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Agronomic Efficiency of Biotite in Soybean and Corn Silage Production

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Abstract

The aim of the present study is to assess the agronomic efficiency and potential of using biotite, a remineralizer, as nutrient source to both soybean (*Glycine max* (L.) Merrill and maize silage (*Zea mays* L.). These crops were grown in succession in different soils. The research was conducted due to the importance of adopting alternative sources of fertilizers for agriculture and the relevance of using ground silicate rock powders to maximize plant growth. The purpose was to also register this product in Ministry of Agriculture, Livestock and Supply (MAPA) as a soil remineralizer. Biotite (BE), a silicate rock powder used as soil remineralizer, was provided by *Embu Mineral Company*, Mogi das Cruzes, São Paulo State, Brazil. BE samples were used for particle size, mineralogical and geochemical analysis in order to assess its classification as a soil remineralizers based on Normative Instruction N. 5/2006, by MAPA. Two experiments, one with each crop, were conducted on a sandy loam texture Yellow Latosol (LA) and a clay Red Latosol (LV) soil. The experiments were zed block design with four replicates. Treatments consisted, witness, biotite (BE) remineralizer at four increasing K_2O rates (30, 60, 120 and 240 kg K_2O ha^{-1}), KCl at 60 kg K_2O ha^{-1}, and FMX remineralizer (fine-graded mica schist from Pedreira Araguaia Mineral Company). Both KCl and FMX were used as reference K_2O sources. Yield data have shown K release in the soil and absorption by the test plants resulted in yield increases. Biotite behavior in the soil is similar to that of FMX and in some cases, to that of KCl. Biotite has great potential to be used as potassium source in soybean and maize crops.

Keywords: potassium fertilization, remineralizer, sustainable agriculture

1. Introduction

Potassium (K) is one of the major nutrients for plant growth and development. It plays an important role in agricultural production, besides its part in helping defensive compounds against stress, pests and diseases (Dhillon et al., 2019). In addition, K is fundamental for many metabolic processes, including photosynthesis, protein synthesis and solute transport (Prajapati & Modi, 2012). Insufficient K replacement in the soil can result in nutritional depletion and, consequently, a decline in crop yield.

Potassium deficiency is observed in many agricultural soils worldwide, mainly in the highly weathered tropical soils of Africa, Southeast Asia, and Latin America (Leonardos et al., 1987). Most agricultural soils in Brazil are highly weathered, acidic and naturally K-deficient, and therefore, the country is strongly dependent on intensive use of K fertilizers (Malavolta, 2006; Hunke et al., 2015); thus, it is the fourth largest consumer and importer of K (IFA, 2020). According to the Food and Agriculture Organization of the United Nations (FAO), national potash consumption, in 2018, reached 6.77 million tons of K_2O, whereas the world's total use corresponded to 38.85 million tons of K_2O (FAO, 2021). Despite its high consumption, potash's national yield only fulfils 6% of demand (DNPM, 2017), since its production capacity is stagnant.

Currently, potassium chloride (KCl) is the major commercial K fertilizer used worldwide. K deposits suitable for KCl production are located in Canada, Russia, Belarus, China and Germany; altogether, they control more than 80% of the world's potash market (Basak et al., 2017); thus, it is essential to find alternative K sources, and in silicate rocks, in order to reduce the need to import soluble fertilizers that are often expensive and have low residual effect on the soil. The use of crushed rocks (known in Brazil as soil remineralizers) is one of the alternative resources to improve soil properties and to increase crop yields.

Based on Brazilian Law 12.890/2013, soil remineralizers (SR) are defined as all mineral materials undergoing size reduction and classification based on mechanical processes; they change soil fertility by adding macro and micronutrients to plants, as well as by improving soil physical or physicochemical properties or its biological activity (Brasil, 2013). Previous studies carried out in tropical Brazilian soils have shown the potential of rock powders, including calxist, acidic volcanic rock, melilitite, olivine, siltstone, tephrite, among others, to be used as SR in agriculture (Ramos et al., 2019; Cunha & Almeida, 2021; Medeiros et al., 2021; Citadin et al., 2022). Although these studies were based on using SR in perennial and annual species, such as oat and barley crops, studies focused on the effect of rock powders deriving from biotite mica on soybean and maize remain scarce.

Therefore, if one takes into consideration the importance of adopting alternative fertilizer sources for agriculture, and the relevance of using ground silicate rock powders plant growth, the aim of the current study was to assess the agronomic efficiency and the potential of using the biotite provided by *Embu Mineral Company* as source of nutrient to soybean (*Glycine max* (L.) Merrill.] and corn silage (*Zea mays* L.) crops grown in succession systems, in different soils.

2. Method

2.1 Silicate Rock Analysis

The biotite (BE) provided by Embu Mineral Company (Mineradora Embu) was the silicate rock powder used as soil remineralizer. This company is located in Mogi das Cruzes, São Paulo State, Brazil. BE samples were used for particle size, mineralogical and geochemical analysis applied to assess its classification as SR, based on NI N. 5/2006 (MAPA, 2016). Particle size distribution was performed at the Soil Physics Laboratory of Federal University of Goiás (UFG). Air-dried samples were mechanically sieved in 2.0-0.84-0.3 mm meshes. Particle size distributions are summarized in Table 1.

Table 1. Particle size distribution of biotite provided by *Embu Mineral Company* based on the sieve analysis

Sieve number	Particle size	Retained mass	Passing mass
	mm	------------------------- %	--------------------------
10	2.00	0	100
20	0.84	0	100
50	0.30	0.1	99.9

Mineralogical and geochemical analyses were performed at the Regional Center for Technological Development and Innovation of UFG (CRTI/UFG). Mineralogical composition (Table 2) was determined through X-Ray Diffraction (XRD), in Bruker D8 Discover diffractometer, at Cu-Kα radiation and X-ray tube operating at 40 kV and 40 mA. Scans were collected with step scan 0.01º2θ and 2 s/step, at angular range of 5-100º 2θ. The estimate of mineralogical phases observed in the samples was obtained through Rietveld refinements (Rietveld, 1969; Young, 1993), which were carried out in TOPAS software V.4.2.

Table 2. Quantitative mineralogical composition of biotite provided by *Embu Mineral Company,* determined through XRD analysis and Rietveld refinements

Aug	Ilm	Goe	Mag	Mic	Ana	Rut	Mus	Bio	Qua	Zir	Oli	Cal	Act	Apa	Pir
--- %															---
0.8	ns	ns	ns	14	ns	ns	ns	26	24	ns	35	ns	ns	ns	ns

Note. Aug: augite, Ilm: ilmenite, Goe: goethite, Mag: magnetite, Mic: microcline, Ana: anatase, Rut: rutile, Mus: muscovite, Bio: biotite, Qua: quartz, Zir: zircon, Oli: oligoclase, Cal: calcite, Act: actinolite, Apa: apatite, Pir: pirite, ns: not detected.

The geochemical characterization of major, minor (SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, and P_2O_5) and trace (Ni, Cr, V, La, Ce, Co, Nb, Ba, Y, Sr, Zr, Zn, Rb, and Pb) elements, in % of oxides weight was determined through X-Ray fluorescence (XRF), in Bruker S8 Tiger WSD X-ray fluorescence spectrometer, with Rh tube (intensity 4 kW and XRF beam of 34 mm). Elemental oxide concentrations of major, minor and trace elements were determined through XRF analysis—they are summarized in Tables 3 and 4.

Table 3. Elemental oxide concentrations of major and minor elements, in the form of oxides, observed in biotite provided by *Embu Mineral Company,* and determined through XRF analysis

SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
------------------------				%					------------------------
62.39	1.39	13.98	9.28	0.14	1.96	2.24	2.41	5.31	0.51

Table 4. Elemental oxide concentrations of trace elements in biotite provided by *Embu Mineral Company*, determined by XRF analysis

Hg	Cd	Pb	As	Cr	Co	Ni	Cu	Mo	Zn	Sn	Ga	La	Pb	U	Cd
------------------------								mg kg^{-1}							------------------------
0.001	ns	22	ns	ns	ns	13	19	ns	117	ns	26	128	22	ns	ns

2.2 Location and Soil Characterization

The study was conducted from 2020 to 2021, in the greenhouse of the Agronomy School of Federal University of Goias (UFG), Midwestern Brazil, at coordinates 16°40′22″S and 49°15′19″W. The experiment was performed in 9-L capacity plastic pots (or 0.009 m^3) filled with soil (experimental unit).

Two soils, with contrasting granulometry, were selected: sandy loam texture Yellow Latosol (Latossolo Amarelo-LA) and clayey Red Latosol (Latossolo Vermelho-LV); they were classified based on the Brazilian Soil Classification System (Santos et al., 2018).

Samples of both soils were collected from the topsoil layer (0.00-0.20 m) in savanna (Cerrado) sites in Goiás State, Brazil. They were air-dried, ground and sieved in 2-mm mesh; subsequently, they were analyzed for selected physical and chemical characteristics (Table 5). Samples were air-dried and sieved in 2-mm mesh for the analysis applied to soil physical and chemical characteristics; then, they were analyzed based on the methods described by Embrapa (2017).

Particle size analysis was performed based on the pipette method after particles were dispersed in 1 mol/L of NaOH. The total clay fraction (Ø < 0.002 mm) of each soil sample was collected through sedimentation, based on the Stokes' law. Soil chemical analyses comprised pH_{CaCl2}, determined at 1:2.5 (v/v) ratio; exchangeable Ca^{2+}, Mg^{2+}, and exchangeable Al^{3+}, extracted with KCl 1 mol L^{-1}; exchangeable K^+, extracted with Mehlich-1; and potential acidity (H + Al), extracted with $Ca(OAc)_2$ 0.5 mol L^{-1} buffered at pH 7.0. Cation exchange capacity at pH 7.0 [$CEC_{pH7.0} = SB + (H + Al)$], sum of bases ($SB = Ca^{2+} + Mg^{2+} + K^+$), base saturation ($BS = 100 \times SB/CEC_{pH7.0}$) and exchangeable Al^{3+} saturation [$(m = Al^{3+}/(SB + Al^{3+}))$] were calculated. Organic matter (OM) was calculated according to the total carbon of organic compounds that were determined through oxidation with potassium dichromate, based on using the Walkley-Black procedure (Nelson & Sommers, 1996).

Table 5. Physical and chemical characteristics of soil types (0.00-0.20 m depth)

Soil characteristics	Value		
	Unit	Clay	Sandy
Clay	g kg^{-1}	480	180
Silt	g kg^{-1}	80	20
Sand	g kg^{-1}	440	800
pH ($CaCl_2$)	-	5.1	4.3
Soil organic matter	dag kg^{-1}	6.0	9.0
Available P (P Mehl)	mg dm^{-3}	1.2	2.7
Exchangeable Ca	$cmol_c$ dm^{-3}	0.5	0.4
Exchangeable Mg	$cmol_c$ dm^{-3}	0.5	0.4
Exchangeable K	mg dm^{-3}	21	18
Exchangeable Al	$cmol_c$ dm^{-3}	0.0	1.0
Potential acidity (H + Al)	$cmol_c$ dm^{-3}	1.7	2.5
Cation Exchange capacity ($CEC_{pH7.0}$)	$cmol_c$ dm^{-3}	2.8	3.3
Base saturation	%	38.2	25.4
Aluminum saturation	%	0.0	54.05

2.3 Experimental Design and Treatments

The study was a completely randomized design with four replicates, and seven treatments, for both soil textures: witness, biotite (BE) remineralizer from *Embu Mineral Company* at four increasing K_2O rates (30, 60, 120 and 240 kg K_2O ha^{-1}), KCl at 60 kg K_2O ha^{-1}, and FMX remineralizer (fine-graded mica schist from *Pedreira Araguaia Mineral Company*) (Table 6). Both KCl and FMX were used as reference K_2O sources. Nutrients, such as N and P, were provided in the form of monoammonium phosphate (MAP), as needed for cultivation.

Table 6. Composition of the applied treatments

Treatments	Description	Source	K_2O	K_2O source
			------------- kg ha^{-1} -------------	
0 (control)	0 × of the recommended rate	-	0	0
30 BE	0.5 × of the recommended rate	Biotite	30	509
60 BE	1.0 × of the recommended rate	Biotite	60	1018
120 BE	2.0 × of the recommended rate	Biotite	120	2037
240 BE	4.0 × of the recommended rate	Biotite	240	4074
60 FMX	1.0 × of the recommended rate	FMX	60	1900
60 KCl	1.0 × of the recommended rate	KCl	60	100

Note. BE: Biotite remineralizer from *Embu Mineral Company*; FMX: fine-graded mica schist remineralizer from *Pedreira Araguaia Mineral Company*; KCl: commercial potassium chloride.

2.4 Soil Incubation and Plant Cultivation

Each pot was filled with a mix of air-dried soils, $CaCO_3$ (100% $CaCO_3$, equivalent to the rate used to obtain 60% base saturation) and specified K_2O rates. This mix was incubated for 30 days to trigger a reaction with the soil, under greenhouse conditions.

Five soybean seeds (cultivar Brasmax Desafio RR-8473 RSF) were sown in each pot after the incubation period was over. The seedlings were thinned to one plant after emergence. Soybean plants were cultivated for three months. Soil moisture was kept close to 80% of field capacity. This was accomplished by replenishing moisture with deionized water in the upper portion of the pots.

Plant shoot and soil samples were collected from each experimental unit at the end of the soybean experiment and maize silage (cultivar BRS 3046) was grown in succession, based on the same treatments and soil samples previously used in soybean. Five maize silage seeds were sown in each pot and seedlings were, once more, thinned to one plant per pot after their emergence. Maize silage plants were cultivated for 75 days; the process to keep soil moisture was repeated. Plant shoot and soil samples were also collected from each pot after maize silage.

2.5 Soil-Plant Sampling and Analysis

Soil samples were air-dried, sieved in 2-mm mesh and analyzed for exchangeable $K^{+,}$ based on methods proposed by Embrapa (2017)—K extraction by using Mehlich-I solution, after collection from each experimental unit. Soybean and maize silage shoots were dried in a forced circulation oven, at 65 °C, until they reached constant weight. The leaves were ground in Willey knife mill (< 40 mesh), packaged, labeled and sent to the laboratory. Total K content was determined based on the methodology proposed by Malavolta et al. (1997).

Soybean grain weight was converted into kilograms per hectare (kg ha^{-1}) after harvest in order to determine the soybean grain yield; then, the results were converted sacks per hectare (sc ha^{-1}), since the 60 kg sack is the unit for soybean sales in Brazil. Maize silage yield was found by converting the shoot dry mass into tons per hectare (t ha^{-1}).

2.6 Data Analysis

Data of each crop (soybean and maize silage) were subjected to analysis of variance through F test, at 5% and 1% significance level, in separate; means were compared through Tukey test, at 5% significance level. K rate effects on soils and plants were assessed through polynomial regression analysis. All analyses were performed in Statical Analysis System (SAS) software. Relative efficiency of biotites' remineralizer potential in comparison to reference sources—FMX remineralizer and potassium chloride—was calculated through the following mathematical expression:

$$\text{RE (\%)} = \frac{\text{Cultures yield value based on equivalent biotite dose}}{\text{Values of reference culture yields (FMX ou KCl)}} \times 100 \tag{1}$$

3. Results and Discussion

3.1 Biotite Characterization

Particle size distribution (Table 1) has shown that BE meets the parameters defined by NI N. 5/MAPA, according to which, it is mandatory to have 100% of the particles passing through the 2-mm sieve, 70% or more has to pass through 0.84 mm sieve, and 50% or more has to pass through 0.3 mm sieve.

XRD results (Table 2) showed that BE is composed of oligoclase (35%), biotite (26%), quartz (24%), microcline (14%) and small occurrences of augite (< 1%). According to geochemical parameters established by NI N. 5/2016, free silica limit (as quartz, SiO_2) in SR must be lower than 25% (v/v). Thus, BE rocks can be classified as SR, as long as the silica content is below the maximum value determined by the legislation.

Elemental oxide concentration results, as well as trace elements determined through XRF analysis, are summarized in Tables 3 and 4. The BE sample had high silica (> 62%), aluminum oxide (14%) and iron oxide (> 9%) contents. Low CaO (2.24%), MgO (1.96%) and K_2O (5.31%) contents were also observed in BE. However, the sum of bases reached values higher than 9.5%, which is higher than the minimum requirement established by the legislation (9%); therefore, this number is enough to classify BE rocks as soil remineralizing product.

Potentially toxic elements (Hg, Cd, Pb and As) (Table 4) recorded values lower than the maximum levels (As: 15, Cd: 10, Hg: 0.1 and Pb: 200 mg kg^{-1}). Further elements, such as Cu, Mo and Ni (which do not have a previously established limit) were detected at levels that represent no potential risk for agricultural use. Accordingly, BE rocks are safe to be used in agriculture as SR.

3.2 Effect of K Sources on Soil and Soybean Parameters

3.2.1 Clayey Red Latosol (LV)

Soybean yield (Table 7) in clayey LV soil has presented significant differences based on the F test (26.1), at 14.74% coefficient variation. Soybean yield ranged from 342.1 to 2,439.5 kg ha^{-1}. According to data by CONAB (2022), soybean 2012/22 harvest season ended in July. The influence of the La Ninã phenomenon on the Southern region and on Mato Grosso do Sul State, which showed significant rainfall decrease, was a determining factor to decrease yield in these regions; consequently, to decrease the total soybean yield in the country. In total 40,950.6 thousand hectares were sown in this crop season; it was 4.5% higher than that of the 2020/21 harvest season. The recorded yield reached 124,047.8 thousand tons; this value is 10.2% lower than that recorded for the 2020/21 season and mean yield reached 3,029 Kg/Ha—this number reflects the water shortage.

Knowing the association between plant growth and development, and genotypes' yield components is essential to define the most productive plant type. Furthermore, knowing the yield components and how they can interfere with soybean final yield can help the positioning of management practices in order to reach higher final yield (Navarro Júnior & Costa, 2002).

Treatments 60 FMX, 60 KCl and 60 kg ha^{-1} of biotite K_2O stood out for recording the highest yields. There were no differences in the Tukey test between treatments, except for the witness. Reference standards 60KCl and 60FMX, and biotite dose differences, evidenced differences in comparison to the witness (Table 7). Table 7 highlights that all doses of EMBU remineralizer did not present significant differences in the Tukey test carried out with 60KCl and 60FMX. The biotite remineralizer increased soybean yield up to the dose of 160 kg ha^{-1} of K_2O.

Soil K extracted through Mehlich-1 cultivated with soybean (Table 7) presented significant differences in comparison to the treatments. K contents ranged from 26 to 98 mg dm^{-3} in the LV soil. Soil K content increase was observed up to dose 140 kg ha^{-1} of biotite remineralizer K_2O, and it points out K release to the soil/plant system.

With respect to reference K source (FMX) at the same dose (60 kg ha^{-1} of K_2O), they did not show significant differences in soil K content and these results are evidence of biotite's potential. FMX showed the highest values and the standards by Souza and Lobato (2004) showed that soil K contents were lower than the proper limits (higher than 50 mg dm^{-3} in LV) in all treatments. Ribeiro et al. (2010) reported the positive effects of using Alkaline ultramafic rocks and pyroclastic breccias due to the high concentrations of exchangeable K^+ in the soil after the administration of high dosages.

Potassium is an essential nutrient to almost all vital processes in plants; they play roles in opening and closing stomata, in transporting carbohydrates and other products (Malavolta et al., 1989). It activates several enzymes involved in breathing and photosynthesis (Taiz et al., 2004). However, K is not part of any organic compound that plays structural functions in plants (Faquin, 2005).

As for K reference source (FMX) at the same dose (60 kg ha^{-1} of K_2O), they did not present significant differences in soil K content, and this finding shows biotite's potential. KCl, FMX and the dose of 120 kg ha^{-1} of biotite K_2O recorded the highest values, but there were no differences between the applied biotite doses. Based on the standards by Souza and Lobato (2004), soil k contents produced by treatments 60 KCl, 60 FMX and the dose of 120 kg ha^{-1} biotite K_2O reached the proper levels (higher than 50 mg/dm^3 in LV). Ribeiro et al. (2010) reported the positive effect of using high concentrations of exchangeable K^+ in the soil after the administration of high doses due to the use of Alkaline ultramafic rocks and pyroclastic breccias.

The highest levels of leaf K were found with 60 FMX and 60 KCl. There were no differences in biotite doses and in reference standards FMX and KCl. Leaf K contents in soybean were close to those found in assays that were lower than the levels referred as proper by Raij et al. (1997) (1.7 to 2.5 dag kg^{-1}), Ribeiro et al. (1999) (1.7 dag/kg) and EMBRAPA (2020) (1.8 to 2.5 dag kg^{-1}). It is important highlighting that these interpretation criteria are set for soybean in the field and that there is variation in contents and interpretations depending on several factors, on cultivation conditions between them and on cultivars (Fontes, 2016). Results recorded for relative soybean yield efficiency in Red Latosol, of biotite remineralizer potential (%) with remineralizer FMX and potassium chloride (%)—at standard equivalent dose—presented relative efficiency of 94.18% FMX and 97.31% KCl, in comparison to the biotite's relative efficiency (Figure 1). Based on results in the present study, biotite's remineralizer potential allows the release of nutrients that reflect on the expression of soybean culture yield relative efficiency in Red Latosol.

Table 7. Mean values of soil potassium (K), leaf K content availability, and soybean (*Glycine max*) grain yield in crop affected by K sources and rates in clay Red Latosol (LV)

Treatments	Soil K availability	Leaf K	Grain yield
	mg dm^{-1}	decagran kg^{-1}	kg ha^{-1}
0 (control)	23.5 a	0.88 a	342.1 b
30 BE	16.5 a	0.69 a	2022.6 a
60 BE	22.0 a	0.80 a	2297.6 a
120 BE	41.0 a	0.49 a	1881.8 a
240 BE	24.5 a	0.88 a	2173.9 a
60 FMX	19.5 a	1.08 a	2439.5 a
60 KCl	29.0 a	1.04 a	2361.2 a
F test	1.9 ^{ns}	1.56 ^{ns}	26.0**
CV (%)	32.75	27.5	14.76

Note. Means followed by equal letters in the rows did not differ in the Tukey test, at 5% probability level. ^{ns}, * and **: not significant, at 5% and 1% significance levels in the F test, respectively. BE: Biotite remineralizer from *Embu Mineral Company*; FMX: fine-graded mica schist remineralizer from *Pedreira Araguaia Mineral Company*; KCl: commercial potassium chloride.

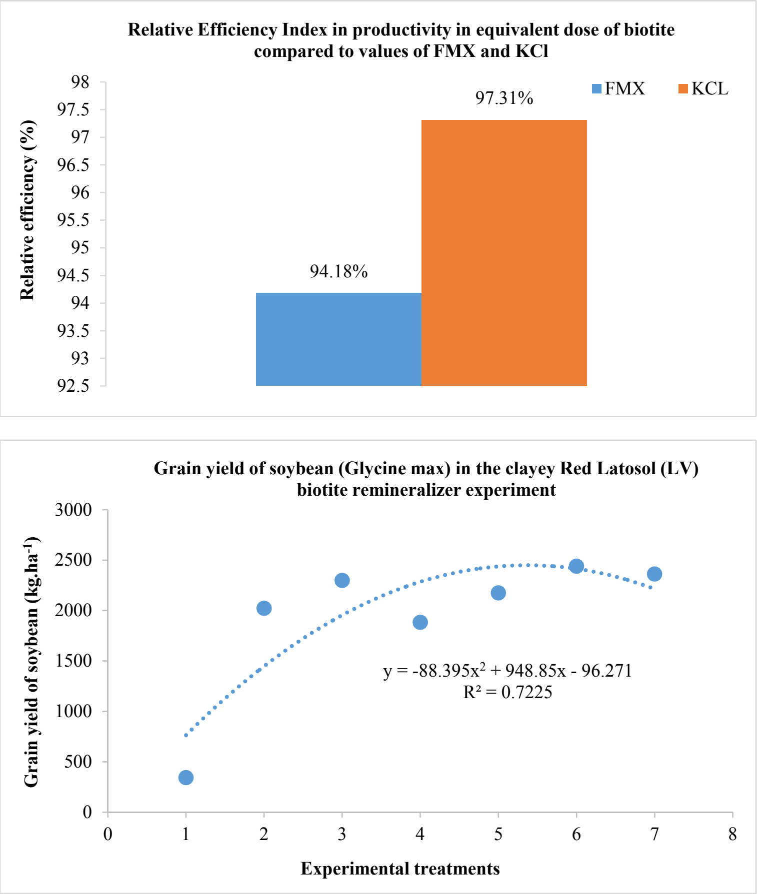


Figure 1. Effect of potassium sources and rates on relative values recorded for soybean (*Glycine max*) grain yield and relative efficiency index in yield recoded in equivalent biotite remineralizer, fine-graded mica schist remineralizer e potassium chloride values in crops grown in clay Red Latosol (LV)

Note. BE Biotite remineralizer from *Embu Mineral Company*; FMX: fine-graded mica schist remineralizer from *Pedreira Araguaia Mineral Company*; KCl: commercial potassium chloride.

3.2.2 Sandy Loam Texture Yellow Latosol (LA)

Soybean yield (Table 8) presented significant differences in the F test carried out in LA (11.21) at variation coefficient of 19.18%. Yield ranging from 683.1 to 2,615.3 kg ha^{-1} were recorded, with emphasis on treatments 60 kg/ha of Biotite, which recorded the highest yield rates. According to CONAB (2022), yield reached 124,047.8 tons; this value is 10.2% lower than that recorded for the 2002/21 crop season; mean reached yield was 3,029 kg/ha. There were differences in Tukey test between treatments, except for all in comparison to the witness (Table 8).

Biotite undergoes chemical and physical changes after it is added to the soil; these changes influence its ability to provide nutrients, mainly K. Soils present responses to soybean yield similar to FMX and KCl (at higher biotite doses) due to their particular features and properties—they are more yield responsive at the first cultivation after application.

If one takes into account that most potassium silicate minerals have low solubility in water and gradually release nutrients, we can assume that solubilization in the first cultivation year did not happen at the time needed for yield responses in the culture to be equal to those of soluble sources. On the other hand, biotite presented behavior similar to that of FMX.

The remineralizer biotite undergoes chemical and physical changes after it is added to the soil; these changes influence its ability to provide nutrients, mainly K. Soils present responses to soybean yield similar to those of FMX and KCl (at higher doses) due to their particular features and properties—they are more responsive to yield.

Soil K extracted through Mehlich-1 cultivated with soybean (Table 8) presented significant differences in treatments K contents ranged from 18 to 33.5 mg dm^{-3} in LA soil. Treatment 60 KCl recorded the highest contents and 30 kg ha^{-1} of biotite K_2O presented the lowest contents. The other treatments did not present differences from one another.

As for reference K source (FMX and KCl), at the same dose (60 kg ha^{-1} of K_2O); they did not present significant differences in soil K content and this finding shows biotite's registering potential. KCl presented the lowest values due to its solubility in water. Based on the standards by Souza and Lobato (2004), soil K contents are at adequate levels (higher than 40 mg dm^{-3} no LA). Ribeiro et al. (2010) reported the positive effect of using Alkaline ultramafic rocks and pyroclastic breccias due to the high concentration of exchangeable K^+ in the soil after the administration of higher doses. Theodoro et al. (2013) carried out an experiment with five rocks—among them there were some basic rocks—in five cultures (maize, beans, garlic, okra and carrots); they showed that the availability of nutrients in all fractions of Latosols evidenced the interactions among agro-minerals, soil and plants. Reis (2013) tested a treatment in Latosol with micaschist and amphibolite rocks, in millet culture, and reported that these agro-minerals act as the source of these nutrients to plants. They also observed increase in root dry mass (RDM). Duarte et al. (2012) observed that the highest dry matter contents met the highest doses administered to the soil due to the application with silicate rocks in millet culture.

Leaf K contents in soybean (Table 8) showed significant differences in treatments in the F test (11.29) and variation coefficient of 15.58% in LA soil. The highest leaf K contents were found in treatments 60 KCl and 60FMX. There were differences in biotite doses in comparison to the witness. As for FMX, there were no differences between biotite doses and the witness.

Leaf K contents in soybean were close to the adequate levels referred by Raij et al. (1997) (1.7 to 2.5 dag kg^{-1}), Ribeiro et al. (1999) (1.7 dag kg^{-1}) and EMBRAPA (2020) (1.8 to 2.5 dag kg^{-1}). Treatment 60 KCl was the exception, since the other ones recorded number lower than the adequate one. It is important highlighting that these interpretation criteria are set for soybean in the field and that there is variation in contents and in interpretations, depending on several factors, among them one finds cultivation conditions and cultivars (Fontes, 2016). Leaf K relative contents in comparison to the standards (KCl and FMX), adjusted itself in 2nd degree polynomial regression (Figure 2), and in growing biotite doses.

Table 8. Mean values of soil potassium (K) and leaf K content availability, and soybean (*Glycine max*) grain yield in crop affected by K sources and rates in sandy loam texture Yellow Latosol (LA)

Treatments	Soil K availability	Leaf K	Grain yield
	mg dm^{-3}	Decagran kg^{-1}	kg ha^{-1}
0 (control)	21.0 AB	0.91 B	681.1 B
30 BE	18.0 B	0.68 B	2182.9 A
60 BE	19.5 AB	0.78 B	2615.3 A
120 BE	24.5 AB	0.68 B	2434.8 A
240 BE	24.0 AB	1.01 B	2008.0 A
60 FMX	19.5 AB	1.26 AB	1763.7 A
60 KCl	33.5 A	1.70 A	2058.3 A
F test	6.69*	11.29**	11.21*
CV (%)	14.40	15.58	19.18

Note. Means followed by equal letters in the rows did not differ in the Tukey test, at 5% probability level. ^{ns}, * and **: not significant, at 5% and 1% significance levels, in the F test, respectively. BE: Biotite remineralizer from *Embu Mineral Company*; FMX: fine-graded mica schist remineralizer from *Pedreira Araguaia Mineral Company*; KCl: commercial potassium chloride.

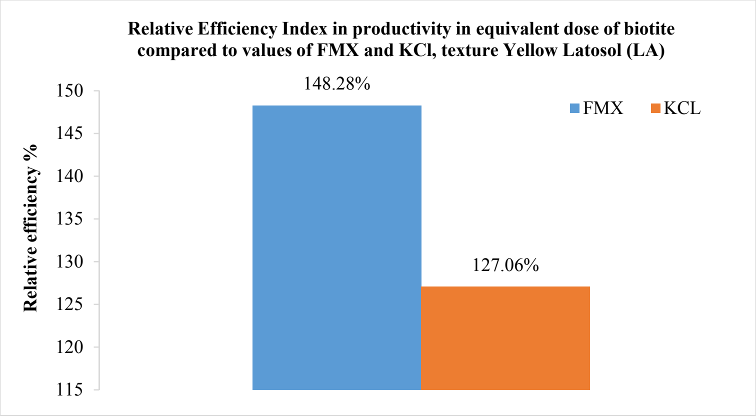


Figure 2. Effect of potassium sources and rates on relative values recorded for soybean (Glycine max) grain yield and relative efficiency index in yield, in equivalent values, and biotite remineralizer, fine-graded mica schist remineralizer and potassium chloride crop int texture Yellow Latosol (LA)

Note. BE Biotite remineralizer from *Embu Mineral Company*; FMX: fine-graded mica schist remineralizer from Pedreira Araguaia Company; KCl: commercial potassium chloride.

3.3 Effect of K Sources on Soil and Maize Silage Parameters

3.3.1 Clayey Red Latosol (LV)

Maize silage yield (Table 9) in clayey LV soil did not show significant differences in the F test (11.76) and variation coefficient of 38.32%. Maize silage yield ranged from 3.9 to 38.5 tons per hectare. According to CONAB (2022), mean maize grain yield in Brazil was 4,366 kg ha^{-1} in the 2020/2021 crop season. Maize crop season in Brazil is basically divided in first and second season, and the yield of maize grown in the first crop season was 5,687 kg ha^{-1} in 2020/2021; it was higher than the second crop season, which reached 4,050 kg ha^{-1} (CONAB, 2022). It is worth recalling that cultivation in the first crop season is performed in the best sowing times, and it meets the meteorological parameters and physiological aspects inherent to maize plants; these parameters optimize these plants' yield capacity. Treatments 120 kg ha^{-1} of biotite K_2O presented yield equivalent to that of tested standards (KCl and FMX), as observed in Table 9. It is essential that doses of 120 BE of remineralizer by EMBU (Table 9) did not present significant differences in the Tukey test applied to standards FMX and KCl. The increasing biotite doses led to increased maize silage yield until dose 150 kg ha^{-1} de K_2O.

Soil K extracted through Mehlich-1 and cultivated with silage maize (Table 9) did not present significant differences among treatments (F tests of 2.05 and VC = 55.46). K contents ranged from 22 to 72 mg dm^{-3} in LV soil. Increased soil K contents were significant up to dose 240 kg/ha of biotite K_2O; these results indicate the release of K into the soil/plant system. Biotite doses did not show significant differences in the Tukey test applied to 60 KCl and 60 FMX (Table 9). The biotite doses led to increase in soil K contents until the dose of 240 kg ha^{-1} of K_2O. With respect to the reference K source (FMX) at the same dose (60 kg ha^{-1} of K_2O), it did not present significant differences in soil K content, a fact that showed biotite's potential. Based on standards by Souza and Lobato (2004); soil K contents of 240 BE and 60 FMX met the adequate levels (higher than 50 mg dm^{-3} in LV). Ribeiro et al. (2010) reported the positive effect of using Alkaline ultramafic rocks and pyroclastic breccias, at high exchangeable K^+ concentrations on soils after the administration of high doses.

Theodoro et al. (2013) carried out an experiment with five rocks, among them, basic rocks, in five cultures, namely: maize, beans, garlic, okra and carrots; they found that nutrients' availability in Latosol, in all fractions, has shown interaction among agro-minerals, soil and plant. Reis (2013) tested a treatment in Latosol with micaschist and amphibolite rocks, in maize culture, and reported that these agro-minerals act as source of these nutrients to plants; they increased root dry mass (RDM). Duarte et al. (2012) observed that the highest dry mass contents were proportional to the highest doses of silicate rocks applied in the soil.

As for leaf K content in silage maize (Table), it was possible observing significant differences in treatments subjected to F test of 4.64 and variation coefficient of 21.64% in LV soil. Leak K contents in silage maize were below the levels referred to as adequate by Raij et al. (1997) (1.7 to 5.5 dag kg^{-1}) and Ribeiro et al. (1999) (1.75

to 22.5 dag kg^{-1}), except for treatments 120 BE, 240 BE, 60 FMX and 60 KCl. The growing biotite doses led to increase in leaf K contents until the dose of 210 kg ha^{-1} of K_2O.

It is important to point out that these interpretation criteria were set for maize, in general, in the field; furthermore, there is a whole variety of contents and interpretations that depend on several factors, among them one finds cultivation conditions and cultivars (Fontes, 2016). If one takes into account the criteria by Sousa & Lobato (2004), treatments 30 BE, 60 BE, 120 BE, 240 BE, 60 FMX and 60 KCl are at adequate level, despite the low K contents in the soil. These outcomes may have resulted from leaf sampling, which was carried out at flowering, and from soil collection, which took place at the end of the maize cultivation time. It is also essential highlighting that the soil presented very low K contents before the experiment was installed.

Table 9. Mean values of soil potassium (K) availability, leaf K content and grain yield of maize silage (*Zea mays*) in crop affected by K sources and rates in clayey Red Latosol (LV)

Treatments	Soil K availability	Leaf K	Yield
	mg dm^{-1}	dag kg^{-1}	t ha^{-1}
0 (control)	22 A	0.7 C	9.1 Bc
30 BE	23 A	1.3 Bc	3.9 C
60 BE	43 A	1.5 Ab	14.9 Bc
120 BE	48 A	1.8 Ab	26.1 Ab
240 BE	72 A	2.2 A	15.8 Bc
60 FMX	50 A	1.8 Ab	38.4 A
60 KCl	44 A	1.6 Ab	38.5 A
F test	2.05^{ns}	7.23**	11.76*
CV (%)	55.46	22.35	38.32

Note. Means followed by equal letters in the rows did not differ in the Tukey test, at 5% probability level.^{ns}, * and **: not significant, at 5% and 1% significance levels, in the F test, respectively. BE: Biotite remineralizer from *Embu Mineral Company*; FMX: fine-graded mica schist remineralizer from *Pedreira Araguaia Mineral Company*; KCl: commercial potassium chloride.

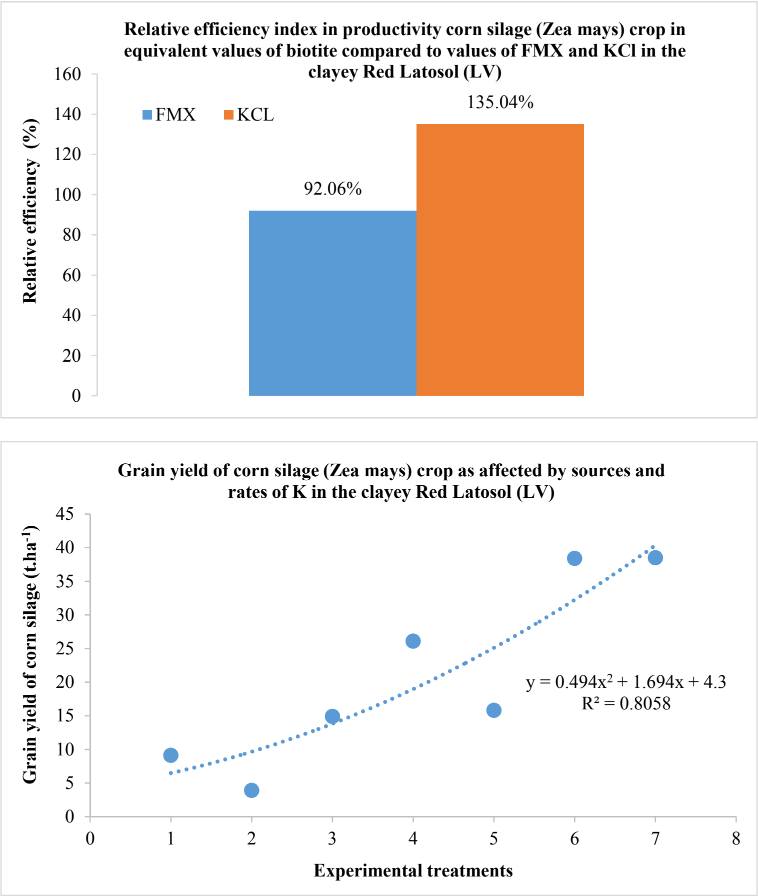


Figure 3. Yield of maize silage (*Zea mays*) crop (c) in clayey Red Latosol (LV)

Note. BE Biotite remineralizer from *Embu Mineral Company*; FMX: fine-graded mica schist remineralizer from *Pedreira Araguaia Mineral Company*; KCl: commercial potassium chloride.

3.3.2 Sandy Loam Texture Yellow Latosol (LA)

Silage maize yield (Table 10) did not present significant differences in the F test in LA (1.77) and variation coefficient 58.8%. Yield ranging from 10.5 to 26.1 tons per hectare were recorded, with emphasis on treatments 240 kg/ha of Biotite and KCl, which accounted for yield higher than 20 t ha^{-1}. Mean yield was close to the means recorded for Goiás State, and for Brazil, based on CONAB (2022). The growing biotite doses led to soybean yield increase until the dose of 240 kg ha^{-1} of K_2O.

Biotite undergoes chemical and physical changes after it is added to the soil and these changes influence its nutrient-availability capacity, mainly K availability. Soils presented soybean yield response similar to that of FMX and KCl at higher biotite doses due to their particular characteristics and properties – they were more responsive to yield.

Assumingly, most potassium silicate minerals present low solubility in water and gradually release nutrients. Hence, it is possible saying that solubilization, at the first cultivation year, did not happen at the time necessary to achieve yield response in this culture, similar to that of other soluble sources. On the other hand, biotite presented behavior similar to that of FMX, and it is a quite positive and promising outcome in the remineralizer category.

Soil K extracted through Mehlich-1 cultivated with silage maize (Table 10) did not present significant differences among treatments (F tests of 1.05 and variation coefficient of 40.33%). K contents ranged from 29 to 50 mg dm^{-3} in LA soil. All soil K contents were within the class lower than adequate, based on interpretation criteria by CFSG (1988), except for treatment 60 KCl.

With respect to reference K source (FMX) at the same dose (60 kg ha^{-1} of K_2O), they did not present significant differences in soil K contents; this finding points towards biotite's registration potential in the remineralizer category. Based on standards by Souza and Lobato (2004), soil K contents are at levels lower than the adequate one (higher than 40 mg dm^{-3} in LA), except for 60 FMX and 60 KCl. Ribeiro et al. (2010) reported the positive effect of using Alkaline ultramafic rocks and pyroclastic breccias with high exchangeable K^+ concentrations on soil after the administration of high doses.

Theodoro et al. (2013) carried out an experiment with five ricks, among them basic rocks, in five cultures, namely: maize, beans, garlic, okra and carrots, and found nutrient availability in Latosol fractions; this outcome highlights interaction among agro-minerals, soil and plants. Reis (2013) tested a treatment in Latosol with micaschist and amphibolite rocks, in millet culture, and reported that these agro-minerals act as source of these nutrients to plants; furthermore, they have increased root dry mass (RDM).

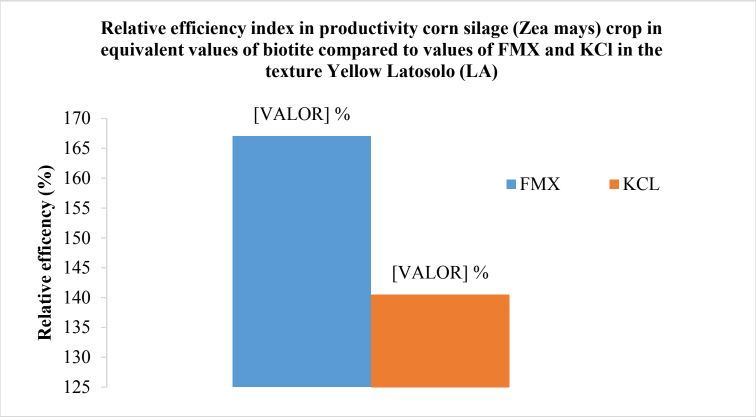
Leaf K content in silage maize (Table 10) showed significant differences in treatments in the F test of 5.93 and variation coefficient of 24.86% in LA soil. The highest leaf K content was recorded for treatment 60 KCl. There were no differences in levels referred to as adequate by Raij et al. (1997) (1.7 to 5.5 dag kg^{-1}), Ribeiro et al. (1999) (1.75 to 22.5 dag kg^{-1}). However, based on the criteria by Sousa and Lobato (2004) (1.3 to 3.0 dag kg^{-1}), all treatments were at adequate levels, except for 30 BE. The culture's nutritional management can be improved by the application of leaf analysis as operational tool (Brockley, 2001). The growing biotite doses led to increase in leaf K content until the dose of 180 kg ha^{-1} of K_2O.

According to criteria by Sousa and Lobato (2004), treatments 60 BE, 120 BE, 240 BE and 60 FMX were at adequate levels, despite the low soil K contents. These outcomes may have resulted from leaf sampling, which was carried out at flowering; moreover, soil samples were collected at the end of maize cultivation time. It is important highlighting that the behavior of these biotite doses in comparison to the remineralizer registered in MAPA (FMX). Its performance was similar.

Table 10. Mean values of soil potassium (K) availability, leaf K content and grain yield of maize silage (*Zea mays*) in crop affected by K sources and rates in sandy loam texture Yellow Latosol (LA)

Treatments	Soil K availability	Leaf K	Yield
	mg dm^{-1}	dag kg^{-1}	t ha^{-1}
0 (control)	30 A	1.4 B	10.8 a
30 BE	29 A	1.1 B	10.5 a
60 BE	34 A	1.6 B	14.9 a
120 BE	33 A	1.4 B	17.5 a
240 BE	35 A	1.5 B	21.4 a
60 FMX	43 A	1.6 B	10.2 a
60 KCl	50 A	2.6 A	26.1 a
F test	1.08^{ns}	5.93**	1.77^{ns}
CV (%)	40.33	24.86	58.67

Note. Means followed by equal letters in the rows did not differ in the Tukey test, at 5% probability level. ^{ns}, * and **: not significant, at 5% and 1% significance levels in the F test, respectively. BE: Biotite remineralizer from *Embu Mineral Company*; FMX: fine-graded mica schist remineralizer from *Pedreira Araguaia Mineral Company*; KCl: commercial potassium chloride.



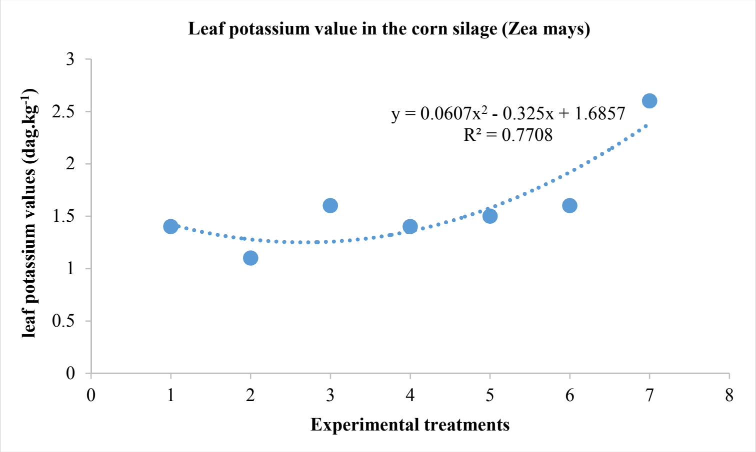


Figure 4. Relative efficiency index recorded for maize silage (*Zea mays*) yield in crop, leaf K content values in sandy loam texture Yellow Latosol (LA)

Note. BE Biotite remineralizer from *Embu Mineral Company*; FMX: fine-graded mica schist remineralizer from *Pedreira Araguaia Mineral Company*; KCl: commercial potassium chloride.

4. Conclusions

Yield data point towards K release in the soil, and it is absorbed by plants during the tests, a factor that reflects on yield increase due to biotite application. Product biotite presented behavior in the soil similar to that of FMX and, in some cases, to that of KCl. Biotite has the potential to act as Potassium source in soybean and maize crops.

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