils, these materials have demonstrated significant benefits for local agriculture, especially when they are modified or mixed with locally available organic materials.

In a study directed at the consumption of mineral fertilizers in the Brazilian Midwest, Ogino et al., (2020), highlight that the scarcity of these mineral sources in Brazil, especially potassium, puts the country in a situation of vulnerability in the face of possible fluctuations in the market for this input, which could have negative impacts on national agricultural production. The national dependence on potassium is compromising in this context, it is essential to find new sources of this mineral, which are not limited only to solubility, but also take into account the minimization of environmental impacts during its application (Kinpara, 2003).

In Brazil, phonolites are widely used as direct potassium fertilizers, and according to plate tectonic models, the igneous deposits of potassium silicates, such as phonolites, are found in continental intraplate extension environments (Van Straaten, 2022).

Manning (2010) reports this possibility of silicate rocks as a source of potassium in agriculture, but that the rate of dissolution of these should be observed and points out as a priority the rocks that contain nepheline. The nepheline syenite is an igneous rock that stands out for its composition, characterized by the scarcity of quartz and the presence of the nepheline feldspathoid. This rock is formed from alkaline magmas that have a low silica content. (Sampaio, France & Braga, 2008).

In 2021, Brazil imported 96% of the potassium chloride it consumed; this dependence became more evident during the war between Russia and Ukraine, highlighting the country's vulnerability in this regard and showing the need for strategic policies for risk mitigation in agriculture (Caligaris et al., 2022; Osaki, 2022).

In this context, thinking about food security and reducing the country's vulnerability to external geopolitical issues due to dependence on fertilizer imports, in 2022 the Brazilian government launched a public policy, the National Fertilizer Plan (PNF 2022-2050), which has as one of the objectives to increase the national production of fertilizers through guidelines such as the discovery of new alternative sources of nutrients (Caligaris et al., 2022; Ministry of Agriculture, Livestock and Supply of Brazil [MAPA], 2022). Although there are few studies on the use of rock dust in agriculture, they have shown positive effects as a soil remineralizer and advantages such as not harming the environment because it is natural (Castro et al., 2021; Writzl et al., 2019).

This work aims to characterize and evaluate the use of a new alternative source of natural potassium supplementation for agriculture, the agromineral saprolite nepheline syenite was extracted from a deposit located in the Brazilian Midwest, for which it was evaluated as this new source contributes to productivity, exchangeable potassium content in the soil and leaves in three crops: corn, soybean and the residual effect of the product on beans.

## 2. Methods

The rock used in the research was removed from a deposit located in the municipality of Montes Claros de Goiás-GO (Figure. 1), product due to the place found, and the nutrient of interest was named KMC (Potassium of Montes Claros) for sounding and initial characterization of the product were used both mechanized auger and air core probes. With a representative sample of the site, the chemical characterization analyses were sent to the laboratory of SGS – Geosol, in Belo Horizonte-MG and CRTI of the Federal University of Goias (UFG). For the macroscopic description, micrographs were used, while for the microscopic characterization and mineralogical composition, X-Ray Fluorescence (quantification of oxides) and X-Ray Diffraction (quantification of minerals in the crystalline phase) technique were used.

### *2.1 Rock Characterization*

After analysis, the rock was classified as nepheline syenite, of high crystallinity, with coarse phaneritic texture and light brown coloration. The product tested (called KMC) was obtained from the saprolite of nepheline syenite. In saprolite, there is alteration from primary minerals to secondary and often amorphous minerals. The nepheline syenite is classified as a plutonic igneous rock, characterized by a slower cooling, which results in mineral crystals of dimensions visible to the naked eye. On the other hand, phonolite is considered a hypabyssal rock, which has undergone a faster cooling, resulting in mineral crystals that are not visible to the naked eye. These rocks are formed from alkaline magmas with low silica content and are characterized by the scarcity of quartz and the presence of the nepheline feldspathoid (Sampaio & Braga, 2008). Table 1 shows the composition found by the X-ray fluorescence method of the product tested.

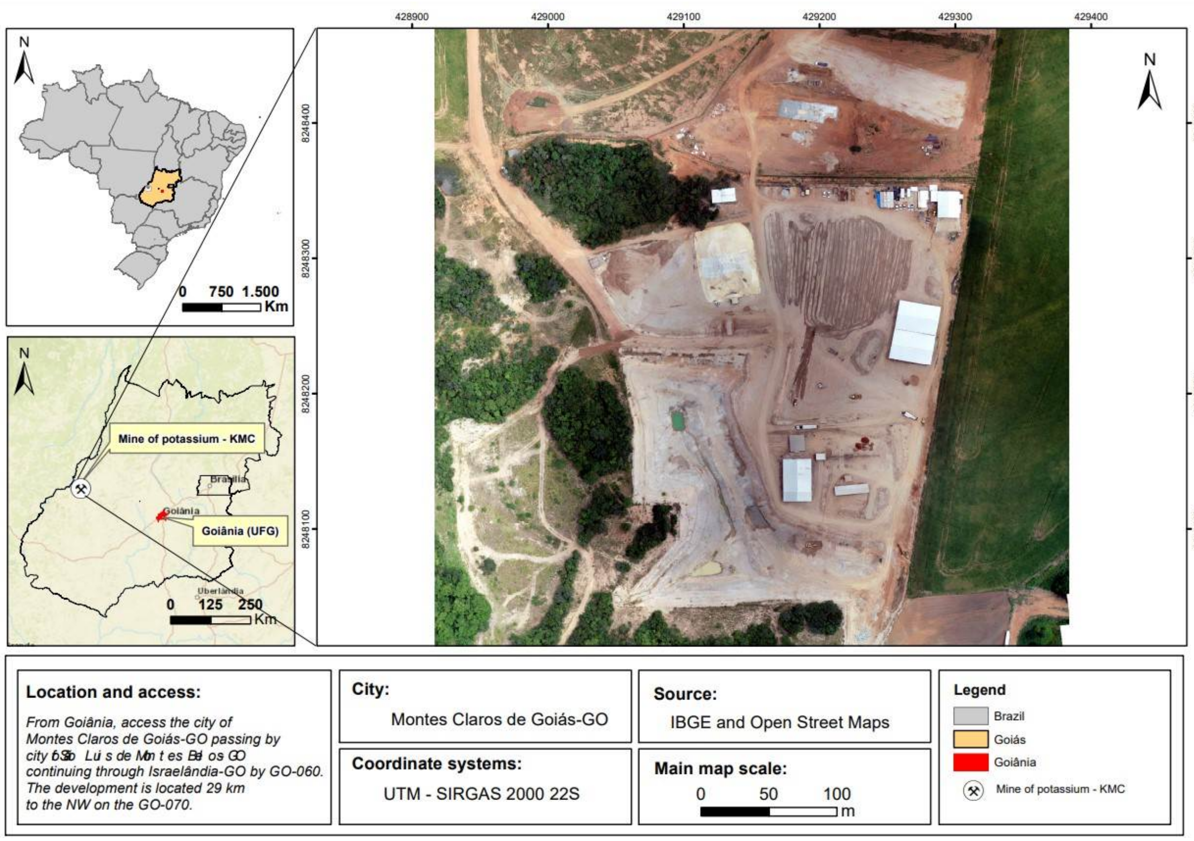

Figure 1. Map of the location of the material extraction area and study

Table 1. Results of KMC samples regarding the composition of the main oxides

| Sample | Laboratory | $K_2O$ | $Na_2O$ | $Fe_2O_3$ | $Al_2O_3$ | $SiO_2$ | CaO | MgO |
|---|---|---|---|---|---|---|---|---|
| | | | ---------------------------------------- | | % | | ------------------------------ | |
| KMC | CRTI | 11.6 | 0.67 | 2.36 | 2.36 | 58.0 | <LQ* | 0.39 |

*<LQ = Below the quantifiable limit.

In the X-ray Diffraction analysis performed by CRTI-UFG, using the Rietveld method, it was found that the sample has a predominant composition of 51.59% orthoclase, followed by microclinium, with 24.01% of its composition. Ortoclasium is potassium aluminosilicate and is present in both syenite and phonolite, which have the same mineralogical constitution, differing from each other by the size of the minerals (Sampaio; France & Braga, 2008). The contaminants were also quantified, and all were below the limits established by the Brazilian legislation annex II IN SDA nº 27/ 2006 (Brazil, 2006).

### *2.2 Evaluation of Agronomic Efficiency*

For the agronomic tests, a representative sample was taken that went through the process of grinng and sieving 0.425 mm (sieve No. 40). The experiment was conducted under greenhouse conditions located at the School of Agronomy of UFG in Goiania, GO, using pots filled with two types of Oxisols: The Yellow Latosol (LA), with a sandy loam texture, and the Red Latosol (LV), with a clayey texture. The relief of the region is characterized as moderately flat to slightly undulating, with an average altitude of 730 m. The climate is classified as B2 WB 42' according to the classification of (Lobato, 1978), with an average temperature of 21°C, a maximum of 29°C, and a minimum of 15°C. The annual relative humidity is 41.5%, the average annual rainfall is 1487.2 mm, and the total solar radiation is 2645.7 hours. Prior to the experiment, the soils Yellow Latosol and Red Latosol were previously characterized in the soil laboratory of the School of Agronomy/UFG and presented the results as shown in Table 2. The soils used in the experiment were air-dried and sieved with a 2 mm mesh. The fertilization used was calculated as a function of soil analysis (C.F.S.G, 1988). The liming was performed with dolomitic limestone based on the method of raising the Soil Base Saturation to 60% (Sousa & Lobato, 2004).

Table 2. Results chemical and texture analysis of the soils used in the experiment.

| **Soil** | M.O. | pH | P(Mehl) | K | Ca | Mg | H+Al | Al | CTC | M | V |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | % | ($CaCl_2$) | mg dm$^{-3}$ | mg dm$^{-3}$ | | | cmolc dm$^{-3}$ | | | % | % |
| **LV** | 1.1 | 5.3 | 1.2 | 38 | 1.8 | 0.6 | 3.9 | 0 | 6.4 | 0 | 39 |
| | Clayey soil | | | Clay (g kg-1) | | | Silt (g kg-1) | | | Sand (g kg-1) | |
| | | | | 480 | | | 80 | | | 440 | |
| | M.O. | pH | P(Mehl) | K | Ca | Mg | H+Al | Al | CTC | M | V |
| | % | ($CaCl_2$) | mg dm$^{-3}$ | mg dm$^{-3}$ | | | cmolc dm$^{-3}$ | | | % | % |
| **LA** | 0.3 | 5.2 | 2.7 | 15 | 1.4 | 0.3 | 2.3 | 0 | 4.0 | 0 | 43 |
| | Sandy loam soil | | | Clay (g kg-1) | | | Silt (g kg-1) | | | Sand (g kg-1) | |
| | | | | 180 | | | 20 | | | 800 | |

Different doses of KMC fertilizer (Potassium of Montes Claros) were used, being 0, 1/2; 1, 2 and 4x the recommended dose. In addition, two additional treatments were used as a reference for comparison: the agromineral based on phonolite (Ekosil) and the traditional chemical fertilizer potassium chloride (KCl). The calculations were performed to ensure that the recommended dose of the reference treatments corresponded to an amount of 60 kg ha$^{-1}$ of $K_2O$.

All seven treatments were conducted in quadruplicate and used two soil types, identified as LA (Yellow Latosol) and LV (Red Latosol). The treatments were organized as follows: (1) Witness (without the application of KMC); (2) 30 KMC kg ha$^{-1}$ of $K_2O$ (half of the recommended dose); (3) 60 KMC kg ha$^{-1}$ of $K_2O$ (recommended dose); (4) 120 KMC kg ha$^{-1}$ of $K_2O$ (twice the recommended dose; (5) 240 KMC kg ha$^{-1}$ of $K_2O$ (four times the recommended dose); (6) 60 kg ha$^{-1}$ of $K_2O$ of reference remineralizer Ekosil; (7) 60 kg ha$^{-1}$ of KCl $K_2O$.

In the agronomic efficiency experiment conducted in a greenhouse, millet was the first crop to be planted with the ADR 3000 variety. This was done during the winter. Subsequently, the experiment was carried out with soybeans in the spring with the same treatments, using the variety Brasmax Desafio RR-8473 RSF, and finally the experiment with beans in the fall with the early variety Jalo. The bean planting was carried out without the application of $K_2O$ doses in all treatments to evaluate the effects of the residuals.

### *2.3 Variables Evaluated*

The variables studied in the present study for the three crops were yield, potassium content in the soil, using the Mehlich 1 extractor according to the methodology proposed by The Brazilian Agricultural Research Corporation [Embrapa], (1997), and potassium content in the leaves following the methodology proposed by Malavolta et al, (1997*).* The productivity of millet was assessed based on biomass weight, whereas for soybeans and beans, productivity was measured in terms of dry grain mass per pot and subsequently converted to megagrams per hectare (Mg ha$^{-1}$).

Given the uniqueness of the agromineral under study, whose targeted nutrient is not readily available like the commercial fertilizer KCl, it becomes interesting to consider variables such as the analysis of exchangeable soil potassium content and leaf content evaluation. As this is a source that has never been agronomically assessed before, these variables provide a broader perspective on the behavior of the examined crops when exposed to this new potassium source and in specific soil types. This allows for comparison with traditional sources.

### *2.4 Statistics and Data Analysis*

The experiment was conducted using a completely randomized experimental design, with four replications for each treatment in two types of soil, resulting in a total of 56 experimental plots for each evaluated crop.

For the statistical analysis of productivity data, soil potassium content, and leaf potassium content, two main approaches were adopted. Firstly, an analysis of variance (ANOVA) was performed with a factor to assess the equality among treatment means. To achieve this, the F statistic was calculated (National Institute of Standarts and Technology [NIST], 2012; Shimakura, 2005; Paulista State University [UNESP], 2019). The F statistic allows us to gauge the extent of variation between groups compared to the variation within groups that cannot be explained. The calculations were carried out using the statistical software SAS®, but can be explained in a simplified manner as follows:

Considering the hypotheses for applying the F-test:

$$H_0: \mu_1 - \mu_2 = 0 \tag{1}$$

$$H_1: \mu_1 - \mu_2 \neq 0 \tag{2}$$

Where:

$H_0$ = There is no difference between the means of the treatments

$H_1$= The means of the treatments are not equal

$$F = \frac{s_1^2}{s_2^2} \quad \frac{(Variance\ between\ the\ groups)}{(Variance\ within\ the\ groups)} \tag{3}$$

In equation (3), the F value is calculated and then compared with an F distribution table, taking into account the number of data points in the experiment for calculating degrees of freedom.

When F calc ≥ F tab, the test is significant at the considered significance level $\alpha$. In this work, for the * test, significance was observed at the $\alpha$=0.05 level, and for the ** test, significance was observed at the $\alpha$=0.01 level.

In these cases, the null hypothesis ($H_0$) is rejected, and it is assumed that the differences between the treatments are not due to chance.

The second approach occurs after a significant F-test, indicating evidence that the means of the treatments are significantly different. In this case, the Tukey test (Gomes, 1952; NIST, 2012) was applied for pairwise multiple comparisons among the treatment means. Calculations were performed using statistical software SAS®. This test allows for the identification of treatments that exhibit statistically significant differences in their means, represented by letters. Equal letters do not differ statistically by the test at a significance level of 5%.

A second-degree polynomial regression was used to evaluate the dose-response relationship between different doses of the KMC agromineral and the analyzed variables. This type of quadratic curve is commonly used in soil fertility because it's easy to derive fertilizer rates that yield maximum or optimal outcomes (Mbissik et al., 2023). These forms are also frequently employed for evaluating designed experiments (NIST, 2012). The choice of a second-degree polynomial regression is based on the assumption that the relationship between KMC doses and the variable is not linear but might exhibit curvature. This curvature indicates that at some point, the response of the crops to KMC doses might reach a maximum and subsequently decrease or stabilize the observed variable. By fitting a curve to the experimental data, one aims to infer the KMC dose that resulted in the best performance in terms of productivity, soil potassium content, and leaf potassium content for the evaluated crops. High values of the coefficient of determination R$^2$ are associated with the quality of the model's fit to the observed data.

## 3. Results and Discussion

### *3.1 Productivity*

The millet yields in the Red Latosol (LV) and Yellow Latosol (LA) soils showed significant differences by the F test (2.6) and (6.59), respectively, with coefficients of variation of 27.65% and 32% (Table 3). Millet produced dry biomass between 3.5 and 11.2 Mg $ha^{-1}$ in LV and between 2.4 and 9.5 Mg $ha^{-1}$ in LA. It is noteworthy the treatment 60 KCl, which obtained the highest yields in both soils, however in soil LV the treatment 60 KMC had productivity higher than its reference standard 60 Ekosil, and this did not present significant differences by Tukey's test about the control (0 KMC) in LV. The results obtained are consistent with previous studies conducted by (Menezes & Leandro, 2004) and (Pacheco et al., 2011), which reported very similar millet dry matter yields. Crusciol and Soratto (2007) obtained biomass yields of millet higher than those of the present assay in the value of 14.8 Mg $ha^{-1}$. As for the LA sandy soil, the reference 60 Ekosil obtained productivity greater than 60 KMC. However, no significant differences were found by the Tukey test for the LA treatments, except for the reference treatment 60 KCl.

The results of KMC treatments indicated an adjustment in a 2nd degree polynomial regression ($R^2$) in the increasing doses of KMC for both LV and LA with high determining factors indicating a positive dose-response correlation with an increase in millet biomass up to the dose of 170 kg $ha^{-1}$ of $K_2O$ in LV and 160 kg $ha^{-1}$ of $K_2O$ in LA (Figure 2). It is also possible to observe in Figure 2 that the reference treatment 60 KCl stands out as the highest millet yields in both soils. Considering that most potassium silicate minerals have low solubility in water and the release of nutrients is gradual, it is possible that the solubilization in the first year of cultivation was not in the time necessary for the responses in the crop productivity equal to the soluble sources in the sandy loam soil, despite the positive responses in the clayey soil. On the other hand, KMC behaved similarly to Ekosil.

Table 3. Productivity of millet, soybean and bean according to the treatments used.

| **PRODUCTIVITY (Mg $ha^{-1}$)** | | | | | | |
|---|---|---|---|---|---|---|
| **Treatment** | **Millet** | | **Soybean** | | **Beans** | |
| | **LV** | **LA** | **LV** | **LA** | **LV** | **LA** |
| 0 KMC | 3.5 d | 2.4 b | 1.9 b | 1.1 c | 1.9 c | 1.8 c |
| 30 KMC | 7.5 abcd | 3.8 b | 2.0 b | 1.5 b | 2.4 b | 2.1 bc |
| 60 KMC | 8.6 abc | 4.8 b | 2.1 b | 1.5 b | 3.9 a | 2.2 ab |
| 120 KMC | 7.4 abcd | 5.7 b | 2.6 ab | 2.5 a | 3.5 a | 2.3 a |
| 240 KMC | 9.6 ab | 5.6 b | 2.6 ab | 2.0 ab | 3.1 b | 2.2 ab |
| 60 Ekosil | 6.0 bcd | 5.5 b | 3.2 a | 2.3 a | 3.1 ab | 2.4 a |
| 60 KCl | 11.2 a | 9.5 a | 3.0 a | 2.5 a | 2.3 b | 2.2 a |
| F test | 2.60* | 6.59** | 2.70* | 2.30* | 7.88** | 3.21* |
| CV % | 27.65 | 32.00 | 36.13 | 24.72 | 15.78 | 18.46 |

Means followed by the same letter in the same column are not statistically different at 5% probability by Tukey's test. ** and * are significant at 1% and 5%, respectively, in the analysis of variance (F test). CV (%): coefficient of variation.

Regarding cereals, it is observed that over 70% of the present potassium (K) is retained in the straw. This observation holds practical significance in agriculture, as the straw, and consequently substantial amounts of K, can either remain in the field or be removed for use as biomass. In this context, the way harvest residues are managed becomes a crucial aspect in determining fertilizer requirements (Zörb et al., 2014).

Regarding the soybean crop, the yield results also indicated significant differences in F in LV (2.7) and LA (2.3) with coefficients of variation of 36.13% and 24.72%, respectively (Table 3). For VL, soybean yield was between 1.9 and 3.2 Mg $ha^{-1}$. The reference treatments 60 Ekosil and 60 KCl obtained the highest yields. KMC did not demonstrate significant differences by Tukey's test concerning the standards only at higher doses, such as 120 KMC, and 240 KMC (Table 3). The average soybean yields of all treatments were below the national average of 3.3 Mg $ha^{-1}$ for the 2019/20-second harvest (National Supply Company [CONAB], 2020). Higher yields for soybeans of 3.6 Mg $ha^{-1}$ were achieved by taking into account treatments such as the use of crop rotation, adequate soil management, and fertilization (Embrapa, 2018).

In LA soil, soybean yield ranged from 1.1 to 2.7 Mg $ha^{-1}$. The treatments 60 Ekosil and 60 KCl stand out, which obtained the highest yields. In KMC, the higher doses, such as the 120 KMC treatment, were able to produce yields like the reference treatments.

For soybean yield about increasing KMC doses, Figure 2 shows that there was an adjustment in a polynomial regression of the 2nd degree and that they provided increases in soybean yield up to the dose of 240 kg ha$^{-1}$ of $K_2O$ in LV and 180 kg ha $^{-1}$ of $K_2O$ in LA. In a similar study, but conducted in the field with microgabbro rock powder in red argisol, soybean yields above the national average were found by Almeida Júnior *et al.* (2020) as well as De Medeiros *et al.* (2021), which also obtained soybean productivity above the national average, but using dacite rock powder as a source of nutrients.

The soybean yields in LV and LA soils, together with the results of the treatments with different sources of potassium, evidence the importance of the appropriate choice of the source and the dosage of potassium fertilizer, considering the characteristics and specific properties of the soil. The use of soluble sources KCl can be advantageous in some cases, but fertilization with natural products from rocks can also play an important role in promoting soybean growth and productivity, especially in crops after its application. According to Embrapa (2018), the soybean crop is demanding potassium, exporting from the crop after harvest, a value of 22 kg ha$^{-1}$ of $K_2O$ per ton of grains, while for corn, this value is much lower, around 2.6 kg ha$^{-1}$ of $K_2O$, demonstrating the need for attention to fertilization planning in soybean crops.

From a pedological perspective, the incorporation of minerals in highly weathered soils seems to be a viable intervention. In addition to the fertilizer effect, there are indications of possible co-benefits that can be obtained by the use of silicate rock powder as carbon sequestration, advantages provided by silicon for plants, roots of the most abundant, greater humidity around the plants due to the clays contained in the material and ability to retain water, more lush foliage, lower application cost due to long-term effect (Swoboda; Döring & Hamer, 2022; Theodoro & Leonardos, 2006).

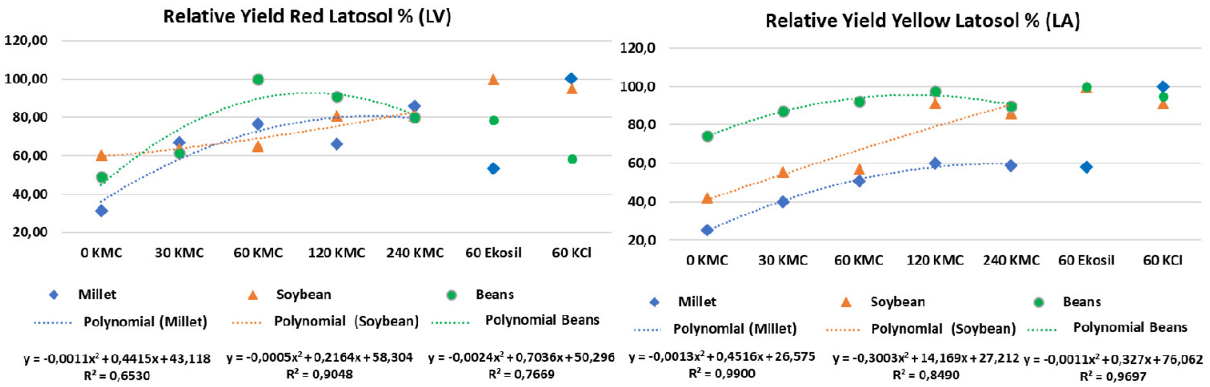

Figure 2. The polynomial curve for evaluation dose-response and relative efficiency of KMC about productivity. It normalized the relative biomass production of millet, soybean, and beans in LV and LA

As for bean yield, the study was conducted to evaluate the residual effect after soybean harvest without adding new dosages in the treatments. The bean yields in LV and LA soils showed significant differences by the F (7.88) and F (3.21) tests, respectively, with relatively low coefficients of variation of 15.78% and 18.46% (Table 3).

In the LV soil, the bean yield ranged from 1.9 to 3.9 Mg ha$^{-1}$ with emphasis on the 60 KMC treatment, which obtained the highest yields, evidencing a residual effect of the application of KMC from soybean. This obtained result aligns with the findings of Mbissik et al. (2023), who evaluated 16 types of rock powders as potassium sources with and without thermal treatment (hydrothermal). They observed that over the long term, untreated rocks exhibited better performance in ryegrass productivity compared to hydrothermally treated ones, attributed to the long-term availability of potassium for plants. The reference treatment 60 KCl obtained the worst performance (not counting the control), possibly because it is a residual evaluation study. The losses of the soluble source by leaching probably contributed to these results. The yields obtained were higher than the averages of the State of Goias, which is the third largest producer, with 367.7 thousand tons in a planted area of 156.3 thousand hectares, having the highest productivity in the country of 2.3 Mg ha$^{-1}$ (CONAB, 2020). The bean productivity results were higher than those obtained by Soratto et al. (2021) in an experiment with the same dose of $K_2O$ from alkaline rock on clayey red latosol. Their yields were around 2.1 Mg kg$^{-1}$ in the first planting, and they showed values very close to the bean productivity with the KCl source in their experiment.

In the LA soil, the bean produced between 1.8 and 2.4 Mg ha$^{-1}$, the 60 Ekosil treatment obtained the highest yields, with no significant differences between the 60 KMC, 60 KCl, and 60 Ekosil treatments by the Tukey test. It is noteworthy that the LA is considered a soil with greater limitations to obtain high yields due to the low clay content of this soil, despite the yields of 3.6 Mg ha$^{-1}$ obtained by Brasil *et al.* (2020) using glauconitic siltstone in neosols of Goiás. In another study of bean yield using slate powder, Alves *et al.* (2021) obtained significant increases in bean production of the order of 0.22 Mg ha$^{-1}$ for each ton of slate powder applied to the soil. The increments were verified in all doses tested under the experimental conditions. According to the author, the improvements may be related mainly to the contribution of nutrients present in the added material, especially potassium.

As for the dose-response evaluations, it is verified that there was an adjustment in the 2nd degree polynomial regression and that the increasing doses of KMC provided increases in bean productivity up to the dose of 60 kg ha$^{-1}$ $K_2O$ in LV and 120 kg ha$^{-1}$ $K_2O$ in LA (Figure 2).

### *3.2 Soil Exchangeable Potassium Content*

For several decades of research, efforts have been directed towards establishing methods for correlating the concentrations of exchangeable potassium (K) in the soil with the needs, uptake, and yield of crops. However, most soil K extraction tests do not provide information about the release rate of this element during the growing season. This release rate is crucial, as it determines whether the crop will or will not respond to fertilizer application (Goulding et al., 2020).

In this study, the levels of available potassium ($K^+$) in the soil were assessed using the Mehlich 1 solution extraction method for all crops. This methodology is the officially recommended approach by the Brazilian Agricultural Research Corporation. For millet, the $K^+$ contents in the soil ranged from 44.8 to 93.3 mg dm$^{-3}$ for the LV soil, while in the LA soil ranged from 32.5 to 94.8 mg dm$^{-3}$ The results indicated significant differences in the $K^+$ contents between the treatments for both soils, as evidenced by the F test of 5.9 and CV of 22.27 % for LV, and F test of 5.28 with CV of 38.4% for LA (Table 4). Concerning standard values of Sousa and Lobato (2004) of potassium content expected for a soil, it was found that in LV soil, the contents for the treatments are at adequate levels (above 50 mg dm$^{-3}$), except for the control. In LA soil, on the other hand, $K^+$ levels are below adequate levels (less than 40 mg dm$^{-3}$) in KMC treatments, except for 120 KMC treatment and within the appropriate limits for the reference treatments 60 Ekosil and 60 KCl for millet.

Table 4. Exchangeable potassium content in millet, soybean, and bean soil depends on the treatments used

| | **Exchangeable K in the soil (mg dm$^{-3}$)** | | | | | |
|---|---|---|---|---|---|---|
| **Treatment** | **Millet** | | **Soybean** | | **Beans** | |
| | **LV** | **LA** | **LV** | **LA** | **LV** | **LA** |
| 0 KMC | 44.8 b | 33.8 b | 26.0 b | 25.0 b | 31.0 bc | 22.0 c |
| 30 KMC | 49.8 b | 32.5 b | 67.5 b | 58.0 a | 33.0 b | 25.2 c |
| 60 KMC | 56.0 b | 37.4 b | 61.9 b | 55.5 a | 33.1 b | 30.0 d |
| 120 KMC | 52.3 b | 45.0 b | 56.9 b | 57.7 a | 36,0 bc | 40.0 b |
| 240 KMC | 58.8 b | 33.0 b | 56.8 b | 60.6 a | 28.0 c | 37.1 ab |
| 60 Ekosil | 57.5 b | 54.8 ab | 98.0 ab | 71.0 a | 84.0 a | 90.0 a |
| 60 KCl | 93.3 a | 94.8 a | 65.0 a | 75.0 a | 63.0 b | 92.0 a |
| F test | 5.90 ** | 5.28 ** | 18.90 ** | 12.89 ** | 5.20 ** | 5.20 ** |
| CV % | 22.27 | 38.40 | 16.92 | 7.66 | 33.80 | 33.01 |

Means followed by the same letter in the same column are not statistically different at 5% probability by Tukey's test. ** and * are significant at 1% and 5%, respectively, in the analysis of variance (F test). CV (%): coefficient of variation.

Comparatively, the reference source of agromineral K (Ekosil) and KMC, at the same dose (60 kg ha$^{-1}$ of $K_2O$), did not present significant differences according to Tukey's test concerning the $K^+$ content in the two soils for millet. However, the use of KCl resulted in the highest K+ content values, which may indicate a potential relationship with the high solubility of the product. This finding is consistent with other studies suggesting that the use of rock powder in agriculture serves as an alternative source of slow-release potassium supplementation (Da Silva et al., 2012; Teixeira et al., 2012). In the dose-response evaluation for millets, a high R² was observed in the 2nd degree polynomial adjustment of potassium ($K^+$) for both soils (Figure 3), indicating potassium increases in the soil up to the maximum tested rate of 240 kg $ha^{-1}$ of $K_2O$ for clayey LV soils. For sandy soils, the polynomial model indicated potassium increases in pearl millet up to a rate of 110 kg $ha^{-1}$ of $K_2O$ from KMC in sandy loam soils (LA).

Previous studies, such as that of Theodoro *et al.* (2013), evidenced the interaction of agro minerals from five different types of rocks with the soil and plant system, demonstrating the availability of nutrients in Oxisols in various crops. Similarly, Reis (2013) reported the positive effect of agro minerals, such as micaxiste and amphibolite rocks, on the millet crop, acting as a source of these nutrients and increasing the dry matter of the roots. These results corroborate the findings of Ribeiro *et al.* (2010), who highlighted the positive effects of high concentrations of exchangeable $K^+$ in the soil when alkaline ultramafic rocks and pyroclastic breaches were used at high dosages.

Regarding the potassium contents (Table 4) in the soil cultivated with soybean, there were significant differences between the treatments in both LV soil and LA soil (F tests of 18.90 and CV 16.9% for LV and F tests of 12.89 and CV 7.7% for LA). In both soils, $K^+$ levels ranged from 26 to 98 mg $dm^{-3}$ in LV and from 25 to 75 mg $dm^{-3}$ in LA (Table 4). In the KMC dose-response evaluation in clayey LV soils, the 2nd degree polynomial fit displayed a low R² for soil K content in soybeans (Figure 3). Despite this limitation, the model indicated the rate of 140 kg $ha^{-1}$ of $K_2O$ from KMC as the most efficient for potassium availability in clayey soils for soybeans. One possible explanation is that the timeframe might not have been sufficient for the release and availability of potassium contained within the KMC, given that potassium is within the crystal lattice of the material. On the other hand, for sandy soils (LA), the 2nd degree polynomial fit displayed a high R² for soybeans, indicating increases in available soil potassium up to the rate of 160 kg $ha^{-1}$ of $K_2O$ from KMC. Although the regression didn't fit well in the LV as it did in LA, the maximum dose value was close for soybeans in both soil types.

For LV, the reference treatment 60 Ekosil obtained the best result of $K^+$ in the soil for soybean, although at the same dose (60 Kg $ha^{-1}$ of $K_2O$), the KMC did not present statistically significant differences according to the Tukey test. The results found for soybean in the potassium contents in the soil are by the standards established by Souza and Lobato (2004) for all treatments evaluated, except of the control.

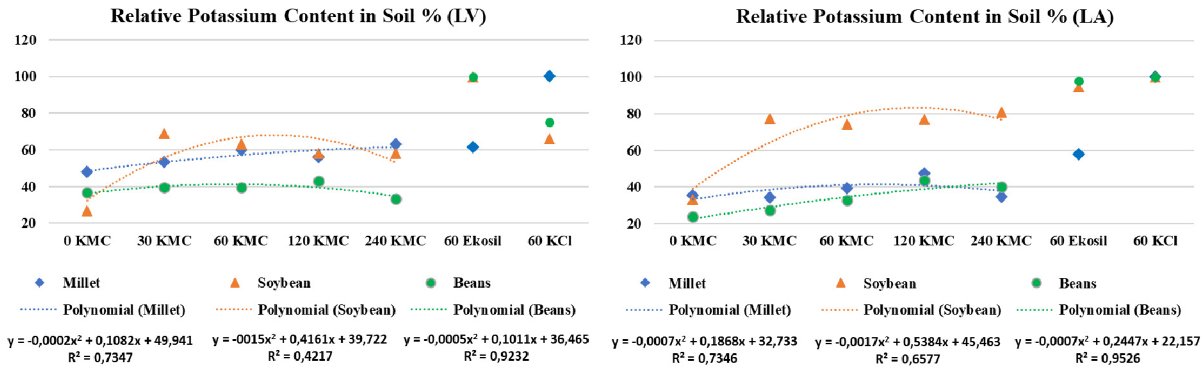

Figure 3. The Polynomial curve for evaluation dose-response and relative efficiency of KMC about the relative content of potassium in millet, soybean, and bean soil in LV and LA

For LA soil, the highest value found for $K^+$ in soybean was for the reference treatment 60 KCl, although Ekosil and KCl, at the same dose 60 Kg $ha^{-1}$ of $K_2O$ of KMC, did not present significant differences into potassium content in the soil by Tukey's test, besides having close values, which can be observed by the low value of CV (7.66%). The levels of $K^+$ in LA soil are also at adequate levels for soybean, except for the control, according to the standards of Souza and Lobato (2004).

De Mello Cunha (2022), in a similar study in the greenhouse, compared three types of rock powders in two types of soil Cambisol and Nitisol, in soybean production and found that the results are related to the chemical characteristics of the soils, nutrient contents were obtained in the seeds and dry matter production similar or superior to conventional fertilization treatments with better results observed in the less fertile soils.

Regarding soybeans, Embrapa (2018) emphasizes the importance of maintaining potassium levels in soybean fields, pointing out that potassium is responsible for several important functions in plants, such as osmotic control, regulation of stomata, and enzymatic activation, and that with adequate levels, there is an increase in nodulations and consequently the oil content, since when the level is not adequate part of the reserves used by soybean are removed from the soil.

In a large study conducted by Theodoro (2006), it was found that the combination of rock dust and organic composting was doubly effective. In addition to accelerating the availability of nutrients to plants at the same time, it reduced the volume of waste (garbage) on the properties involved.

These results indicate that the use of the KMC remineralizer promoted increases in potassium contents in both soils cultivated with soybean in the release of potassium in the soil-plant system showing the ability to increase the availability of potassium in the soil, the appropriate use can contribute to optimize soil fertility, increase the productivity of soybean crop, in addition to promoting sustainable practices with lower environmental impacts when compared to the use of traditional soluble sources such as KCl.

In the bean tree, according to Table 4, it is possible to verify that when analyzing the potassium contents ($K+$) in the soil extracted by the Mehlich 1 method in the LV and LA soils, a significant difference was observed between the treatments (F tests of 5.2 and coefficient of variation of 33.8% for the LV; F tests of 5.2 and coefficient of variation of 33.0% for LA). In soil LV, K contents ranged between 33 and 84 mg $dm^{-3}$, while in LA soil, they ranged between 22 and 92 mg $dm^{-3}$. The polynomial adjustments of the soil K contents for LV and LA, represented in Figure 3, showed that the increasing doses of the KMC remineralizer were adjusted to a 2nd degree polynomial regression with elevated $R^2$, indicating that the KMC promoted increments in the soil potassium contents up to the dose of 110 kg $ha^{-1}$ of KMC $K_2O$ in the LV and up to the dose of 170 kg $ha^{-1}$ of $K_2O$ of the KMC in LA.

When comparing the sources of $K^+$ (Ekosil, KCl, and KMC) at the same dose of 60 Kg $ha^{-1}$ of $K_2O$, it was found that the performance of KMC in both soil LV and LA was much lower than the reference treatments and that only these showed adequate levels (above 50 mg $dm^{-3}$) concerning the standards of Souza and Lobato (2004). Regarding the low performance of KMC, the results indicate that there were probably mechanisms of decrease in soil content such as losses and mainly of absorption by plants, which is corroborated with the bean yields presented in Table 1, wherein in LV soil the highest yield performance of all treatments was KMC at the recommended dose of 60 $K_2O$, in addition to the leaf contents of the common bean that can be observed in Table 5, showing that the bean absorbed practically the same amount in the standard dose 60 $K_2O$ KMC and its reference 60 Ekosil, already 60 KCl had lower values in the leaf content.

More positive results for the adoption of rock dust as a source of potassium were observed for soils with low cation exchange capacity, typical of latosols found in tropical/subtropical regions, and that have poor nutrient retention characteristics (Manning & Manning, 2010). The Mehlich 1 solution, which was used in the methodology to determine the exchangeable potassium content in soil, is able to evaluate the kinetics of potassium release from minerals and soils of different particle sizes through the acids in the extraction solution (Da Silva et al., 2012).

The agronomic use of rock dust in agriculture presents promising potential as an alternative to remineralizing soil fertilizer and offers advantages such as the insolubility of nutrients in the water, reducing losses by leaching and fixation, and the solubility of nutrients in the solution of weak acids such as those occurring in the soil, resulting in a slow and efficient release to crops (Ramos et al., 2015). These studies corroborate the results obtained, strengthening the understanding of the influence of the use of agro minerals as an alternative source of potassium on soil fertility and bean crop development.

Gaining a deeper understanding of the underlying mechanisms behind the release of potassium (K) from minerals present in the soil is crucial for advancing innovative approaches in sustainable agriculture. However, accurately determining the source of absorbed K by crops and the contribution of non-exchangeable K has been a significant challenge due to the scarcity of suitable methods, both under field conditions and in microcosm experiments (Zörb et al., 2014).

### *3.3 Foliar Potassium Content*

The analyses of the leaf plant tissue were made for the three crops evaluated and obtained the following results:

For millet, the results obtained for the leaf contents of potassium ($K^+$) in the LV and LA soils showed significant differences between the treatments. In soil LV, an F test of 6.03 and a coefficient of variation of 26.4% were observed, while in LA soil, the F test was 5.77, and the coefficient of variation was 25.0% (Table 5).

Table 5. The Leaf potassium content of millet, soybean, and beans depends on the treatments used.

| Treatment | Foliar Potassium Content (dag kg$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | Millet | | Soybean | | Beans | |
| | LV | LA | LV | LA | LV | LA |
| 0 KMC | 0.4 b | 1.0 B | 0.8 b | 1.0 b | 0.9 c | 0.8 c |
| 30 KMC | 0.4 b | 2.0 ab | 1.6 b | 2.0 ab | 1.8 b | 1.1 bc |
| 60 KMC | 0.4 b | 2.0 ab | 1.7 b | 2.0 ab | 2.1 ab | 1.3 b |
| 120 KMC | 0.8 ab | 2.1 ab | 2.4 ab | 2.1 ab | 2.4 ab | 1.6 a |
| 240 KMC | 0.8 ab | 2.1 ab | 2.6 ab | 2.9 a | 2.3 ab | 1.3 b |
| 60 Ekosil | 0.8 ab | 1.9 ab | 2.7 ab | 1.9 ab | 2.5 ab | 1.5 b |
| 60 KCl | 1.3 a | 3.0 A | 2.9 a | 3.0 a | 1.9 b | 1.1 bc |
| F test | 6.03 ** | 5.77 ** | 4.51 ** | 6.42 ** | 4.50** | 3.20 * |
| CV % | 26.4 | 25.0 | 23.0 | 13.0 | 19.7 | 25.8 |

Means followed by the same letter in the same column are not statistically different at 5% probability by Tukey's test. ** and * are significant at 1% and 5%, respectively, in the analysis of variance (F test). CV (%): coefficient of variation.

In both soils, the highest leaf K contents were obtained with the reference treatment 60 KCl, indicating the efficiency of this source in the availability of potassium for the millet crop. As for the agro mineral reference treatment, no significant differences were found by Tukey's test between the doses of 60 kg ha$^{-1}$ of $K_2O$ of the KMC remineralizer and the Ekosil reference standard in the leaf analyses of millet in the two soils. The foliar potassium levels in pearl millet in the clayey LV soil are similar to those obtained in the study by Crusciol and Soratto (2007), but they remained below the values found by Bossolani et al. (2018), which recorded 1.6 dag kg$^{-1}$ in clayey Oxisol with KCl doses. However, in the sandier LA soil, the foliar potassium values were considerably higher in all treatments.

When analyzing the adjustments of the 2nd degree polynomial regressions of the leaf $K^+$ contents about the KMC $K_2O$ rates, it was observed that, in the LV soil, there were increments in the leaf $K^+$ contents up to the dose of 240 kg ha$^{-1}$ of KMC $K_2O$ in the millet for LV, while for LA the increase was observed up to the dose of 150 kg ha$^{-1}$ of KMC $K_2O$, as shown in Figure 4. These results are consistent with those obtained by Menezes & Leandro (2004), who found $K^+$ levels of 1.04 dag kg$^{-1}$ in millet plants. Considering the yields achieved in this assay for LV, which were around 10 t/ha, these contents represent a soil extraction capacity of 80 to 140 kg ha$^{-1}$ of K, corroborating the results of Pacheco *et al.* (2011), which obtained 130 kg ha$^{-1}$ of potassium in millet in Santo Antônio de Goiás.

As for soybean analyzing the results LV and LA (Table 5), significant differences were observed in the leaf contents of potassium ($K^+$) of the soybean crop. In soil LV, the F test was 4.51, with a coefficient of variation of 23.0%, while in LA soil, the F test was 6.42, with a coefficient of variation of 13.0%. In LV and LA soil, the highest levels of leaf $K^+$ were obtained with the treatment of the 60 KCl standard, while for the agro mineral sources tested, no significant differences were found by Tukey's test at the doses of 60 KMC and 60 Ekosil. The leaf contents of $K^+$ in soybean found are close to the levels considered adequate by Embrapa (2021) and Raij (2011), which range from 1.70 to 2.50 dag kg-$^1$. The values found for foliar potassium content in soybeans were higher in both soils at the standard dose of 60 $K_2O$ kg ha-1 compared to the value of 1.3 dag kg$^{-1}$ reported by De Oliveira et al. (2022) using phonolite rock as a potassium source.

When analyzing the 2nd degree polynomial regressions of leaf $K^+$ contents about KMC $K_2O$ doses in LV and LA soils for dose-response evaluation, it was found that there were significant increments up to the dose of 240 kg ha$^{-1}$ of KMC $K_2O$ in both soils (Figure 4). In a study in clay soil, Embrapa (2018) observed a relationship between the apparent deficiency symptoms in soybeans and the potassium content in the leaves. It was found that in areas where deficiency symptoms were severe and visible in the leaves, the leaf potassium content was 0.25 dag kg$^{-1}$. On the other hand, in nearby areas that had no apparent symptoms of deficiency, the values of leaf potassium content were 0.40 dag kg$^{-1}$. This phenomenon of low potassium availability and no apparent symptoms is known as "hidden hunger." These findings reinforce the importance of the appropriate use of remineralizers in the optimization of soil fertility.

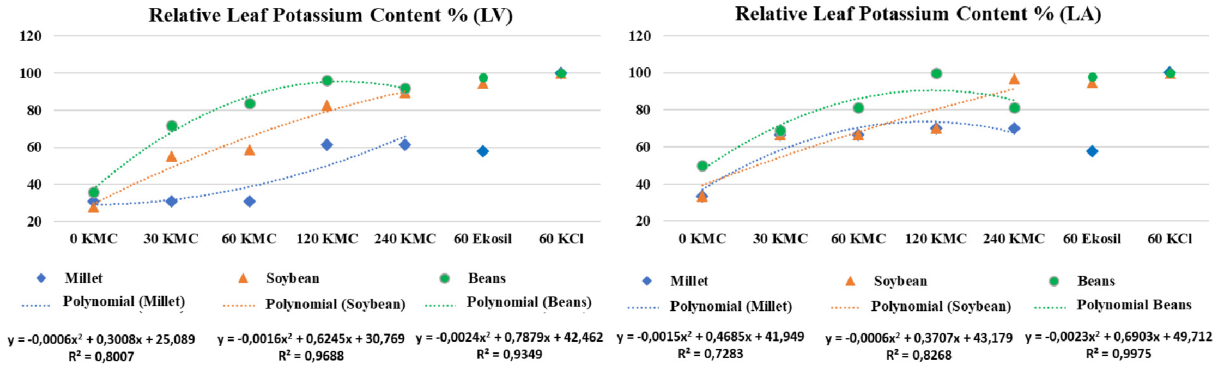

Figure 4. The polynomial curve for evaluation dose-response and relative efficiency of KMC about the relative content of leaf potassium in millet, soybean, and beans in LV and LA

Regarding the leaf contents of potassium found for common beans in LV and LA soils, it was observed that there were significant differences in the treatments in both soils. In the LV soil, the F test was 4.5, with a CV of 19.70%, while in the LA soil, the value of the F test was 3.20%, with a CV of 25.8% (Table 5).

For both LV and LA soils, the highest $K^+$ content found was related to the reference treatment 60 Ekosil, not differing statistically from the 60 KMC treatment in both soils. For the LV, the values found for the standard dose of 60 $K_2O$ for Ekosil and KMC treatments presented adequate levels within the values proposed by Malavolta (1997), ranging from 2.0 to 2.5 dag $kg^{-1}$. However, according to these values, no treatment presented an adequate level of leaf $K^+$ in the LA soil. As for the reference treatment, 60 KCL presented lower results compared to the standard dose of 60 $K_2O$ of Ekosil and KMC. Favorable conditions for leaching losses may explain the lower levels of leaf potassium in the bean, along with the non-application of fertilizers in the crop. The values found for the common bean are in accordance with the study conducted by Soratto et al. (2021), using alkaline rocks and phonolite as potassium sources for bean cultivation in clayey Oxisol. On average, the author found values of 2.2 dag $kg^{-1}$, similar to the values obtained in this study for the same soil classification, Clayey Oxisol (LV).

When analyzing the 2nd degree polynomial regression of leaf $K^+$ contents in common beans about KMC $K_2O$ rates in LV and LA soils, it was found that there were significant increments up to the dose of 160 kg $ha^{-1}$ and 150 kg $ha^{-1}$ of KMC $K_2O$ in LV and LA soil, respectively (Figure 4). Bean is a nutrient-demanding crop due to its limited and shallow root system, as well as its relatively short growing cycle. For this reason, it is of utmost importance to ensure the proper availability of nutrients to the plant at the appropriate times and places. The analysis of plant tissues plays a key role in the assessment of nutritional status, especially for nutrients such as nitrogen and micronutrients (Faquin, 2002).

Supporting the conducted study on the potential use of rocks as a source of potassium, a comprehensive investigation involving 16 types of rocks found that the utilization of rock powder is highly advantageous due to its gradual and slow-release attributes. This characteristic allows residual portions of the rock powder to transform into clay over time, establishing a significant "nutrient bank." This nutrient reservoir ensures a consistent release over extended periods, resulting in enduring effects on soil fertility and optimization of costs linked to fertilizer application (Mbissik et al., 2023).

Comparing the agronomic efficacy of the use of silicate rock powders with soluble fertilizers is a challenging task, as conventional fertilizers often provide readily available isolated nutrients for the growth cycle, while the potential effects of rock powder uses are diverse but generally slower and may be long-term and more difficult to quantify (Swoboda et al., 2022).

### *3.4 Limitations of the Study and Areas for Further Research*

In terms of the potential applications of the study, it is important to note that we have explored the possibility of a new source of potassium for agriculture from a local deposit that has not yet been agronomically tested. As mentioned above, Brazil is a major agricultural producer, but faces a significant dependence on potash imports. However, the viability of this type of rock material is limited to a local scale due to its low $K_2O$ content, which requires significantly higher quantities compared to traditional fertilizers. This characteristic, in turn, poses logistical and financial challenges for its use over long distances. On the other hand, its low cost makes it an attractive alternative for local producers.

The positive results obtained in this study are in line with the Brazilian regulations for agrominerals. However, there are opportunities for future research, especially in field experiments with other crops, preferably those grown in the Brazilian Midwest, such as sugarcane. In addition, it is crucial to conduct long-term follow-up studies, as residual effects have shown promising results.

## 4. Conclusion

Based on the results of this study, it is possible to infer that the use of agromineral from saprolite of nepheline syenite extracted from the deposit in the Brazilian Midwest can be utilized as an alternative source for supplementing $K_2O$ in agriculture due to its pulverization into particles with a granulometric size smaller than 0.42 mm and a content of 11.6% $K_2O$, which facilitates weathering for more efficient release of K.

The results demonstrated that the agromineral was capable of increasing potassium levels in all treatments in both evaluated soil types, both in the soil itself and in the leaves, when compared to the control group. Furthermore, there was also an increase in productivity. The residual effect of the agromineral stood out with higher bean plant productivity compared to reference treatments in the clayey LV soil.

In conclusion, the tested agromineral has the potential to reduce the dependency on KCl imports for local producers. It presents itself as an alternative for potassium supplementation, with long-term residual effects, while also addressing the demands for more natural and sustainable agricultural practices, which aligns with the public policy of the National Fertilizer Plan (2022-2050). Conducting field studies with subsequent harvests is recommended to validate the benefits under more realistic environmental conditions.

## Acknowledgments

EDEM Agrominerals, for the supply of agromineral and logistical support. To Funape for the financial management of the Project and to the Laboratory of Soils and Substrates of the School of Agronomy of the Federal University of Goias for the analyses carried out.

## References

Almeda Júnior, J. J., Lazarini, E., Smiljanic, K. B. A., Simon, G. A., Matos, F. S. A., Barbosa, U. R., Silva, V. J. A., Miranda, B. C., & Silva, A. R. da. (2020). Analysis of technological variables in soybean crop (Glycine max) using soil remineralizer as fertilizer. *Brazilian Journal of Development*, *6*(8), 56835–56847. https://doi.org/10.34117/bjdv6n8-190

Alves, P. F. S., Sampaio, R. A., Kondo, M. K., Ferreira, V. G., & Pegoraro, R. F. (2021). Rock dust as a soil conditioner for bean in northern Minas Gerais. *Research, Society and Development, 10*(10), e45101018331. https://doi.org/10.33448/rsd-v10i10.18331

Bossolani, J. W., Lazarini, E., de Souza, L. G. M., Parente, T. de L., Caioni, S., & de Biazi, N. Q. (2018). Potassium doses in previous crops and effect on soybean in succession. *Revista Brasileira de Engenharia Agricola e Ambiental*, *22*(2), 90–94. https://doi.org/10.1590/1807-1929/agriambi.v22n2p90-94

Brazil. (2006). *NORMATIVE INSTRUCTION SDA No 27, 05 JUNE 2006 (Amended by IN SDA no 7, of 12/04/2016, republished on 02/05/2016)*. Retrieved June 16, 2022, from www.gov.br/agricultura/pt-br/assuntos/insumos-agropecuarios/insumos-agricolas/fertilizantes/legislacao/in-sda-27-de-05-06-2006-alterada-pela-in-sda-07-de-12-4-16-republicada-em-2-5-16.pdf

Brasil, E. P. F., Leandro, W. M., Teixeira, W. G., Vieira, M. A., Souza, J. P. N. de, & Vieira, H. V. (2020). Chemical Extractors to Assess Potassium Availability in Glauconitic Siltstone. *Journal of Agricultural Science*, *12*(9), 166. https://doi.org/10.5539/jas.v12n9p166

Caligaris, B. S. A., Rangel, L. E. P., Polidoro, J. C., & Farias, P. I. V. (2022). The importance of the National Fertilizer Plan for the future of agribusiness and Brazil. *Journal of Agricultural Policy*, *31*(1), 3–8.

Castro, V. R., Santos, L. J. da C., & Gomes, E. R. (2021). Use of Silicatic Rock Powder as a Source of Nutrients for Agricultural Soils: Review. *Impacts of Technologies on Materials and Metallurgical Engineering*, *2*(1), 107–118. https://doi.org/10.22533/at.ed.31421190111

CFSG, C. D. F. D. S. (1988). *Recommendation of concealers and fertilizers for Goiás: Vol. Recomendaç.* Retrieved from www.nutricaodeplantas.agr.br/site/downloads/RECOMENDACOES_DE_CORRETIVOS_E_FERTILIZANTES_PARA_GOIAS.pdf

CONAB – National Supply Company. (2020). *Grain survey confirms production above 250 million tons in the 2019/2020 harvest*. Retrieved April 26, 2023, from https://www.conab.gov.br/ultimas-noticias/3371-levantamento-de-graos-confirma-producao-acima-de-250-milhoes-de-toneladas-na-safra-2019-2020

Crusciol, C. A. C., & Soratto, R. P. (2007). Nutrition and productivity of peanuts in succession to the cultivation of cover crops in the no-tillage system. *Pesquisa Agropecuária Brasileira*, *42*(11), 1553–1560. https://doi.org/10.1590/s0100-204x2007001100006

Da Silva, A. de A. S., Medeiros, M. E., Sampaio, J. A., & Garrido, F. M. dos S. (2012). Characterization of the verdete of Abaeté cedar for the development of a material with controlled release of potassium. *Holos*, *5*, 42–51. https://doi.org/10.15628/holos.2012.1093

de Medeiros, D. S., Sanchotene, D. M., Ramos, C. G., Oliveira, L. F. S., Sampaio, C. H., & Kautzmann, R. M. (2021). Soybean crops cultivated with dacite rock by-product: A proof of a cleaner technology to soil remineralization. *Journal of Environmental Chemical Engineering*, *9*(6), 106742. https://doi.org/10.1016/j.jece.2021.106742

De Mello Cunha, G. O., De Almeida, J. A., & Medeiros Coelho, C. M. (2022). Chemical composition of soybean seeds subjected to fertilization with rock dusts. *Acta Scientiarum - Agronomy*, *44*(2009). https://doi.org/10.4025/actasciagron.v44i1.53312

De Oliveira, L. R., Filho, M. C. F., Montes, R. M., Benett, K. S. S., & Benett, C. G. S. (2022). Sources and doses of potassium on yield components of soybean and sorghum. *Revista de Agricultura Neotropical*, *9*(4), 1–8. https://doi.org/10.32404/rean.v9i4.7016

Embrapa. (1997). *Manual-of-Soil-Analysis Methods* (M. E. C. CLAESSEN (Ed.)). Retrieved June 15, 2022, from http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/330804

Embrapa. (2018). *Potassium: care for the maintenance of the nutritional balance of soy*. Retrieved March 16, 2023, from https://ainfo.cnptia.embrapa.br/digital/bitstream/item/178923/1/folder-nutricao-2018-OL-1.pdf

Embrapa. (2021). *Interpretation of leaf/soybean analysis*. Retrieved June 28, 2022, from https://www.embrapa.br/agencia-de-informacao-tecnologica/cultivos/soja/producao/manejo-da-fertilidade-do-solo/exigencias-minerais-e-adubacao/analise-foliar/interpretacao-da-analise-de-folhas

FAO. (2022). World Food and Agriculture – Statistical Yearbook 2022. *World Food and Agriculture – Statistical Yearbook 2022*. https://doi.org/10.4060/cc2211en

Faquin, V. (2002). *Diagnosis of the nutritional status of plants* (UFLA/FAEPE (Ed.)). Retrieved April 18, 2022, from http://repositorio.ufla.br/jspui/handle/1/15097

Globalfert. (2021). *Fertilizer imports hit record in 2020*. Retrieved June 05, 2022, from https://globalfert.com.br/analises/importacao-de-fertilizantes-bate-recorde-em-2020/

Gomes, F. P. (1952). The comparison between treatment means in the analysis of variance. *Annals Luiz de Queiroz School of Agriculture/USP*. https://doi.org/https://doi.org/10.1590/S0071-12761954000100002

Goulding, K., Murrell, T. S., Mikkelsen, R. L., Rosolem, C., Johnston, J., Wang, H., & Alfaro, M. A. (2020). Outputs: Potassium losses from agricultural systems. In *Improving Potassium Recommendations for Agricultural Crops*. https://doi.org/10.1007/978-3-030-59197-7_3

Kinpara, D. I. (2003). *The Strategic Importance of Potassium for Brazil*. Retrieved March 16, 2022, from http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/568191

*Book Proceedings III Brazilian Congress of Rocking*. (2017). Retrieved January 12, 2023, from https://www.embrapa.br/documents/1354346/26325871/Livro+Congresso+de+rochagem+Formato+Web.pdf/29be78a9-dd7a-8050-5b31-2b02c583589e

Lobato, O. J. S. M. (1978). *Availability and climatological formula of the Municipality of Goiânia and Boundary Municipalities. Manual of the School of Agronomy and Veterinary* (U. F. de Goiás (Ed.); Vol. 2, Issue 1).

Malavolta, E., Vitti, G. C., & Oliveira, S. A. de. (1997). *Evaluation of the nutritional status of plants: principles and applications* (Potafos/ESALQ).

Malavolta, E., VITTI, G. C., OLIVEIRA, S. A. (1997). *Evaluation of the nutritional status of plants: principles and applications* (POTAFOS/ESALQ).

Manning, D. A. C., & Manning, D. A. C. (2010). Mineral sources of potassium for plant nutrition . A review To cite this version : Mineral sources of potassium for plant nutrition . A review. *Agronomy for Sustainable Development*, *30*, 281–294.

Manning, D. A. C., & Theodoro, S. H. (2020). Enabling food security through use of local rocks and minerals. *Extractive Industries and Society*, *7*(2), 480–487. https://doi.org/10.1016/j.exis.2018.11.002

MAPA, Ministry of Agriculture, Livestock and Supply. (2022). *The National Fertilizer Plan*. Retrieved November 15, 2022, from https://www.gov.br/agricultura/pt-br/assuntos/insumos-agropecuarios/insumos-agricolas/fertilizantes/plano-nacional-de-fertilizantes/o-plano-nacional-de-fertilizantes

Mbissik, A., Khiari, L., Raji, O., Elghali, A., Lajili, A., Ouabid, M., Jemo, M., & Bodinier, J. L. (2023). Potassium Fertilizer Value of Raw and Hydrothermally Treated Igneous Rocks. *Journal of Soil Science and Plant Nutrition*, *23*(1), 1030–1045. https://doi.org/10.1007/s42729-022-01101-6

Menezes, L. A. S., & Leandro, W. M. (2004). Evaluation of soil cover species with potential use in no-tillage systems. *Tropical Agricultural Research*, *34*(3), 173–180. Retrieved June 16, 2023, from https://repositorio.bc.ufg.br/xmlui/bitstream/handle/ri/13106/Artigo - Luiz Antonio Silva Menezes - 2004.pdf?sequence=5&isAllowed=y

Mores, G. de V., Dewes, H., Talamini, E., Vieira-Filho, J. E. R., Casagranda, Y. G., Malafaia, G. C., Costa, C., Spanhol-Finocchio, C. P., & Zhang, D. (2022). A Longitudinal Study of Brazilian Food Production Dynamics. *Agriculture (Switzerland)*, *12*(11), 1–11. https://doi.org/10.3390/agriculture12111811

NIST. (2012). *NIST/SEMATECH e-Handbook of Statistical Methods*. https://doi.org/https://doi.org/10.18434/M32189

Ogino, C. M., Junior, G. C., Popova, N. D., & Martines Filho, J. G. (2020). Purchase power, price and mineral fertilizers consumption: An analysis for central Brazil. *Revista de Economia e Sociologia Rural*, *59*(1), 1–19. https://doi.org/10.1590/1806-9479.2021.220367

Osaki, M. (2022). *conflict-in-the-east-Europe-completes-a-month-and-fertilizer-sector-follows-apprehensive*. Retrieved April 26, 2023, from https://www.cepea.esalq.usp.br/br/opiniao-cepea/conflito-no-leste-europeu-completa-um-mes-e-setor-de-fertilizantes-segue-apreensivo.aspx

Pacheco, L. P., Monteiro, M. M. de S., da Silva, R. F., Soares, L. dos S., Fonseca, W. L., Nóbrega, J. C. A., Petter, F. A., Neto, F. de A., & Osajima, J. A. (2011). Production of phytomass and accumulation and release of nutrients by cover crops in the safrinha. *Brazilian Agricultural Research Agropec. Bras*, *46*(1), 17–25. https://doi.org/10.1590/brag.2013.041

Raij, B. van. (2011). *Soil fertility and nutrient management* (I. P. N. Institute).

Ramos, C. G., Querol, X., Oliveira, M. L. S., Pires, K., Kautzmann, R. M., & Silva, L. F. O. (2015). A preliminary evaluation of volcanic rock powder for application in agriculture as soil a remineralizer. *Science of the Total Environment*, *512–513*, 371–380. https://doi.org/10.1016/j.scitotenv.2014.12.070

Reis, D. N. dos. (2013). Mineralogy, chemistry, agronomic efficiency and solubilization technologies of agromineral sources of potassium *[UFLA]*. Retrieved March 16, 2023, from *http://repositorio.ufla.br/bitstream/1/10660/1/TESE_Mineralogia%2C chemistry%2C agronomic efficiency and solubilization technologies of agromineral sources of potassium.pdf*

Ribeiro, J. V. S., & Leite, M. M. B. (2017). *Logistics solution for fertilizer import Case study for Mato Grosso*. Retrieved June 06, 2021, from https://esalqlog.esalq.usp.br/upload/kceditor/files/2017/Iniciação/TN_JoaoVictor_Mariane_final.pdf

Ribeiro, L. da S., Santos, A. R. dos, Souza, L. F. da S., & Souza, J. S. (2010). Potassium-bearing silicatic rocks as sources of the nutrient for soil plants. *Brazilian Journal of Soil Science*, *34*(3), 891–897. https://doi.org/10.1590/s0100-06832010000300030

LEAVES. (2020). National fertilizer production: Strategic study. *Special Secretariat for Strategic Affairs*, 26. Retrieved January 08, 2023, from https://www.gov.br/planalto/pt-br/assuntos/assuntos-estrategicos/estudos-estrategicos-2/estudo-producao-nacional-fertilizantes

Sampaio, J. A., France, C. S., & Braga, P. F. A. (2008). Nepheline Sienito. *Industrial Rocks and Minerals – CETEM, 2nd Edition, 30*. Retrieved June 16, 2023, from http://mineralis.cetem.gov.br/bitstream/cetem/1119/1/30. NEPHELINE SIENITE.pdf

Shimakura, S. (2005). *How ANOVA works*. Federal University of Paraná - UFPR. Retrieved July 28, 2023, from http://www.leg.ufpr.br/~silvia/CE701/node91.html

Soratto, R. P., Crusciol, C. A. C., de Campos, M., da Costa, C. H. M., Gilabel, A. P., Castro, G. S. A., & Neto, J. F. (2021). Silicate rocks as an alternative potassium fertilizer for upland rice and common bean crops. *Pesquisa Agropecuaria Brasileira*, *56*, 1–10. https://doi.org/10.1590/S1678-3921.pab2021.v56.01411

Sousa, D. M. G. de., & Lobato, E. (2004). *Cerrado: soil correction and fertilization*. Embrapa Technology Information.

Swoboda, P., Döring, T. F., & Hamer, M. (2022). Remineralizing soils? The agricultural usage of silicate rock powders: A review. *Science of the Total Environment*, *807*. https://doi.org/10.1016/j.scitotenv.2021.150976

Teixeira, A. M. D. S., Sampaio, J. A., Garrido, F. M. dos S., & Medeiros, M. E. (2012). Evaluation of phonolite rock as an alternative potassium fertilizer. *Holos*, *5*, 21. https://doi.org/10.15628/holos.2012.1102

Theodoro, S. H., Leonardos, Othon Henry Rego, Kleysson Garrido Medeiros, F. de P., Talini, N. L., & Santos, Francisca dos Neuza, O. (2013). *Effect of the use of the rocking technique associated with organic fertilization in tropical soils*. Proceedings of the II Brazilian Congress of Rocking. Retrieved April 22, 2022, from http://www.sgb.gov.br/remineralizadores/media/anais_IIcbr_2013.pdf

Theodoro, S. H., & Leonardos, O. H. (2006). The use of rocks to improve family agriculture in Brazil. *Anais Da Academia Brasileira de Ciencias*, *78*(4), 721–730. https://doi.org/10.1590/s0001-37652006000400008

Theodoro, S. H., & Leonardos, O. H. (2011). Rocking: A Question of National Sovereignty. *III Symposium on Geochemistry of the Mercosur Countries*, 337–340.

UNESP. (2019). *Statistics and Biostatistics*. Retrieved July 05, 2023, from https://www.fcav.unesp.br/Home/departamentos/cienciasexatas/alanrodrigopanosso/apostila_bioestatistica_2019.pdf

USDA. (2022). *Brazil's Momentum as a Global Agricultural Supplier Faces Headwinds*. Retrieved July 29, 2022, from https://www.ers.usda.gov/amber-waves/2022/september/brazil-s-momentum-as-a-global-agricultural-supplier-faces-headwinds

Van Straaten, P. (2006). Farming with rocks and minerals: Challenges and opportunities. *Anais Da Academia Brasileira de Ciencias*, *78*(4), 731–747. https://doi.org/10.1590/S0001-37652006000400009

Van Straaten, P. (2022). Distribution of agromineral resources in space and time - a global geological perspective. *Pesquisa Agropecuaria Brasileira*, *57*, 1–22. https://doi.org/10.1590/S1678-3921.PAB2022.V57.01453

Writzl, T. C., Canepelle, E., Eduardo, J., Stein, S., Kerkhoff, J. T., Steffler, A. D., Weber, D., & Redin, M. (2019). Basalt associated with chicken litter in an Oxisol production of popcorn crop with the use of basalt rock. *Brazilian Journal of Sustainable Agriculture*, *9*(2), 101–108. https://doi.org/https://doi.org/10.21206/rbas.v9i2.3077

Zörb, C., Senbayram, M., & Peiter, E. (2014). Potassium in agriculture - Status and perspectives. *Journal of Plant Physiology*, *171*(9), 656–669. https://doi.org/10.1016/j.jplph.2013.08.008

## Copyrights