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Broadcast application of ground silicate rocks as potassium sources for grain crops

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Abstract – The objective of this work was to evaluate the agronomic and economic efficiency of phonolite rock (K2) and alkaline potassium-silicate rock (K3), ground and applied by surface broadcasting, as K sources for the soybean (*Glycine max*), corn (*Zea mays*), common bean (*Phaseolus vulgaris*), and upland rice (*Oryza sativa*) crops. Four experiments – one with each crop – were conducted in two crop years in a Typic Haplorthox in a randomized complete block design with four replicates. The treatments consisted of three sources (the KCl standard source, K2, and K3) and four rates (0, 0.5, 1.0, and 2.0 times the recommended for each crop) of K. The three sources increased similarly the leaf K concentration of soybean, corn, and common bean but had no effect on that of upland rice. The grain yield of all crops increased with the application of K2 and K3, as observed for KCl. The efficiency of the alternative K sources varies depending on the rate and crop. The K3 source is viable to be applied by broadcasting at the recommended K rate for all studied crops, while K2 is suitable only for soybean, corn, and common bean.

Index terms: agronomic efficiency, alternative fertilizer, phonolite, potassic fertilization, potassic rock, silicon.

Aplicação a lanço de rochas silicáticas moídas como fontes de potássio para culturas de grãos

Resumo – O objetivo deste trabalho foi avaliar as eficiências agronômica e econômica da rocha fonolito (K2) e da rocha potássio-silicática alcalina (K3), moídas e aplicadas superficialmente em área total, como fontes de K para as culturas de soja (*Glycine max*), milho (*Zea mays*), feijão comum (*Phaseolus vulgaris*) e arroz de terras altas (*Oryza sativa*). Quatro experimentos – um com cada cultura – foram conduzidos em dois anos agrícolas, em Latossolo Vermelho, em delineamento de blocos ao acaso, com quatro repetições. Os tratamentos consistiram de três fontes (a tradicional KCl, K2 e K3) e quatro doses (0, 0,5, 1,0 e 2,0 vezes a recomendada para cada cultura) de K. As três fontes aumentaram de forma similar os teores de K nas folhas de soja, milho e feijão comum, mas não tiveram efeito sobre o de arroz. A produtividade de grãos de todas as culturas aumentou com a aplicação de K2 e K3, como observado para KCl. A eficiência das fontes alternativas de K varia em função da dose e da cultura. A fonte K3 é viável para ser aplicada a lanço na dose de K recomendada para as culturas estudadas, enquanto K2 é viável apenas para soja, milho e feijão comum.

Termos para indexação: eficiência agronômica, fertilizante alternativo, fonolito, adubação potássica, rocha potássica, silício.

Introduction

The soybean [*Glycine max* (L.) Merr.], corn (*Zea mays* L.), common bean (*Phaseolus vulgaris* L.), and rice (*Oryza sativa* L.) crops cover 91% of the total area planted with grains in Brazil, comprising approximately 60 million hectares in the 2019/2020 harvest (Conab, 2020).

Of the required nutrients, potassium is usually the second most taken up by the soybean, corn, and common bean crops (Soratto et al., 2013; Bender et al., 2013, 2015), but it may be the most taken up by upland rice (Crusciol et al., 2016). Although K has no structural function in plants, it is the most abundant cation in the cytoplasm and has several key functions in the plant metabolism (Marschner, 2012). In addition, in tropical soils, K availability is highly dependent on mineral fertilizers (Fageria et al., 1990; Foloni & Rosolem, 2008; Valderrama et al., 2011; Carvalho et al., 2018).

In Brazil, the fourth largest importer of K fertilizer in the world (Anda, 2014), domestic production is limited to the Taquari-Vassouras mine/power plant complex, located in the state of Sergipe (sylvite mining), meeting only 6% of the national demand (Kulaif & Góes, 2016; Sipert et al., 2020). The main source of K fertilizer worldwide, potassium chloride, is mainly imported from the Northern Hemisphere and, therefore, is susceptible not only to international market prices but also to supply and exchange rate variations, making it a high-cost input (Ciceri et al., 2017; Dias et al., 2018).

Therefore, to meet the high demand of Brazilian agriculture for K fertilizers, alternative sources of the nutrient are required (Kulaif & Góes, 2016; Sipert et al., 2020), with a consequent reduction in costs and in the country's dependence on external markets (Martins et al., 2008, 2015; Mancuso et al., 2014; Dias et al., 2018; Boldrin et al., 2019). Among the alternative sources is rock dusting, a natural fertilization method (Martins et al., 2015; Manning, 2018; Boldrin et al., 2019), which consists of the direct application of finely ground rock or rock dust that normally releases gradually nutrients (Martins et al., 2008; Basak et al., 2017). In Brazil, alkaline K-silicate rocks, such as phonolite and others found in the alkaline massif of the municipality of Poços de Caldas, in the state of Minas Gerais (Kulaif & Góes, 2016), stand out due to their high contents of K and other plant nutrients such as silicon (Mancuso et al., 2014; Martins et al., 2015; Ciceri et al., 2017), as well as for their large reserves (Kulaif & Góes, 2016). The main constituents of these alkaline K-silicate are alkali feldspars (microcline, orthoclase, and sanidine) and feldspathoids (nepheline) (Martins et al., 2008; Teixeira et al., 2012; Kulaif & Góes, 2016), although some of the more weathered ones also contain micas (ilite) (Kulaif & Góes, 2016). Moreover, all alkaline K-silicate rocks are rich in silicon, an element considered beneficial to various crops, especially when under stress conditions (Cooke & Leishman, 2016; Manivannan & Ahn, 2017; Wang et al., 2017; Frew et al., 2018).

Currently, the application method of K sources preferred by an increasing number of farmers is surface broadcasting, particularly in soils with a medium or a high nutrient availability, in order to minimize the saline effect of KCl on the sowing furrow and to streamline farming practices, improving operational yield and labor use during more idle periods and, consequently, reducing costs. However, for an appropriate recommendation of ground-rock fertilizers (Martins et al., 2008), determining their agronomic efficiency is a prerequisite. The reaction dynamics of these materials with the soil and agronomic efficiency is directly affected by mineralogy, particle size ranges, water flow in the system, plant species, and soil types (Wang et al., 2000; Martins et al., 2008; Basak et al., 2017; Manning, 2018). Therefore, further studies are needed to determine the efficiency of ground alkaline K-silicate rocks applied by surface broadcasting as K sources for the main grain crops.

The objective of this work was to evaluate the agronomic and economic efficiency of phonolite rock and alkaline potassium-silicate rock, ground and applied by surface broadcasting, as K sources for the soybean, corn, common bean, and upland rice crops.

Materials and Methods

Four field experiments – one with each crop – were conducted during the crop years of 2008/2009 for soybean, corn, and common bean and of 2009/2010 for rice, in the municipality of Botucatu, in the state of São Paulo, Brazil (22°51'S, 48°26'W, at 740 m altitude). According to Köppen's classification, the predominant climate of the region is Cwa. The climatic data recorded during the experimental period are shown in Figure 1.

The soil of the areas used for the experiments was classified as a clayey Latossolo Vermelho distroférrico (Santos et al., 2018), i.e., a Typic Haplorthox (Soil Survey Staff, 2014). Before the crops were sown, soil samples were collected at the 0.0–0.20 m depth. The area with the soybean, corn, and common bean crops had the following soil chemical characteristics: 4.8 pH($CaCl_2$); 24 g dm^{-3} organic matter; 17 mg dm^{-3} P_{resin}; 1.2, 26, 14, and 54 mmol$_c$ dm^{-3} exchangeable K, Ca, Mg, and H+Al, respectively; and base saturation of 43%. In the area with rice, the soil characteristics were: 4.2 pH($CaCl_2$); 18 g dm^{-3} organic matter; 16 mg dm^{-3} P_{resin}; 1.2, 22, 9.0, and 32 mmol$_c$ dm^{-3} K, Ca, Mg, and H+Al, respectively; and base saturation of 50%. All areas were managed under the no-tillage system.

The experimental design used was a randomized complete block, with four replicates. The treatments consisted of three sources and four rates of K. The used sources were: KCl, standard source, with 58% K_2O; K2, ground phonolite rock containing 8.42% total K_2O, 1.0% soluble K_2O in 2.0% citric acid, 52.5% SiO_2, 1.58% CaO, 0.05% P_2O_5, 20.7% Al_2O_3, and 7.53% Na_2O; and K3, ground alkaline K-silicate rock containing 13.8% total K_2O, 0.2% soluble K_2O in 2.0% citric acid, 58.7% SiO_2, 0.10% P_2O_5, 19.8% Al_2O_3, and 0.61% Na_2O. Both alternative K sources were obtained from the municipality of Poços de Caldas, in the state of Minas Gerais, Brazil, and then finely ground by passing 100% of the particles through a 0.074 mm sieve (ABNT, 1997). The applied rates were 0, 0.5, 1.0, and 2.0 times the recommended K_2O rate for each crop, according to Raij et al. (1997), being 0, 25, 50, and 100 kg ha^{-1} K_2O for soybean; 0, 50, 100, and 200 kg ha^{-1} K_2O for corn; and 0, 20, 40 and 80 kg ha^{-1} K_2O for common bean and rice. The total K_2O content of each K fertilizer was used to calculate the rates to be applied. Each plot consisted of five 5-m-long rows, and the evaluations were carried out in the three central rows, with 0.5 m excluded at the end of each row.

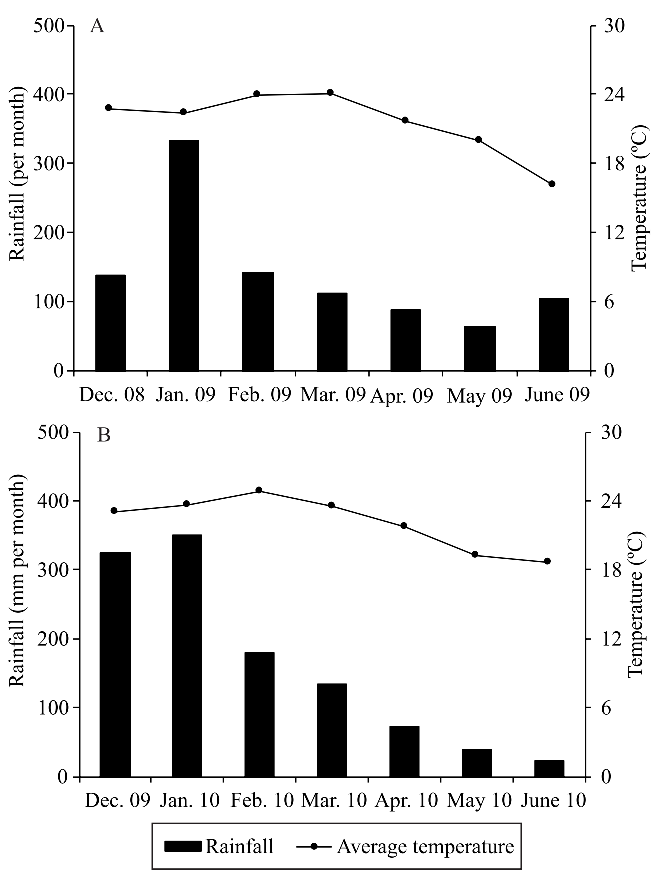

Figure 1. Monthly rainfall and average temperature in the experimental areas from December to June of the 2008/2009 (A) and 2009/2010 (B) growing seasons.

The Embrapa 48 soybean cultivar was sown on 1/14/2009, with rows 0.45 m apart, using 22 seed per meter and 50 kg ha^{-1} P_2O_5 in the sowing furrow. The 2B587 simple corn hybrid was sown on 1/15/2009, with rows 0.90 m apart, using 6 seed per meter and 30 kg ha^{-1} N and 60 kg ha^{-1} P_2O_5 in the sowing furrow, plus 90 kg ha^{-1} N as topdressing in the V_6 stage. The Pérola common bean cultivar was sown on 1/16/2009, with rows 0.45 m apart, using 15 seed per meter and 10 kg ha^{-1} N and 30 kg ha^{-1} P_2O_5 in the sowing furrow, plus 70 kg ha^{-1} N as topdressing in the V_4 stage. The IAC 202 rice cultivar was sown on 12/12/2009, with rows 0.45 m apart, using 70 seed per meter and 10 kg ha^{-1} N and 80 kg ha^{-1} P_2O_5 in the sowing furrow, plus 40 kg ha^{-1} N as topdressing in the tillering stage. For all crops, fertilization with N and P was performed as described in Raij et al. (1997), using urea and simple superphosphate as N and P sources, respectively. One day after sowing, the K fertilizers were broadcast.

In all crops, the diagnostic leaves were sampled according to Raij et al. (1997) and leaf K and Si concentrations were determined following Malavolta et al. (1997) and Korndörfer et al. (2004), respectively. The crops were harvested on the following dates: 4/27/2009 for common bean, 5/7/2009 for soybean, 6/7/2009 for corn, and 4/24/2010 for rice. Grain yield was then evaluated and data were corrected for a water content of 13 g kg^{-1} (wet basis).

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The data obtained for each crop were subjected separately to the analysis of variance. The means of the K sources were compared by the least significant difference t-test, at 5% probability. The SISVAR statistical software package (Ferreira, 2011) was used. In addition, the K rate effects were evaluated by the regression analysis using the PROC MIXED procedure in the SAS software (SAS Institute Inc., Cary, NC, USA).

Regardless of an interaction or not between K fertilizer sources and rates, yield variation (ΔY) was calculated by subtracting the crop yield obtained with the control (without K) from that with each fertilization treatment. Relative yield (RY) was calculated as the percentage ratio between the yields of the treatments with fertilization and of the control, whose yields were the average of 12 plots with 0.0 kg ha^{-1} K. The agronomic efficiency index (AEI) was also determined, being obtained as the percentage ratio between the ΔY values resulting from the K sources applied at the same rate, using the equation: AEI (%) = $(\Delta Y_{K2 \text{ or } K3} / \Delta Y_{KCl}) \times 100$. An analysis of sensibility was carried out to calculate the marginal product (MP) of each K source, as follows: MP (kilogram of grain yield increased per kilogram of K_2O applied) = ΔY / K_2O rate. According to Kinpara (2020), the MP, as an economics concept, is defined as the change in the quantity produced due to a change in a unit of resource.

Results and Discussion

In soybean leaves, K concentrations were significantly affected by fertilizer rates, but not by sources or their interaction with rates (Table 1). Leaf K concentration increased only up to the estimated rate of 21.7 kg ha^{-1} K_2O regardless of the source and increased similarly to that of the control regardless of the applied rate (Figure 2 A). Likewise, Mancuso et al. (2014) and Machado (2016) found no differences between the K2 and KCl sources regarding leaf K concentration in Arabica coffee (*Coffea arabica* L.). However, in the present study, despite the increases due to the applied K rates, the leaf K concentration in soybean remained within the range of 17–25 g kg^{-1} considered suitable for the crop (Raij et al., 1997). Furthermore, in soybean, there were no effects of the studied factors on Si leaf concentrations (Table 1).

Soybean grain yield was affected both by K rates and the source × rate interaction (Table 1). All applied sources showed quadratic effects, with maximum yields obtained with K2, K3, and KCl, respectively, at the rates of 69, 51, and 65 kg ha^{-1} K_2O (Figure 2 B).

Table 1. Leaf potassium and silicon concentrations, as well as grain yield, of the soybean (*Glycine max*), corn (*Zea mays*), common bean (*Phaseolus vulgaris*), and upland rice (*Oryza sativa*) crops as affected by sources and rates of the K fertilizer applied by surface broadcasting[(1)].

Variable	K source[(2)]			Source of variation (P < F)			CV (%)
	K2	K3	KCl	Source (S)	Rate (D)	S × D	
				Soybean			
Leaf K concentration (g kg^{-1})	21.8	21.7	21.8	0.958	0.003	0.470	5.5
Leaf Si concentration (g kg^{-1})	2.2	2.2	2.1	0.081	0.079	0.848	6.3
Grain yield (kg ha^{-1})	2093	2103	2078	0.840	<0.001	0.016	5.8
				Corn			
Leaf K concentration (g kg^{-1})	19.3	19.6	19.5	0.567	<0.001	0.854	3.7
Leaf Si concentration (g kg^{-1})	8.2	8.1	8.0	0.661	0.004	0.430	8.6
Grain yield (kg ha^{-1})	8151	8111	7843	0.030	0.013	0.048	4.1
				Common bean			
Leaf K concentration (g kg^{-1})	18.6	17.9	18.4	0.448	0.044	0.691	7.9
Leaf Si concentration (g kg^{-1})	1.7ab	1.9a	1.6b	0.026	0.186	0.729	14.6
Grain yield (kg ha^{-1})	1953ab	2048a	1914b	0.044	<0.001	0.309	7.6
				Upland rice			
Leaf K concentration (g kg^{-1})	15.7	15.0	15.4	0.094	0.054	0.286	5.5
Leaf Si concentration (g kg^{-1})	21.0a	20.8a	18.6b	0.017	0.136	0.565	12.2
Grain yield (kg ha^{-1})	1519	1581	1538	0.864	<0.001	0.688	21.3

[(1)]Means followed by equal letters, in the rows, do not differ by the least significant difference test, at 5% probability. [(2)]K2, ground phonolite rock; and K3, ground alkaline K-silicate rock.

According to Raij et al. (1997), 50 kg ha^{-1} K_2O is the recommended rate for soybean, with an expected yield of 2–3 Mg ha^{-1}, in soils with low exchangeable K concentrations of 0.8–1.5 mmol$_c$ dm^{-3}, which is consistent with the results of the present study. The estimated rates increased grain yield by 340, 460, and 312 kg ha^{-1}, i.e., by 18, 24, and 16%, when comparing K2, K3, and KCl with the control treatment. At the highest K rate, the highest grain yields were found when the K2 and KCl sources were used (Figure 2 B), whereas, at the rates of 25 and 50 kg ha^{-1} K_2O, K3 stood out, increasing grain yields by 14 and 26%,

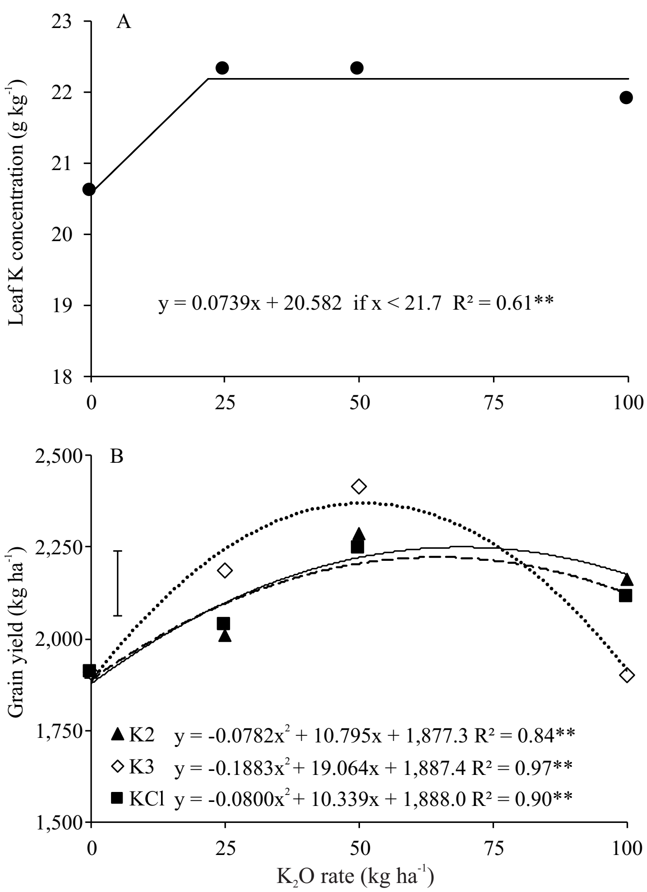

Figure 2. Effect of sources and rates of K fertilizer applied by surface broadcasting on leaf K concentration (A) and grain yield (B) of the soybean (*Glycine max*) crop. Black circles represent the average of the three used K sources: KCl, standard source; K2, ground phonolite rock; and K3, ground alkaline K-silicate rock. Vertical bars indicate the least significant difference (LSD) to separate K sources in a same K rate by the LSD test, at 5% probability. **Significant by the t-test, at 1% probability.

respectively, compared with the control (Table 2). It is noteworthy that the soybean sowing date in January was not the most adequate, which may have limited crop grain yield and response to the treatments. When averaging the rates, each kilogram of K_2O added in the form of the K2 or KCl increased soybean yield in 4.7 kg ha^{-1} (MP = 4.7); however, in the form of K3, the increase in soybean yield was 49% higher (MP = 7.0). Furthermore, the K2 source showed an AEI similar to that of KCl, whereas K3 had a 50% higher AEI. These results are indicative that the K2 and K3 fertilizers can supply K to the soybean crop as efficiently as the standard KCl source.

For corn, K and Si concentrations in the leaves were affected only by K rates (Table 1). Leaf K concentration increased only up to the estimated rate of 38 kg ha^{-1} K_2O (Figure 3 A); however, in all treatments, leaf K concentrations were within the range of 17–35 g kg^{-1} considered suitable for the corn crop (Raij et al., 1997). Studying corn in a soil with medium exchangeable K concentrations, Valderrama et al. (2011) found a linear increase in leaf K with the application of rates up to 120 kg ha^{-1} K_2O. Regarding leaf Si concentrations, there was a linear increase with K rates, regardless of the used source (Figure 3 B). This nutrient indirectly affects some photosynthetic and biochemical aspects of plants, particularly when they are under some kind of biotic or abiotic stress (Cooke & Leishman, 2016; Manivannan & Ahn, 2017; Wang et al., 2017; Frew et al., 2018). Despite the high SiO_2 contents of K2 and K3 – 52.5 and 58.7%, respectively –, the obtained results are indicative that these sources were not able to increase corn Si leaf concentrations compared with KCl, at least not in the short term (Table 1 and Figure 3 B). Machado (2016) also did not find any difference between K2 and KCl in increasing Si concentration in shoots of *Urochloa decumbens* (Stapf) R.D.Webster, which could be attributed to the fact that, in general, grasses are Si-accumulating species (Guntzer et al., 2012).

Corn grain yield was affected by both K sources and rates, as well as by the interaction between them (Table 1). The K2 and K3 sources increased linearly grain yield, but only up to the rate of 81 kg ha^{-1} K_2O (Figure 3 C). At the rate of 50 kg ha^{-1} K_2O, KCl increased corn grain yield when compared with the control; this increase was greater than those with the application of the other sources (Table 2). At the rate of 200 kg ha^{-1} K_2O, K2 and K3 resulted in a greater increase in corn grain yield than KCl, which decreased yield in comparison with the control. These findings may be attributed to the gradual release of nutrients by finely ground rocks, which may avoid soil salinization and decrease leaching (Melamed et al., 2009; Ciceri et al., 2017). Moreover, KCl may have led to Mg deficiency in the plants since it is a source with a high solubility and rapid K release, as well as a high saline index (Rader et al., 1943; Foloni & Rosolem, 2008; Ciceri et al., 2017), decreasing the Ca:K and Mg:K ratios in the soil (Marschner, 2012). At the rates of 100 and 200 kg ha^{-1} K_2O, the K2 and K3 sources stood out, increasing corn yield by 7 and 9%, respectively, in relation to the control (Table 2). At the rate of 100 kg ha^{-1} K_2O, the K2 and K3 sources showed AEI values 3.8 and 3.5 times higher, respectively, than KCl. At 200 kg ha^{-1} K_2O, both of these sources increased corn grain yield, whereas KCl decreased it. When averaging the rates, there was an increase in grain yield of 5.3 and 4.8 kg ha^{-1} with each kilogram of K_2O added in the form of K2 and K3, respectively, but only of 3.5 kg ha^{-1} with each kilogram of K_2O from KCl. The high AEI and MP values found for the K2 and K3 sources were mainly because KCl practically did not increase corn grain yield at the rate of 100 kg ha^{-1} K_2O and decreased it at the rate of 200 kg ha^{-1} K_2O in relation to the control.

As observed for the soybean and corn crops, leaf K concentration in common bean was affected only

Table 2. Yield variation (ΔY), relative yield (RY), and marginal product (MP) of the soybean (*Glycine max*), corn (*Zea mays*), common bean (*Phaseolus vulgaris*), and upland rice (*Oryza sativa*) crops as affected by sources and rates of K fertilizer applied by surface broadcasting, as well as the agronomic efficiency index (AEI) of three rates of ground phonolite rock (K2) and ground alkaline K-silicate rock (K3) compared with KCl.

K_2O rate (kg ha^{-1})	ΔY (kg ha^{-1})(1)			RY (%)(2)			AEI (%)(3)		MP (kg kg^{-1})(4)		
	K2	K3	KCl	K2	K3	KCl	K2	K3	K2	K3	KCl
						Soybean					
0	-	-	-	100	100	100	-	-	-	-	-
25	101	276	128	105	114	107	79	216	4.0	11.0	5.1
50	377	505	339	120	126	118	111	149	7.5	10.1	6.8
100	254	-7	205	113	100	111	123	97	2.5	-0.1	2.1
Mean	-	-	-	-	-	-	104	154	4.7	7.0	4.7
						Corn					
0	-	-	-	100	100	100	-	-	-	-	-
50	332	320	492	104	104	106	68	65	6.6	6.4	9.8
100	593	546	157	108	107	100	378	348	5.9	5.5	1.6
200	686	536	-190	109	107	98	(5)	(5)	3.4	2.7	-1.0
Mean	-	-	-	-	-	-	223	207	5.3	4.8	3.5
						Common bean					
0	-	-	-	100	100	100	-	-	-	-	-
20	88	326	34	105	118	102	257	955	4.4	16.3	1.7
40	288	282	286	116	116	116	101	99	7.2	7.1	7.2
80	231	379	128	113	121	107	181	296	2.9	4.7	1.6
Mean	-	-	-	-	-	-	180	450	4.8	9.4	3.5
						Upland rice					
0	-	-	-	100	100	100	-	-	-	-	-
20	513	229	393	145	120	134	130	58	25.7	11.5	19.7
40	527	760	631	146	166	155	84	120	13.2	19.0	15.8
80	445	743	536	139	165	147	83	139	5.6	9.3	6.7
Mean	-	-	-	-	-	-	99	106	14.8	13.2	14.0

(1)Yield variation in each treatment with fertilizer application relative to the mean yield of the control without K. (2)Relative yield obtained in relation to the mean of the control (control = 100%). (3)AEI of the K2 and K3 sources in relation to KCl, the traditional source. (4)MP, marginal product of the K source in kilogram of grain yield increased per kilogram of K_2O applied. (5)Although the K2 and K3 sources increased corn grain yield at the rate of 200 kg ha^{-1} K_2O, compared with 876 and 726 kg ha^{-1} KCl, respectively, since the grain yield obtained with KCl was lower than that with the control, it was not possible to calculate the AEI at the rate of 200 kg ha^{-1} K_2O for both sources.

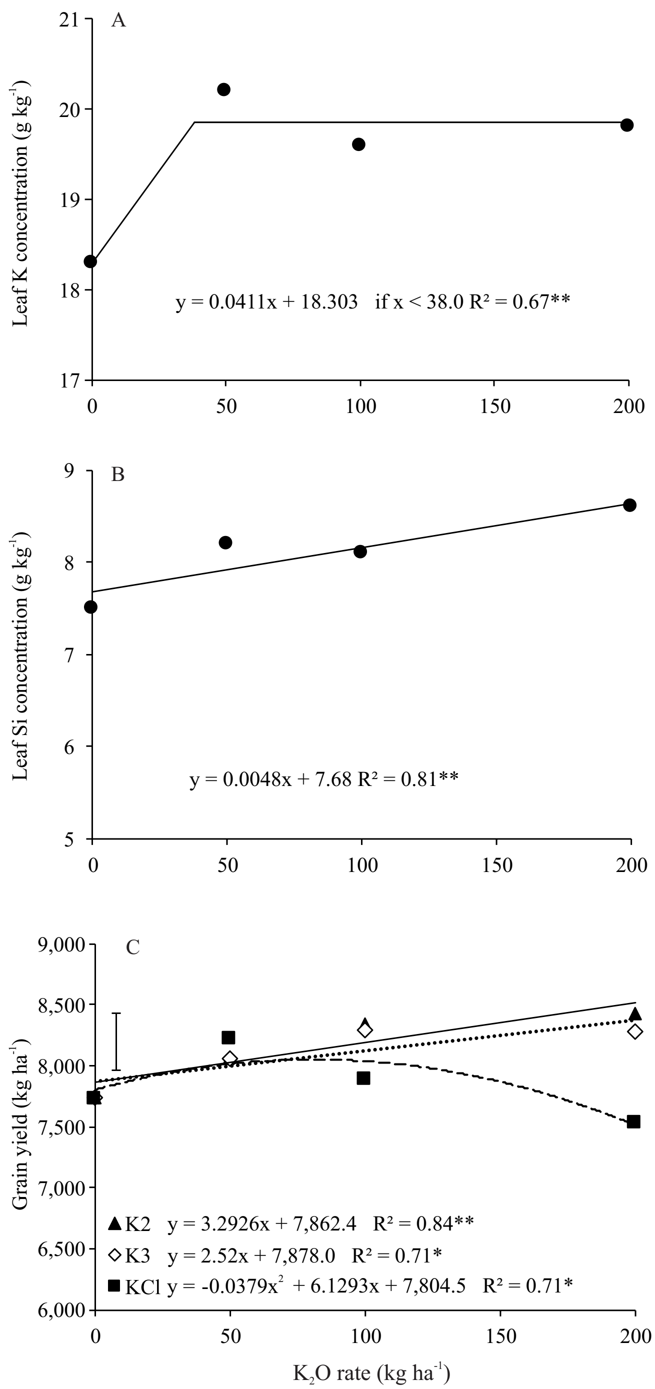

Figure 3. Effect of sources and rates of K fertilizer applied by surface broadcasting on leaf K concentration (A), leaf Si concentration (B), and grain yield (C) of the corn (*Zea mays*) crop. Black circles represent the average of the three used K sources: KCl, the standard source; K2, ground phonolite rock; and K3, ground alkaline K-silicate rock. Vertical bars indicate the least significant difference (LSD) to separate K sources in a same K rate by the LSD test, at 5% probability. * and **Significant by the t-test, at 5 and 1% probability, respectively.

by K rates (Table 1). When averaging the sources, K rates had a quadratic effect, increasing leaf K concentration up to the rate of 45 kg ha^{-1} K_2O (Figure 4 A); however, the highest leaf K concentration was found at the rate of 20 kg ha^{-1} K_2O. Furthermore, leaf K concentrations were below the range of 20–24 g kg^{-1} considered suitable for the crop in all treatments (Raij et al., 1997). When applying 48 kg ha^{-1} K_2O, Soratto & Crusciol (2008) reported similar leaf K concentrations in common bean grown in the same type of soil, with a low exchangeable K content.

For upland rice, none of the studied factors, including K fertilization, affected K leaf concentrations, which were within the suitable range of 13–30 g kg^{-1} for the crop (Raij et al., 1997). These results may also be associated with the high rainfall, especially during December 2009 and January 2010 (Table 1 and Figure 1 B), which may have enhanced K release from the straw mulching of previous crops (Rosolem et al., 2006) and, consequently, K availability even in the control treatment. Fageria et al. (1990) found that upland rice showed a better response to K fertilizer when it was band applied rather than broadcast and that shoot K concentration varied among cultivars, which may also help to explain why no treatment effect was observed on rice K leaf concentration in the present work.

For the common bean and upland rice crops, leaf Si concentrations were significantly affected by K sources (Table 1). For common bean, regardless of the rate, the K3 source resulted in higher leaf Si concentrations than KCl, whereas, for upland rice, both sources derived from ground rocks provided higher concentrations of the nutrient in its leaves. The increase in the leaf Si concentrations of common bean and upland rice is attributed to the high SiO_2 contents of the K2 and K3 sources. Mancuso et al. (2014) also observed a positive effect on Si leaf concentration in Arabica coffee due to the application of the K2 source, when compared with KCl, in the first crop year. Machado (2016), however, evaluating the efficiency of phonolite and thermopotash as alternative sources to KCl, found a higher Si concentration in *U. decumbens* shoots only at the highest rate of thermopotash (400 kg ha^{-1} K_2O) in comparison with KCl and phonolite.

Common bean grain yield was affected by all main factors (Table 1). When averaging the sources, grain yield increased up to the estimated rate of 57 kg ha^{-1} K_2O (Figure 4 B), which is slightly above the rate of

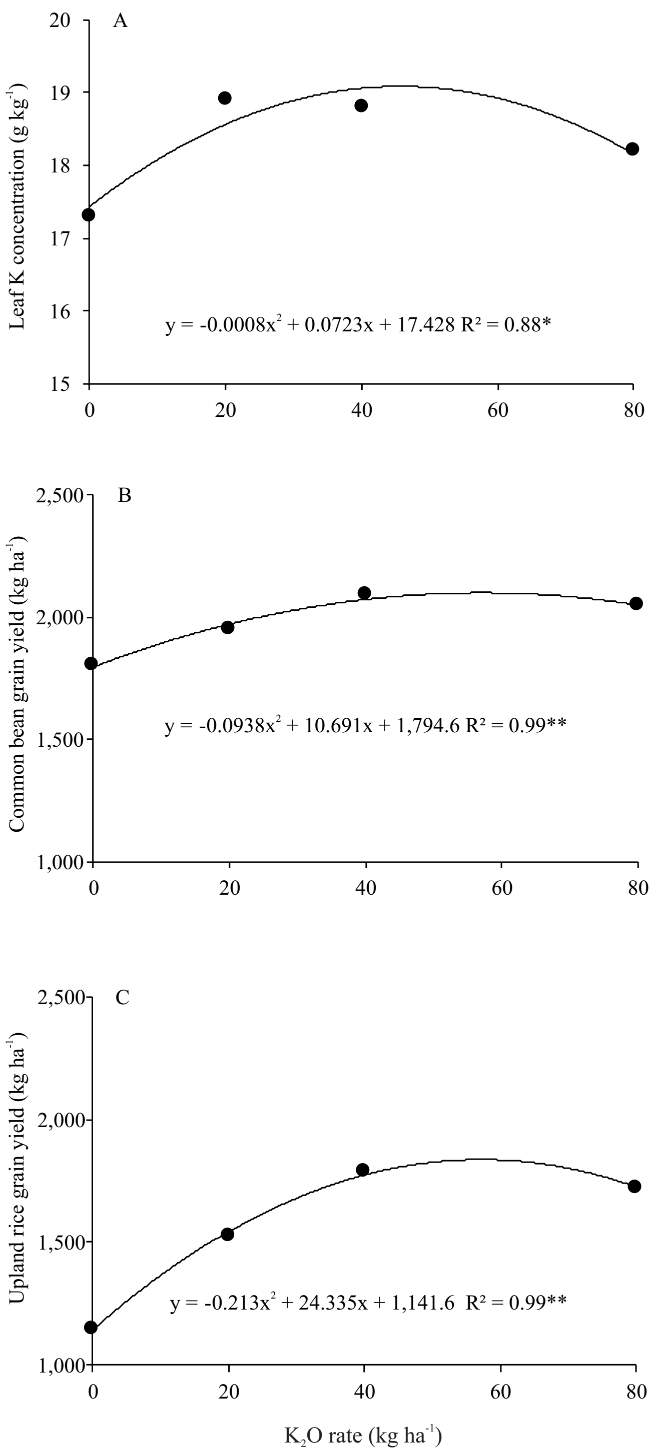

Figure 4. Effect of rates of K fertilizer applied by surface broadcasting on leaf K concentration (A) and grain yield (B) of the common bean (*Phaseolus vulgaris*) crop, as well as grain yield of upland rice (*Oryza sativa*) (C), as affected by the average of three K sources. * and **Significant by the t-test, at 5 and 1% probability, respectively.

40 kg ha^{-1} K_2O recommended for the crop under the conditions of the present study – low K availability in the soil (Raij et al., 1997). In a soil with a high exchangeable K content in Mozambique, Carvalho et al. (2018) observed high common bean grain yields at the rates of 43 and 107 kg ha^{-1} K_2O in two consecutive growing seasons. In the present study, however, regardless of the applied rate, the K3 source increased grain yields, which were up to 6.9% higher than those obtained with KCl (Table 1). In addition, the K3 source at the rates of 20 and 80 kg ha^{-1} K_2O provided grain yields 18 and 21% higher than those of the control, surpassing the other sources (Table 2). When averaging all rates, K3 was 4.5 times more efficient than KCl and 2.5 times more efficient than K2 in increasing the AEI. There was also an increase in common bean yield of 9.4 kg ha^{-1} with each added kilogram of K_2O from K3, but only of 4.8 and 3.5 kg ha^{-1} with each kilogram of K_2O in the form of K2 or KCl, respectively.

Upland rice grain yield was affected only by K rates, with the maximum value observed at an estimated rate of 57 kg ha^{-1} K_2O (Table 1 and Figure 4 C). At the rates of 40 and 80 kg ha^{-1} K_2O, the K3 increased grain yield by 66 and 65% compared with the control, resulting in AEI values 20 and 39% higher than those obtained with KCl (Table 2). Regarding the MP, K2 showed a value higher than that of KCl only at the rate of 20 kg ha^{-1} K_2O, whereas K3 had values that stood out from those of the other K sources at the rates of 40 and 80 kg ha^{-1} K_2O. It should be noted that the low grain yields and levels of response to the treatments of the upland rice crop may have been due to its late sowing date.

The findings of the present study are indicative that the ground K2 and K3 sources efficiently supplied K to the soybean, corn, common bean, and upland rice crops, with equivalent and even better agronomic results than the KCl standard source. Therefore, K2 and K3 can also be interesting alternatives for organic farming, in which the use of KCl is not allowed, and for crops to which high Cl levels may be harmful (Martins et al., 2008; Ciceri et al., 2017; Dias et al., 2018). However, despite their positive effects, two main aspects of K2 and K3 products still require attention: the relatively low K_2O concentrations in both sources compared with that of KCl, which may be a barrier for their use in regions far from the fertilizer production site due to transport and application costs; and the 7.53% Na_2O content in K2, which may be harmful to crops because the continuous application of high K2 rates can increase soil Na content (Martins et al., 2008; Shrivastava & Kumar, 2015; Machado, 2016). Another factor that can greatly interfere in the choice of K fertilizers, especially of KCl, is the variation in their prices, as well as in the prices of the crops. Therefore, further studies, mainly in long-term field experiments, are necessary on these topics in order to extrapolate the findings of the present work, which was performed only in one year for each crop and in a single soil.

Conclusions

1. The alternative potassium sources phonolite rock (K2) and alkaline K-silicate rock (K3), ground and broadcast, are able to supply K to the soybean (*Glycine max*), corn (*Zea mays*), and common bean (*Phaseolus vulgaris*) crops, increasing the leaf concentration of this nutrient similarly to KCl.
2. When broadcast, K2 and K3 increase crop grain yields similarly to KCl.
3. The efficiency of alternative K sources varies depending on the used K rate and fertilized grain crop.
4. K3 is a viable K source to be applied by broadcasting at the recommended K rate for the soybean, corn, common bean, and upland rice (*Oryza sativa*) crops, while K2 is only not suitable for upland rice.

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