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Agronomic efficiency of granite remineralizer K6 in soybean and corn silage production

Eficiência agronômica de remineralizador granítico K6 na produção de soja e milho silagem

Eficiencia agronómica del reminaralizador K6 en la producción de soja y ensilage de maíz

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Abstract

Feeding the world's population, based on the sustainability model is the greatest challenge of the 21st century, mainly in Brazil, which. Is one of the world's main agricultural pillars. Nowadays, it stands out as important producer and exporter of agricultural products; however, it remains highly dependent on imported fertilizers and non-renewable raw materials. Moreover, it suffers from high economic costs. Therefore, remineralizers can be used as alternative to reduce both the use of, and production costs with, soluble mineral fertilizers. The objective of this research is to verify the agronomic efficiency of potential granite remineralizer K6, by Embu Engineering and Business, in soybean and silage corn crops planted in different of textural soil class. Experimental treatments encompassed increasing doses of potential remineralizer K6, namely: 30 kg. ha^{-1} K_2O of K6, 60 kg. ha^{-1} K_2O of K6, 120 kg. ha^{-1} K_2O of K6, 240 kg. ha^{-1} K_2O of K6, the reference treatment namely: 60 kg. ha^{-1} K_2O of FMX remineralizer and, 60 kg. ha^{-1} K_2O added with potassium chloride (KCl); and the witness treatment – all with four repetitions. Yield data have shown K release in the soil, which was absorbed by the test plants. This outcome has evidenced yield increase due to granite K6 application; consequently, K6 behavior was similar to that of FMX in the soil and, in some cases, similar to that of KCl. Potential granite remineralizer K6 helped optimizing the management of the herein tested cultures.

Keywords: Potassium fertilization; Natural fertilizer; Sustainable agriculture.

Resumo

O Brasil é destaque nesse tema, pois é tido como um dos pilares da agricultura mundial. Atualmente, o país é um importante produtor e exportador de produtos agrícolas; entretanto, é altamente dependente da importação de fertilizantes e de matérias-primas não renováveis, além de sofrer com elevados custos econômicos. Logo, remineralizadores podem ser uma alternativa para a diminuição do uso de fertilizantes minerais solúveis, assim como os custos de produção. O objetivo desta pesquisa é verificar a eficiência agronômica do potencial remineralizador granítico K6 da Embu S/A Engenharia e Comércio nas culturas de soja e milho silagem em diferentes classes texturais de solo. Os tratamentos experimentais foram baseados em doses crescentes do potencial remineralizador K6, a saber: 30 kg. ha^{-1} de K_2O de K6; 60 kg. ha^{-1} de K_2O de K6; 120 kg. ha^{-1}de K_2O de K6; 240 kg. ha^{-1} de K_2O de K6; tratamentos de referência: 60 kg. ha^{-1} de K_2O do remineralizador FMX e 60 kg. ha^{-1} de K_2O com cloreto de potássio (KCl); e tratamento testemunha, todos com quatro repetições. Dados de produtividade indicam liberação de K no solo, o qual foi absorvido pelas plantas teste; O remineralizador K6 apresenta comportamento no solo semelhante ao do FMX e, em alguns casos, ao do KCl. O potencial remineralizador granítico K6 contribui para otimizar o manejo nutricional das culturas testes deste estudo.

Palavras-chave: Adubação potássica; Fertilizante natural; Agricultura sustentável.

Resumen

Brasil se destaca en este tema, ya que es considerado uno de los pilares de la agricultura mundial. Actualmente, el país es un importante produtctor y exportador de productos agrícolas; sin embargo, es altamente dependiente de fertilizantes importados y materias primas no renovables, además de altos costos económicos. Por lo tanto, los remineralizantes pueden ser una alternativa para reducer el uso de fertilizantes minerals solubles, así como los costos de producción. El objetivo de la presente investigación es evaluar la eficiencia agronómica del potencial remineralizante granítico K6 de Embu S/A Engenharia e Comércio en cultivos de soja e ensilados de maíz en diferentes clases texturales de suelo. Los tratamientos experimentales se basaron em dosis crecientes de potencial reminralizante K6, a saber: 30 kg. ha^{-1} de K_2O de K6; 60 kilos ha^{-1} de K_2O de K6; 120 kilos ha^{-1} de K_2O de K6; 240 kilos ha^{-1} de K_2O de K6; tratamientos de referencia: 60 kg. ha^{-1} de K_2O del remineralizador FMX y 60 kg. ha^{-1} de K_2O con cloruro de potasio (KCl); y tratamiento de control, todos com cuatro repeticions. Los datos de rendimiento indican la liberación de K en suelo, que fue absorvido por las plantas de prueba;El remineralizador K6 tiene un comportamiento en el suelo similar al FMX y, en algunos casos, al KCl. El potencial remineralizante granítico K6 contribuye a optimizar el manejo de los cultivos de prueba en este estudio.

Palabras clave: Fertilización potássica; Fertilizantes naturale; Agricultura sostenible.

1. Introduction

Global food security depends on soils' ability to provide the necessary macro and micronutrients for agricultural cultures' growth and yield. Conventional high-solubility fertilizers are applied to recover nutrients or to adjust their supply to the needs of a given culture. However, these inputs are often too expensive for farmers, mainly in the poorest countries, besides being quickly absorbed by plants or lost due to runoff in deeply leached soils (Swoboda et al., 2022).

The Brazilian agriculture is highly dependent on imported inputs, mainly on nitrogen, phosphorus and potassium sources, a fact that can lead to food insecurity. Overall, these fertilizers present low efficiency in comparison to the total amount applied in regions presenting tropical or sub-tropical climate, like Brazil (Rosolem et al., 2018). Contributions by Brito et al. (2019), who sought a new regenerative agriculture level, stood out for showing that rock powder application in the soil can present great fertilizing potential at the time to develop an agriculture aimed at joining economy and respect to the environment.

Brazil is the greatest soybean producer in the world; studies carried out by *Agrosatélite* and by the Brazilian Association of Vegetal Oil Industries (Abiove), in 2020, have shown that more than half the area planted with soybean in the country, in the 2018/19 crop season, was found in *Cerrado.* According to the Brazilian Institute of Geography and Statistics (IBGE, 2020), this biome accounts for approximately 45% of the national agricultural area.

Corn farming has reached such rates in the last decades; thus, this cereal has become the biggest culture in the globe; it is the only one to exceed the number of 1 billion tons and to overcome the rice and wheat production (Miranda, 2018). Corn stands out in silage production for animal feeding; its prevalence results from its ability to fulfill the dietary needs of confined animals, either beef or milk livestock (Santos et al., 2017).

Soybean is a quite demanding culture when it comes to all essential macronutrients. In order to be well used by this culture, it must be available in the soil at sufficient amounts and balanced ratios. It is so, because its unbalance or shortage can lead to its excessive absorption or to shortage of other elements (Embrapa, 2008). According to Taiz et al. (2017), potassium is demanded as cofactor for several enzymes in plants, besides being the main cation for both cellular turgor and cell electro-neutrality maintenance. Furthermore, potassium is one of the macronutrients more often demanded by the soybean culture.

According to Malavolta (1980), Marschner (2012) and Parente et al., (2016), potassium (K) is the macronutrient mostly demanded by corn; it is only overcome by nitrogen (N). Gondim et al. (2016) observed great metabolic activity in corn plants, and it causes intense nitrogen absorption at their initial growing phases. Based on Elmer and Datnoff (2014), K is the nutrient mostly absorbed by plants, after N, because it is essential for the photosynthetic process.

Among other outcomes, high-solubility fertilizer application under the Brazilian climate conditions overall leads to low efficiency because of losses resulting from the leaching process. Consequently, these losses can help reducing the quality of water and, then, lead to environmental degradation (Huisman et al., 2018). In light of the foregoing, the possibility of applying remineralizers stands out as alternative for conventional fertilizers to renew poor or leached soils (Swoboda et al., 2022).

The aim of the present study was to assess the influence of potential granite remineralizer K6 on the physical and chemical features of Red Latosol and Yellow Latosol by measuring its agronomic efficiency in test soybean and silage corn cultures, based on provisions on law n. 12.890, from December 10, 2013. This law defines 'remineralizer' as a "material of mineral origin that has undergone only size reduction and classification based on mechanical processes and that changes soil fertility indices by adding macro and micronutrients to plants, as well as that improves soil physical or physical-chemical properties, or its biological activity" (Brasil, 2013). These materials must fulfill the requirements in standard instructions from March 2016, in order to ensure their functionality and to guarantee their parameters.

2. Methodology

Granite K6 was the rock powder used as soil remineralizer; it was provided by Embu Mineral Company, which is located in Mogi das Cruzes City, São Paulo State, Brazil. BE samples were used in particle size, mineralogical and geochemical analyses in order to assess its classification as remineralizer, according to Normative Instruction n. 5/2006 (MAPA, 2016).

Particle size distribution was performed at Soil Physics Laboratory. Air-dried samples were mechanically sieved in the following meshes: 2.0 - 0.84 - 0.3 mm. The fraction retained in each mesh was weighed and the corresponding percentage (that had passed though each mesh) was also calculated. Particle size distributions are summarized in Table 1.

Table 1 - Classification of granulometric fractions of granite remineralizer K6 potential.

Sieve number	Particle size	Retained mass	Passing mass
	mm	%	%
10	2.00	0.4	99.6
20	0.84	1.6	98.4
50	0.30	8.5	91.5

Source: Soil Analysis Laboratory, UFG School of Agronomy, Goiânia, Goiás.

The 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 by 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), 2 s/step, at angular range of 5-100º 2θ. Estimate of mineralogical phases in the samples was calculated through Rietveld refinements (Rietveld, 1969; Young, 1993), which were carried out in TOPAS software (V.4.2).

Table 2 - Quantitative mineralogical composition of granite remineralizer K6 by Embu Mineral Company, based on XRD analysis and Rietveld refinements

Aug	Ilm	Goe	Mag	Mic	Ana	Rut	Mus	Bio	Qua	Zir	Oli	Cal	Act	Apa	Pir
								%							
ns	ns	ns	ns	31.9	Ns	ns	6.67	8.71	24.9	ns	25.4	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.
Source: Regional Center for Technology and Innovation (CRTI) at UFG, using the X-Ray diffraction method.

Geochemical featuring 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 % weight of oxides, 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 recorded for major, minor and trace elements were found through XRF analysis (Tables 3 and 4).

Table 3 - Elemental oxide concentrations of major and minor elements, in the form of oxides, in granite remineralizer K6 by Embu Mineral Company, based on X-Ray fluorescence analysis.

SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
					%				
68.75	0.71	13.49	4.60	ns	0.99	2.13	2.63	5.89	0.36

Note. SiO_2: silicon dioxide, TiO_2: titanium dioxide, Al_2O_3: aluminum oxide, Fe_2O_3: iron III oxide, MnO: manganese oxide, MgO: magnesium oxide, CaO: calcium oxide, Na_2O: sodium oxide, K_2O: potassium oxide and P_2O_5: diphosphorus pentoxide, ns: not detected
Source: Regional Center for Technology and Innovation (CRTI) at UFG, using the X-Ray diffraction method.

Table 4 - Elemental oxide concentrations of trace elements in granite remineralizer K6 by Embu Mineral Company, based on X-Ray fluorescence analysis.

Hg	Cd	Pb	As	Cr	Co	Ni	Cu	Mo	Zn	Sn	Ga	La	Th	Zr	Ba	V	Y	Nb	Ce	Rb	Sr
									mg kg^{-1}												
0.001	ns	29	ns	ns	ns	11	22	ns	77	ns	23	126	42	550	782	42	31	31	240	280	199

Note: Hg: Mercury, Cd: cadmium, Pb: lead, As: arsenic, Cr: chrome, Co: cobalt, Ni: nickel, Cu: copper, Mo: molybdenum, Zn: zinc, Sn: tin, Ga: gallium, La: lanthanum, Th: thorium, Zr: zirconium, Ba: barium, V: vanadium, Y: yttrium, Nb: niobium, Ce: cerium, Rb: rubidium, Sr: strontium, ns: not detected.
Source: Regional Center for Technology and Innovation (CRTI) at UFG, using the X-Ray diffraction method.

2.1 Location and soil featuring

The study was conducted from 2020 to 2021, in the greenhouse of the Agronomy School, Federal University of Goiás (UFG) in Central-West Brazil, at coordinates 16°40’22” S and 49°15’19” W. The experiment was performed in plastic pots (9-L capacity or 0.009 m^3) filled with soil (experimental unit). Two soils, presenting contrasting granulometry, were selected: sandy loam texture Yellow Latosol (Latossolo Amarelo - YL) and clayey Red Latosol (Latossolo Vermelho - RL). They were classified according to the Brazilian Soil Classification System (Santos et al., 2018).

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

Particle size analysis was performed through pipette method, after particles were dispersed in 1 mol/L NaOH. Then, the total clay fraction (Ø < 0.002 mm) of each soil sample was collected through sedimentation, based on Stokes' law. Soil chemical analyses comprised pH_{CaCl2}, determined in 1:2.5 (v/v) ratio; exchangeable Ca^{2+}, Mg^{2+}, and exchangeable Al^{3+}, extracted in KCl 1 mol L^{-1}; exchangeable K^+, extracted in Mehlich-1; and potential acidity (H + Al), extracted in $Ca(OAc)_2$ 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 based on the total carbon of organic compounds determined by oxidation with potassium dichromate, according to the Walkley-Black procedure (Nelson & Sommers 1996).

Table 5 - Physical and chemical attributes of Yellow Latosol and Red Latosol soils, in the 0 to 20 cm layer.

Soil attributes	Unit	Red Latosol	Yellow Latosol
		Value	
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}	0.6	6.9
Available P (P Mehl)	mg dm^{-3}	0.9	0.9
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

Source: Soil Analysis Laboratory, UFG School of Agronomy, Goiânia, Goiás.

2.2 Experimental Design and Treatments

The study was a completely randomized design with four replicates, and seven treatments, for both soil textures: witness, K6 remineralizer from Embu Mineral Company at four increasing K2O rates (30, 60, 120 and 240 kg K2O ha-1), KCl at 60 kg K2O ha-1, and FMX remineralizer (fine-graded mica schist from Pedreira Araguaia Mineral Company) (Table 6). Both KCl and FMX were used as reference K2O 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.

Treatment	Description	Source	K_2O kg ha^{-1}
0 (control)	0 x the recommended rate	-	0
30 K6	0.5 x the recommended rate	K6	30
60 K6	1.0 x the recommended rate	K6	60
120 K6	2.0 x the recommended rate	K6	120
240 K6	4.0 x the recommended rate	K6	240
60 FMX	1.0 x the recommended rate	FMX	60
60 KCl	1.0 x the recommended rate	KCl	60

Note. *Granite* remineralizer K6 from Embu Mineral Company; FMX: fine-graded mica schist remineralizer from Pedreira Araguaia Mineral Company; KCl: commercial potassium chloride. Source: Brasil, E. P. F. (2021).

2.3 Soil incubation and plant cultivation

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

After the incubation period was over, five soybean seeds (cultivar Brasmax Desafio RR – 8473 RSF) were sown per pot; seedlings were thinned to one plant per pot, after emergence. Soybean plants were cultivated for four months.

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

2.4 Soil-Plant Sampling and Analysis

After soil samples were collected from each experimental unit, they were air-dried, sieved in 2-mm mesh and analyzed for exchangeable K^+, based on methods proposed by Embrapa (2017), with K extracted in *Mehlich-I* solution.

Soybean and corn silage shoots were dried in forced air-circulation oven, at 65 °C, until reaching constant weight. The leaves were ground in Willey knife mill (<40 mesh), packed, labeled and sent to the laboratory. Total K content was determined based on the methodology proposed by Malavolta et al. (1997).

After harvest, soybean grains' weight was converted into kilograms per hectare (kg ha^{-1}) to find the soybean grain yield. Then, these values were turned into sacks per hectare (sc ha^{-1}), since the 60-kg sack corresponds to the measurement unit for soybean sales in Brazil. Corn silage yield was found by converting the shoot dry matter mass into tons per hectare (t ha^{-1}).

Relative efficiency of potential granite remineralizer K6 in comparison to reference sources - remineralizer FMX and potassium chloride - was calculated by the following mathematical expression:

$$\text{RE (\%)} = \frac{\text{value of cultures' yield at dose equivalent to granite K6 x 100}}{\text{Values of yield recorded for reference cultures (FMX or KCl)}}$$

2.5 Data analysis

Data of each crop (soybean and corn silage) were subjected to analysis of variance (F test), at 5% and 1% significance level; means were compared by Tukey test, at 5% significance level. Effects of K rate on soils and plants were assessed through polynomial regression analysis. All analyses were performed in Statistical Analysis System (SAS) software.

3. Results and Discussion

3.1 Granite remineralizer K6 featuring

Law n. 12.890, from December 2013, provides on the term 'remineralizer' by defining it as "material of mineral origin that has only undergone size reduction and classification based on mechanical processes and that changes soil fertility indices due to the addition of macro and micronutrients to plants, as well as that improves soil physical or physical-chemical properties, and its biological activity" (Brasil, 2013). These materials must fulfill requirements in the Standard Instruction from March 2016 in order to ensure their functionality and to guarantee their parameters. Briefly, they must present the following features in comparison to the total chemical composition: a) at least 9% of the sum of bases (CaO + MgO + K_2O); b) at least

1% of potassium oxide (K_2O); at most 25% of free SiO_2 (quartz) found in the product; c) at most 15 mg kg^{-1} arsenic (As), 10 mg kg^{-1} cadmium (Cd), 0,1 mg kg^{-1} Mercury (Hg) and 200 mg kg^{-1} lead (Pb).

Particle size distribution shown in Table 1 has evidenced that granite remineralizer K6 meets the parameters defined by NI n. 5/MAPA (from March 10, 2016), according to which, it is mandatory to have 100% of particles passing through a 2-mm mesh; 70%, or more, passing through a 0.84-mm mesh; and 50%, or more, passing through a 0.3-mm mesh.

The results presented in Table 2 have shown that the granite remineralizer K6 is composed of oligoclase (25.4%), biotite (8.71%), quartz (24.9%), microcline (31.9%), and small occurrences of muscovite (6.67%). According to the geochemical parameters established by NI n. 5/2016, the limit of free silica (quartz, SiO_2) in SR must be lower than 25% (v/v). Thus, granite remineralizer K6 rocks can be classified as remineralizer, since their silica content was below the maximum value determined by law.

Elemental oxide concentrations and trace elements were determined through XRF analysis (Tables 3 and 4). Granite remineralizer K6 samples had the following contents of elements: silica (68.75%), aluminum oxide (13.49%) and iron oxide (4.60%). Contents of CaO (2.13%), MgO (0.99%), K_2O (5.89%) and Na_2O (2.63%) were also assessed in granite remineralizer K6. Therefore, the sum of bases reached 11.64%; the minimum requirement established by law for it is 9.0% - this number is good enough to classify granite remineralizer K6 rock as soil remineralizing product.

Potentially toxic elements (Hg, Cd, Pb and As) shown in Table 4 were below the maximum levels established by Normative Instruction n. 5/2016 (As: 15, Cd: 10, Hg: 0.1 and Pb: 200 mg kg^{-1}).

3.2 Effect of K sources on soil and soybean parameters

3.2.1 Clayey Red Latosol (RL)

Soybean yield (Table 7) in clayey Red Latosol presented significant differences in the F test (32.53), and coefficient of variation = 14.82%. Soybean yield ranged from 530.4 to 2,620.9 kg ha^{-1}. According to data by Conab (2022), 40,950.6 thousand hectares were sown at this crop season; it was 4.5% higher than the number of hectares sown in crop season 2020/21. Production reached 124,047.8 thousand tons and this value was 10.2% lower than that recorded for 2020/2021 crop season; mean yield reached 3,029 kg ha^{-1} – this number reflects water shortage. Treatments 60, 120, 240 kg ha^{-1} K_2O of granite K6 stood out for recording the highest yields and for accounting for higher values than those recoded for the tested standards (KCl and FMX). They differed among all treatments in the Tukey test in comparison to the witness (Table 7).

According to Almeida Júnior et al (2022), the use of mica schist remineralizer affected soybean culture yield, cultivar Agroeste, when it was applied at the tested remineralizer doses (3,730 $kg.ha^{-1}$); it was not possible concluding about any significant difference between treatments. Yield remained at high levels and the best outcome was recorded for treatment T5, at dose 16 $Mg.ha^{-1}$ remineralizer mica schist, at average of 3,614 Kg per hectare; “doze zero” absolute witness T1 recorded average of 2,930 Kg per hectare. This outcome evidences difference by 684 Kg; in other words, 11.4 sacks (60Kg capacity). It was not detected in the Tukey test at 5% probability level, but it is highly observable in comparison to cost/benefit, a fact that favors the rural product. The work carried out by Almeida Júnior et al. (2020) did not show differences between treatments in technological variables of the soybean culture; but the number remained at high levels for agronomic and productivity features, since they were above the national average. Aloivisi et al (2017) assessed corn and soybean cultures and found that basalt powder and bioactive addition have influenced technological variables, yield in kilogram for hectare and weight of one thousand grains.

Soybean shoot K contents (Table 7) showed significant differences among treatments, in the F test (4.64), with coefficient of variation = 21.64% in Red Latosol. There were no differences between granite K6 doses and reference FMX and KCl standards. Soybean shoot K contents, in all treatments, were below the levels referred to as adequate by Raij et al., 1997

(1.7 to 2.5 dag/kg), Ribeiro et al., 1999 (1.7 dag/kg) and Embrapa, 2020 (1.8 to 2.5 dag/kg). It is essential highlighting that these interpretation criteria are set for soybean, in the field; there is content and interpretation variability in compliance with several factors, among them, cultivation conditions and cultivars (Fontes, 2016). It is also important pointing out that this was the first cultivation in soil presenting too low K contents.

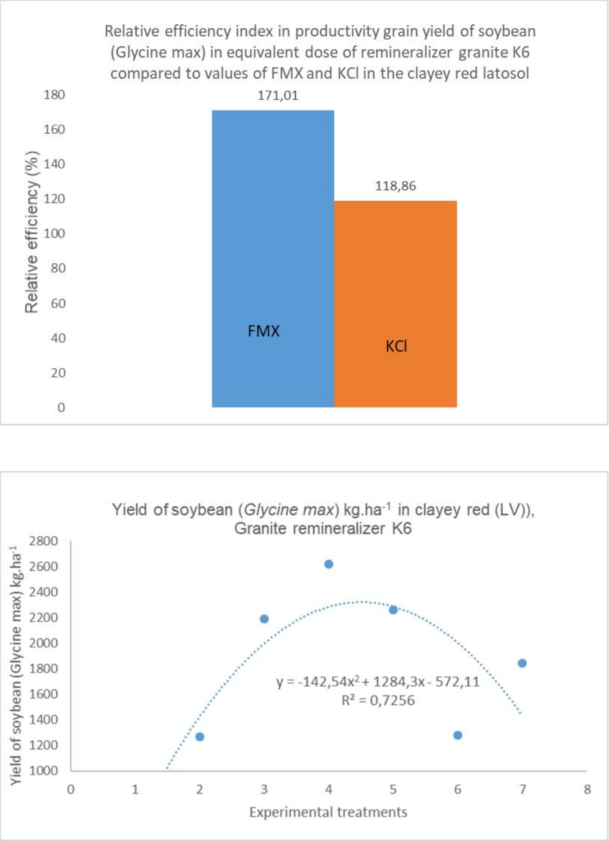
Potassium (K) in Red Latosol planted with soybean, extracted in *Mehlich* 1, presented significant difference among experimental treatments in the current study (F test = 13.65 and CV=12.76%). Soil K ranged from 15 to 56.0 mg.dm^{-3}, i.e., it corresponded to range from 0.04 to 0.14 Cmolc.dm^{-3}, at dose of 120 of remineralizer K6, which presented responses similar to those by 60FMX and 60KCL to soil potassium. Raij *et al.* (2001) highlighted that adequate K availability levels ranged from 0.08 to 0.21 Cmolc dm^{-3}, and it shows that the potential granite remineralizer K6 has significant effects on the dynamics of residual soil potassium, and on its positive influence on soil fertility.

Table 7 - Mean values of potassium soil availability (K), leaf K content and soybean grain yield (*Glycine max*) affected by granite remineralizer K6 sources and rates in clayey Red Latosol (LV). Goiania, Goias State.

Treatments	K Soil availability	K Leaf	Grain yield
	mg dm^{-1}	dag kg^{-1}	kg ha^{-1}
0 (control)	15.5 c	0.62 b	530.4 d
30 K6	33.5 ab	0.67 b	1270.7 c
60 K6	41.5 ab	1.28 a	2190.7 ab
120 K6	53.0 a	1.32 a	2620.9 a
240 K6	32.0 ab	1.41 a	2261.8 ab
60 FMX	54.5 a	1.42 a	1281.0 c
60 KCl	56.0 a	1.67 a	1843.10 bc
F test	13.65**	4.64*	32.53**
CV (%)	12.76	21.64	14.83

Note. Granite remineralizer K6 from Embu Mineral Company; FMX: fine-graded mica schist remineralizer from Pedreira Araguaia Mineral Company; KCl: commercial potassium chloride. Means followed by the same letter in the column did not differ from each other in the Tukey test at 5%. ** and* means significant at 1% and 5%, respectively, in the analysis of variance (F test). Source: Brasil, E. P. F. (2021)

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 K6 remineralizer, fine-graded mica schist remineralizer e potassium chloride.



Note. K6 remineralizer from Embu Mineral Company; FMX: fine-graded mica schist remineralizer from Pedreira Araguaia Mineral Company; KCl: commercial potassium chloride. Source: Brasil, E. P. F. (2021).

The table shows results of soybean yield relative efficiency in Red Latosol after the application of granite remineralizer K6 (%) in comparison to standard dose 60 kg. ha^{-1} K_2O of remineralizer FMX, which showed mean superiority of 71.01%. The comparison of yield efficiency recorded for potential granite remineralizer K6 to the application of a dose equivalent to that of synthetic fertilizer KCl showed silicon efficiency of 18.86% (Figure 1). Based on the present study, the potential granite remineralizer K6 (%) leads to nutrients' release, and it reflects on the expression of the highest relative efficiency of soybean culture yield in Red Latosol. The highest yield was recorded for treatment 120 kg. ha^{-1} K_2O of granite remineralizer K6 (Figure 1).

3.2.2 Yellow Latosol (LA)

Soybean yield (Table 8) presented significant differences in the F test, in Yellow Latosol (11.21), with coefficient of variation = 19.18%. Yield ranged from 333.0 to 3,113.8 kg ha^{-1}, with emphasis on the treatment with 120 kg. ha^{-1} of granite remineralizer K6, which recorded the highest mean yield and yield superiority. According to Conab (2022), mean yield reached 3,029 kg.ha^{-1}.

Potassium (K) content in soil planted with soybean (Table 8), extracted in *Mehlich-1*, presented significant differences among treatments, in the F test (3.29), with coefficient of variation = 14.49%. Potassium (K) contents ranged from 16 to 67.5 mg dm^{-3} in Yellow Latosol. Treatment 60 KCl showed the highest content, and treatment 30 kg ha^{-1} K_2O of granite remineralizer K6 presented the lowest content (17.0 mg.dm^{-3}); there were no significant differences among the other experimental treatments. With respect to reference K sources in remineralizer FMX, there were no significant differences at different K soil doses, a fact that shows its potential to be registered in the Ministry of Agriculture, Livestock and Supply, due to its solubility in water. Standards by Souza and Lobato (2004) show that K soil contents are at adequate levels when they reach values higher than 40 mg dm^{-3}. The 5th Recommendation for Corrections and Fertilizers for Goiás State (1988) records potassium values lower than 25 mg.dm^{-3} as low content, and values ranging from 25 to 50 mg.dm^{-3} as medium contents; values higher than 50 mg.dm^{-3} are considered high for K+, whose absorption can be affected by calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations. It happens due to competitive inhibition, because these elements dispute the same ligation sites in plants. Minerals are the main availability form for these nutrients; they are mostly available in primary minerals (feldspar, muscovite and biotite). Their availability is amplified when pH increases due to a larger number of loads in colloids for K ligation (Duarte, 2019). Potassium (K) availability and its supply ability in the soil depend on the presence of primary and secondary minerals, on the application of fertilizers and on soil CEC, besides nutrient cycling by plants. In other words, K availability depends on its observed forms and on its amount stored in each of its forms (McLean & Watson, 1985; Nachtingall & Vall, 1991), on aspects contributing to its moves and to its dynamics in soil profile.

Soybean shoot K contents (Table 8) showed significant differences among treatments, in the F test (11.29), with coefficient of variation = 15.58%, in Yellow Latosol. The highest k contents in the shoot were recorded for treatments 60 KCl and 60FMX. There were no significant differences at different doses of granite remineralizer K6, and it differed from the witness. Potassium (k) contents in the shoot recorded for treatments 120K6, 240K6, 60 FMX and 60KCl, respectively, were close to levels referred to as adequate 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}). It is important highlighting that these interpretation criteria were set for soybean, in the field; there are variability in contents and interpretations depending on several factors, among them cultivation conditions and cultivars (Fontes, 2016).

Table 8 - Mean values recorded for potassium soil availability (K), leaf K content and soybean grain yield (*Glycine max*) affected by granite remineralizer K6 sources and rates, in texture Yellow Latosol (YL). Goiania, Goiás State.

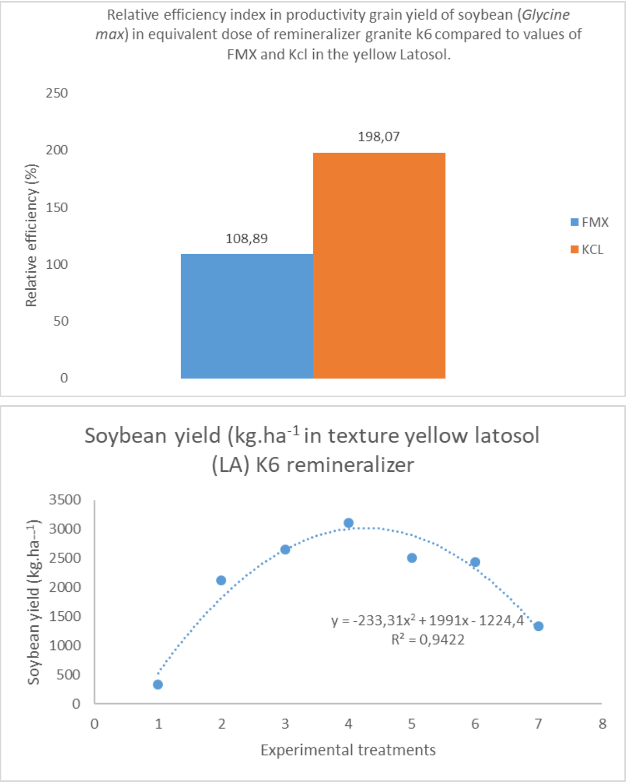
Treatment	K soil availability	Leaf K	Grain yield
	mg dm^{-3}	dag kg^{-1}	kg ha^{-1}
0 (control)	16.0 b	0.58 c	333.0 d
30 K6	17.0 b	0.75 b	2130.5 b
60 K6	18.0 b	0.76 b	2650.00 ab
120 K6	18.0 b	0.84 ab	3113.8 a
240 K6	21.0 b	1.08 ab	2515.9 b
60 FMX	21.5 b	1.26 a	2433.6 b
60 KCl	67.5 a	1.34 a	1337.9 c
F test	3.29*	11.29**	11.21*
CV (%)	14.49	15.58	19.18

Note. Granite remineralizer K6 from Embu Mineral Company; FMX: fine-graded mica schist remineralizer from Pedreira Araguaia Mineral Company; KCl: commercial potassium chloride. Means followed by the same letter did not differ from each other in the Tukey test, at 5%. **and * significant at 1% and 5%, respectively, in the analysis of variance (F test). Source: Brasil, E. P. F. (2021)

Results of soybean yield relative efficiency in sandy texture soil, treated with potential granite remineralizer K6, in comparison to the treatments with remineralizer FMX and potassium chloride (%), have evidenced mean superiority of 8.89%. The comparison between yield efficiency of potential silica remineralizing to the application of equivalent dose of remineralizer FMX showed 98.07% silica efficiency (Figure 2).

With respect to soybean yield in sandy texture soil, due to the herein installed experimental treatments, evidenced the superiority of responses to potential granite remineralizer K6 at the dose of 120K6. On the other hand, there were similar responses to treatments 30K6, 240 K6 and 60 FMX – they differed from, and recorded, lower yield than treatment 60KCL.

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 K6 remineralizer, fine-graded mica schist remineralizer and potassium chloride crop int texture Yellow Latosol (LA). Note. K6 remineralizer from Embu Mineral Company; FMX: fine-graded mica schist remineralizer from Pedreira Araguaia Company; KCl: commercial potassium chloride.



Source: Brasil, E. P. F. (2021).

3.3 Effect of K sources on soil and corn silage parameters

3.3.1 Red Latosol

Corn silage yield (Table 9) in clayey RL did not present significant differences in the F test (2.05), with coefficient of variation of 61.15%. Corn silage yield ranged from 9.1 to 22.1 tons per hectare. According to Conab, the 2022/23 harvest will reach 126.9 million tons. This number means a rise by 12.5% in yield, in comparison to the previous harvest. Pasa and Pasa (2015) reported that corn plants are the most used forage for silage because their chemical composition presents the ideal conditions for a good silage production – MS content ranging from 30% to 35%, and at least 3% soluble carbohydrates in the original matter, low buffer power and good fermentation profile. High-quality silage is set by the ideal cut-off point or harvest; it is recommended to proceed with the harvest when the crop presents corn dry matter (DM) content ranging from 33% to 37%. According to Pescumo and Igarasi (2013), grains' consistence will be like farinaceous or hard farinaceous at this stage; it means higher total DM digestibility, good material consistence at the time to be chopped, higher DM yield per hectare, higher rate of grains in the DM, higher energetic density, higher DM intake by animals, and higher milk and beef yield.

Potassium (K) in soil planted with corn silage, extracted in *Mehlich*-1 (Table 9), did not present significant differences among treatments, in the F test (0.77), with CV = 40.99%. Potassium (K) contents ranged from 25 to 50 mg dm^{-3} in RL. Based on interpretation of the 5th approximation of Recommendations of Correction and Fertilizer for Goiás State, contents ranging from 25 to 50 mg.dm^{-3} present medium contents.

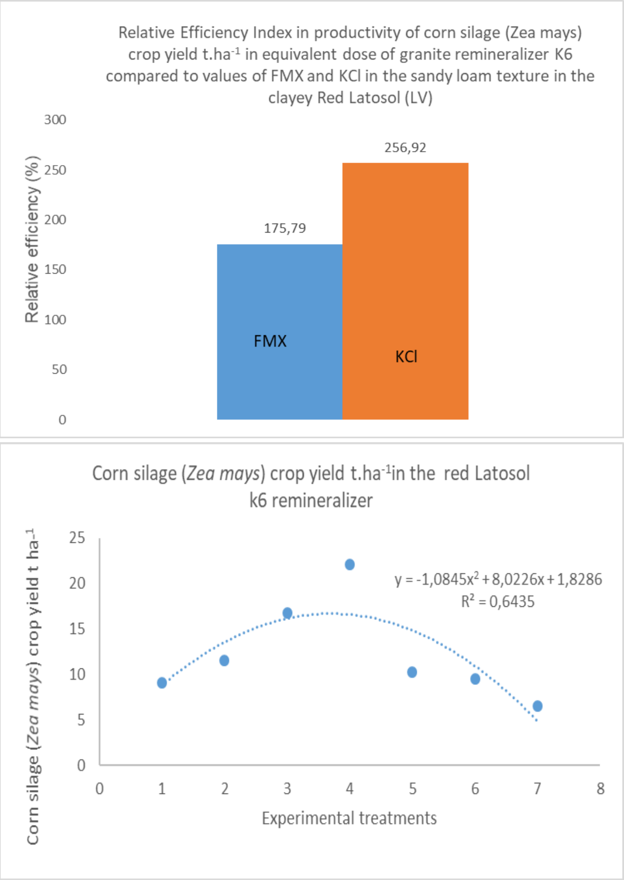
Potassium (K) content in corn silage shoot (Table 9) showed significant differences among treatments in the F test (3.81) and coefficient of variation = 45.86%, in RL. These same contents laid below the levels referred to as adequate by Raij et al. (1997) (1.7 to 5.5 dag kg^{-1}) and Ribeiro et al., 1999 (1.75 to 22.5 dag kg^{-1}), except for treatment 60 KCl, which showed the highest shoot concentration (2.2 dag.kg^{-1}) – these values are statistically equivalent to doses 60K6, 120K6, 240K6 and 60FMX. According to Sousa and Lobato (2004), adequate contents range from 1.3 to 3.0 dag kg^{-1}. Growing K6 doses have reflected on growing shoot potassium contents.

Table 9 - Mean values recorded for K soil availability, K shoot content and corn silage grain yield (*Zea mays*) affected by K sources and rates in clayey Red Latosol (RL).

Treatments	K soil availability	Leaf K	Yield
	mg dm^{-3}	dag kg^{-1}	t ha^{-1}
0 (control)	25 a	0.7 b	9.1 a
30 K6	28 a	0.8 b	11.5 a
60 K6	28 a	0.9 ab	16.7 a
120 K6	26 a	1.2 ab	22.1 a
240 K6	44 a	1.6 ab	10.2 a
60 FMX	50 a	1.9 ab	9.5 a
60 KCl	48 a	2.2 a	6.5 a
F test	0.77 ^{ns}	3.81**	2.05 ns
CV (%)	40.99	45.86	61.15

Note. Granite remineralizer K6 from Embu Mineral Company; FMX: fine-graded mica schist remineralizer from Pedreira Araguaia Mineral Company; KCl: commercial potassium chloride. Means followed by the same later in the column did not differ from each other in the Tukey test, at 5%. ** and * significant at 1% and 5%, respectively, in the analysis of variance (F test). Source: Brasil, E. P. F. (2021)

Figure 3. Effect of potassium sources and rates on corn silage relative yield values (*Zea mays*) and relative yield efficiency index, at equivalent doses of granite remineralizer K6, fine mica schist remineralizer and potassium chloride, in clayey Red Latosol. Granite remineralizer K6 from Embu Mineral Company; FMX: fine mica schist remineralizer from Araguaia Mineral Company; KCl: commercial potassium chloride.



Source: Brasil, E. P. F. (2021).

3.3.2 Yellow Latosol

Corn silage yield (Table 10) presented significant differences, in YL, in the F test (8.3), with coefficient of variation = 21.87%. It was possible recording yield ranging from 12.9 to 24.9 tons per hectare, with emphasis on treatments 60K6 and 120K6 kg .ha^{-1}, and 60KCl, which recorded the highest yields. Based on data by the 1st Survey of the 2022/2023 Grain Harvest, corn silage yield in Goiás State must reach 32.4 million tons in the current season, and it means growth by 12.6% in comparison to that recorded for the 2021/22 harvest. The report was disclosed by the National Supply Company (Conab, 2022). This is the first time in Conab's historical series that yield estimates exceed 30 million tons in Goiás State. There is upward trend for the total planted area and for mean state yield: 3% and 9.4%, respectively. Corn silage is an important strategy for bovine feeding in regions showing times of low pasture yield, or for food supplementation (Placido, 2019).

Potassium (K) in soil planted with corn silage, extracted in *Mehlich 1* (Table 10), did not present significant differences among treatments, in the F test (2.05), with coefficient of variation = 61.15%. Potassium (K) content ranged from 21 to 32 mg dm^{-3} in YL. According to interpretation criteria by C.F.S.G (1988), these contents in soil lay on the low class limit when they are lower than 25 mg dm^{-3}, and on the medium class limit when they range from 25 to 50 mg dm^{-3}.

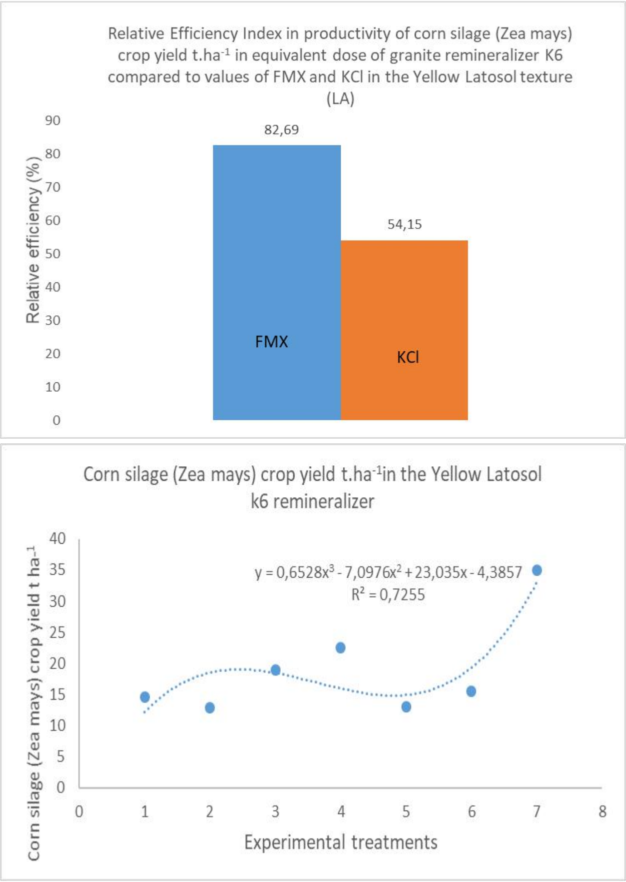
Potassium (k) content in corn silage (Table 10) showed significant differences among treatments in F test (5.39), with coefficient of variation = 29.3%, in YL. The highest K shoot contents were recorded for treatments 60 KCl and 60 FMX. Treatments 60KCl, 60FMX and 240K6 showed adequate levels of shoot K content. Shoot K content in corn silage was lower than the 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, criteria by Sousa and Lobato (2004) (1.3 to 3.0 dag kg^{-1}) were taken into considerations.

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

Treatments	K Soil availability	Leaf K	Yield
	mg dm^{-3}	dag kg^{-1}	t ha^{-1}
0 (control)	21 a	1.0 c	14.6 b
30K6	30 a	1.5 abc	12.9 b
60K6	28 a	1.1 bc	18.9 ab
120K6	22 a	1.5 abc	22.5 ab
240K6	25 a	1.9 abc	13.0 b
60 FMX	27 a	2.2 ab	15.6 b
60 KCl	32 a	2.6 a	34.9 a
F test	2.05 ns	5.39 **	8.3**
CV (%)	61.15	29.3	21.87

Note. Granite remineralizer K6 from Embu Mineral Company; FMX: fine-graded mica schist remineralizer from Pedreira Araguaia Mineral Company; KCl: commercial potassium chloride. Means followed by the same letter in the column did not differ from each other in the Tukey test, at 5%. ** and * significant at 1% and 5%, respectively, in the analysis of variance (F test). Source: Brasil, E. P. F. (2021).

Figure 4 - Relative efficiency index of corn silage (*Zea mays*) yield, leaf K content, in sandy loam texture Yellow Latosol (LA). Granite remineralizer K6 from Embu Mineral Company; FMX fine-graded mica schist remineralizer from Pedreira Araguaia Mineral Company; KCl: commercial potassium chloride.



Source: Brasil, E. P. F. (2021).

4. Conclusion

Yield data evidence K release in the soil, absorbed by the test plants soybean and silage corn, a fact that reflect yield increase due to remineralizer K6 application.

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