

Efficiency and residual effect of alternative potassium sources in grain crops








Abstract – The objective of this work was to evaluate the efficiency and the residual effects of both molten and ground alkaline potassium-silicate rocks (K1) and of ground phonolite rock (K2), as sources of potassium, compared with the traditional source (KCl), in grain crop successions. Two experiments – one with the succession soybean-wheat-corn and the other with the succession corn-millet-soybean – were conducted on a Typic Haplorthox in a randomized complete block design with four replicates. The treatments consisted of three sources (KCl, K1, and K2) and four rates of K (corresponding to 0, 0.5, 1.0, and 2.0 times the recommended rates for soybean and corn). The used sources did not affect leaf K concentration in soybean, but KCl and K2 similarly increased leaf K concentration in corn. Regardless of the source, K application increased the yield of all crops. The K1 and K2 sources present agronomic efficiencies equivalent to that of KCl. K1 and K2 show a more pronounced residual effect than KCl, especially on crops grown approximately one year after their application and under K rates above those recommended for the crops.

Index terms: agronomic efficiency, phonolite, potassium fertilization, residual effect, rock dust, silicon.

Eficiência e efeito residual de fontes alternativas de potássio em culturas graníferas

Resumo – O objetivo deste trabalho foi avaliar a eficiência e o efeito residual de rochas potássico-silicáticas alcalinas fundidas e moídas (K1) e de rocha de fonolito moída (K2), como fontes alternativas de potássio, em comparação à fonte tradicional (KCl), em sucessões de culturas graníferas. Dois experimentos – um com sucessão soja-trigo-milho e outro com sucessão milho-milheto-soja – foram conduzidos em Latossolo Vermelho argiloso, em delineamento de blocos ao acaso, com quatro repetições. Os tratamentos consistiram de três fontes (KCl, K1 e K2) e quatro doses de K (correspondentes a 0, 0,5, 1,0 e 2,0 vezes a dose recomendada para a cultura da soja e do milho). As fontes não afetaram a concentração de K nas folhas da soja, mas KCl e K2 aumentaram de forma semelhante a concentração de K nas folhas do milho. Independentemente da fonte, a aplicação de K aumentou as produtividades de todas as culturas. As fontes alternativas K1 e K2 apresentam eficiências agrônomicas equivalentes à do KCl. K1 e K2 têm efeitos residuais mais pronunciados que o do KCl, especialmente em cultivos realizados aproximadamente um ano após suas aplicações e com doses de K acima das recomendadas para as culturas.

Termos para indexação: eficiência agrônômica, fonolito, adubação potássica, efeito residual, pó de rocha, silício.


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Introduction

Potassium is essential for plant nutrition, being the second most required nutrient by most crops and the most abundant cation in the cytoplasm, contributing to maintaining the osmotic potential of plant cells (Malavolta et al., 1997; Hasanuzzaman et al., 2018). The element plays a role in activating several enzymatic systems, many of which are involved in photosynthesis, respiration, protein synthesis, and photoassimilate transport by the phloem (Hasanuzzaman, et al., 2018), affecting grain yield and quality (Mancuso et al., 2014; Lima et al., 2017; Fan et al., 2021).

The demands for K_2O in Brazilian agriculture reached 6.7 Tg in 2019 (FAO, 2021). However, the Brazilian production of K_2O was only of 240,000 Mg (400,000 Mg KCl), which corresponds to less than 4.0% of the domestic agricultural demand, leading Brazil to spend more than USD 3.0 billion with K_2O imports (Oliveira, 2015; Kulaif & Góes, 2016; Manning, 2018; Sipert et al., 2020; FAO, 2021). Overall, more than 95% of K is used as fertilizer – with 90% as KCl, making it the main K_2O source used in the domestic market (Martins et al., 2008; Sipert et al., 2020). The high import volume of KCl negatively affects Brazilian trade balance and shows the need of negotiating with a restricted group of supplier countries, emphasizing the importance of exploring alternatives to this fertilizer (Mancuso et al., 2014; Oliveira, 2015).

In this scenario, a natural fertilization technique called “rocks for crops” stands out. It consists of directly using, in agriculture, finely ground rock or rock dust, with a slow decomposition and gradual release (Van Straaten, 2002; Martins et al., 2008). Its dynamic reaction with the soil is directly influenced by the system’s mineralogy, grain size, and water flow (Martins et al., 2008, 2015; Manning, 2018). Because of Brazil’s great geological diversity, rock dust may help to reduce KCl imports and, consequently, production costs, optimizing local agriculture (Kulaif & Góes, 2016; Santos et al., 2016; Nogueira et al., 2021).

Mineralogy is one of the most important factors in the selection of such materials. Minerals containing alkali feldspars and feldspathoids, for example, are considered potential K sources for manufacturing fertilizers to be applied directly to the soil, as is the case for the alkaline K-silicate phonolite rock (Martins et al., 2008; Teixeira et al., 2015; Manning, 2018; Nogueira et al., 2021).

According to Teixeira et al. (2012), phonolite rocks have volcanic origin and are formed by SiO_4 tetrahedral groups bound by cations whose main mineralogical constituents are microcline, orthoclase (alkali feldspar), sanidine (alkali feldspar), and nepheline (feldspathoid), which all have K feldspar as their main constituent. Phonolite contains approximately 7.0–8.0% (w/w) K_2O , in addition to other nutrients and elements beneficial to plants (Teixeira et al., 2012, 2015; Tavares et al., 2018). Other products produced from molten and ground alkaline K-silicate rocks, also called thermopotash, have also been studied as alternative K sources in Brazil (Kulaif & Góes, 2016; Machado, 2016).

Some researches in the country have shown the feasibility of using alternative K sources in different crops. In a pot experiment, Santos et al. (2016) verified that acidified verdete and calcinated verdete increased K uptake and dry matter yield similarly to KCl, in both corn (*Zea mays* L.) and grass (*Panicum maximum* Jacq. cultivar Mombaça) grown in succession; however, verdete rock in natura had a significative residual effect only on the second crop (grass). Nogueira et al. (2021) reported the agronomic efficiency of nepheline syenite and phonolite as alternative K sources for corn. In field conditions, Pádua (2012) evaluated the agronomic feasibility of using rock dusts (amphibolite, mica schist, and phonolite) as K sources for sunflower (*Helianthus annuus* L.), as well as their residual effects on the following soybean [*Glycine max* (L.) Merr.] crop, finding positive results for rock dusts, when compared with KCl. Mancuso et al. (2014) assessed the use of ground phonolite in arabica coffee (*Coffea arabica* L.) and observed an increased coffee bean yield, with an efficiency similar to that of KCl at the K rate recommended for the crop.

In addition to K, alkaline K-silicate rocks may also provide Si for plants (Mancuso et al., 2014; Teixeira et al., 2015). Although Si is not considered physiologically essential for plant growth, the deposition of Si as amorphous silica on the cell wall keeps plants more upright, besides causing stimulating effects, enhancing photosynthetic capacity, and protecting against and/or reducing biotic and abiotic stresses (Guntzer et al., 2012; Savvas & Ntatsi, 2015). According to Frew et al. (2018), Si alters defense enzyme and metabolite expression and increases phytolith deposition and antioxidant enzyme activity.

Evidence also shows that Si plays roles in plant primary metabolism, growth, and development.

The direct application of alkaline K-silicate ground rocks in natura or after melting at high temperatures may result in a satisfactory supply of K to grain crops and, depending on the used rate, may also produce residual effects for subsequent crops due to the gradual release of K (Martins et al., 2008; Santos et al., 2016; Nogueira et al., 2021); however, results in field conditions are still scarce.

The objective of this work was to evaluate the efficiency and the residual effects of both molten and ground alkaline potassium-silicate rocks (K1) and of ground phonolite rock (K2), as sources of potassium, compared with the traditional source (KCl), in grain crop successions.

Materials and Methods

Two field experiments were conducted in the municipality of Botucatu, in the state of São Paulo, Brazil (22°51'S, 48°26'W, at an altitude of 740 m), during the growing seasons of summer 2007/2008, winter 2008, and summer 2008/2009. Experiment I evaluated the annual effects of K fertilizer sources and rates applied to soybean in the summer of 2007/2008, as well as the residual effects on wheat (*Triticum aestivum* L.) in the winter of 2008 and on corn in the summer of 2008/2009. Experiment II assessed the annual effect of K fertilizer sources and rates when applied to corn in the summer of 2007/2008, besides the residual effects on millet [*Pennisetum glaucum* (L.) R. Br.] in the winter season of 2008 and on soybean in the summer of 2008/2009. Crops were cultivated in succession in both experiments.

According to Köppen's classification, the predominant climate in the experimental region is Cwa. The climatic data recorded during the experiment are shown in Figure 1. The soil for both areas was classified as a clay-textured Latossolo Vermelho distroférico, i.e., a Typic Haplorthox (Santos et al., 2018). The chemical characterization (Raij et al., 2001) of the topsoil (0.0–0.20 m) showed, for experiment I: 4.8 pH (CaCl₂); 23 g dm⁻³ organic matter; 19 mg dm⁻³ P_{resin}; 1.4, 23, 13, and 55 mmol_c dm⁻³ exchangeable K, Ca, Mg, and H+Al, respectively; and base saturation (BS) of 41%. For experiment II, the values found were: 4.6 pH (CaCl₂); 37 g dm⁻³ organic matter; 21 mg dm⁻³

P_{resin}; 1.2, 28, 15, and 62 mmol_c dm⁻³ exchangeable K, Ca, Mg, and H+Al, respectively; and BS of 42%.

Both experiments were carried out in a randomized complete block design with a 3×4 factorial arrangement and four replicates. The treatments consisted of three sources and of four rates of K. Each experimental plot comprised 30 m² (5 rows that were 6 m long and 5 m wide); the central rows were evaluated, excluding 0.5 m at the end of each row.

The used K sources were: KCl, standard source (58% K₂O); K1, K fertilizer made from molten and ground alkaline K-silicate rocks, containing 11.0% K₂O, 51.7% SiO₂, 16.8% CaO, 0.18% P₂O₅, 16% Al₂O₃, and 0.38% Na₂O; and K2, ground in natura phonolite rock, containing 8.42% K₂O, 52.5% SiO₂, 1.58% CaO, 0.05% P₂O₅, 20.7% Al₂O₃, and 7.53% Na₂O. The K1 source was produced by melting alkaline K-silicate rocks at 1,500°C, with further fine grinding after cooling, whereas K2 was produced by fine grinding the phonolite rock; both sources were passed completely (100%) through a 0.074 mm sieve (ABNT, 1997). The two alternative K sources were obtained from the municipality of Poços de Caldas, in the state of Minas Gerais, Brazil.

The four applied rates were: 0, 25, 50, and 100 kg ha⁻¹ K₂O for soybean in experiment I; and 0, 50, 100, and 200 kg ha⁻¹ K₂O for corn in experiment II, equivalent to 0, 0.5, 1.0, and 2.0 times the recommended K₂O rates for these crops (Raij et al., 1997). Therefore, the rates of each source applied were: in experiment I, 43, 86, and 172 kg ha⁻¹ KCl; 227, 455, and 909 kg ha⁻¹ K1; and 297, 594, and 1,188 kg ha⁻¹ K2; and, in experiment

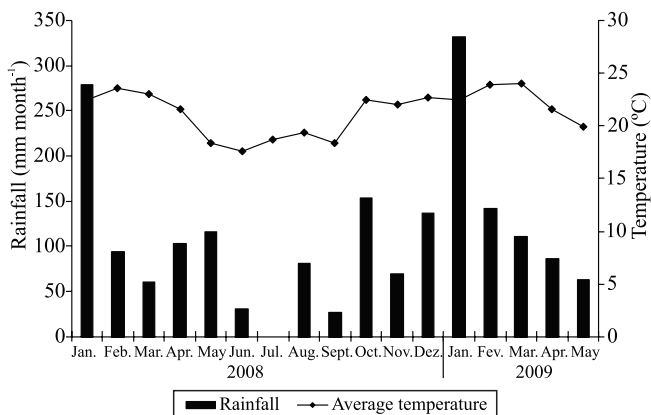


Figure 1. Monthly rainfall and average temperatures, from January 2008 to May 2009, in the experimental area located in the municipality of Botucatu, in the state of São Paulo, Brazil.

II, 86, 172, and 345 kg ha⁻¹ KCl; 455, 909, and 1,818 kg ha⁻¹ K1; and 594, 1,188, and 2,375 kg ha⁻¹ K2.

In both experiments, soybean was sown 0.45 m apart, using 22 seed per meter of cultivar Embrapa 48, and 50 kg ha⁻¹ P₂O₅ (single superphosphate) were applied as sowing fertilization. Corn was sown 0.9 m apart, using 6 seed per meter of the 2B587 simple hybrid (Dow Agrosiences, Midland, MI, USA), and 30 kg ha⁻¹ N (urea) and 60 kg ha⁻¹ P₂O₅ (single superphosphate) were applied as sowing fertilization, plus 90 kg ha⁻¹ N (urea) as topdressing in stage V₆ (Raij et al., 1997). For the winter crops, in experiments I and II, respectively, the CD 107 wheat cultivar and the millet BN-2 cultivar were sown 0.17 m apart, with 50 seed per meter, without any fertilization. In both experiments, sown seed and fertilizers were distributed mechanically, under a no-tillage system. All seed were treated with carboxin + thiram (50 + 50 g a.i. 100 kg⁻¹ seed). In experiment I, soybean, wheat, and corn were sown on 1/14/2008, 5/12/2008, and 1/15/2009, respectively. In experiment II, corn, millet, and soybean were sown on 1/10/2008, 5/12/2008, and 1/14/2009, respectively. In the soybean and corn crops, in experiments I and II, respectively, the treatments were applied three days after emergence, in a single rate and in a continuous fillet, 5.0 cm from the plant rows.

The diagnostic leaves of soybean (R2, full flowering) and corn (VT, tasseling) were sampled according to the methods described by Raij et al. (1997), whereas leaf K and Si concentrations were assessed as in Malavolta et al. (1997) and Korndörfer et al. (2004), respectively. In experiment I, grain yield was evaluated in the wheat crop, and, in experiment II, shoot dry matter yield was analyzed, at the flowering stage, in millet. The grain yield data were corrected for a water content of 130 g kg⁻¹ (wet basis).

Data for each crop were separately subjected to the analysis of variance. The K source means were compared using the t-test (LSD), at 5% probability. The K rate effects were evaluated by the regression analysis using the SISVAR statistical software package (Ferreira, 2014).

Regardless of whether an interaction occurred between the sources and rates of the K fertilizer, the agronomic efficiency index (AEI) was calculated as the percentage ratio between yields resulting from the K sources applied at the same rate. The crop yield obtained in the treatment with no K application

was subtracted from both yields, as follows: AEI (%) = [(Y₂ - Y₁) / (Y₃ - Y₁)] × 100, where Y₁ is crop yield in the zero-K control treatment, obtained by the average of 12 zero-K control plots; Y₂ is crop yield with an alternative source (K1 or K2) at the corresponding rate; and Y₃ is crop yield with the traditional source (KCl) at the corresponding rate.

Results and Discussion

In experiment I, with the soybean/wheat/corn crop rotation, the K sources and rates applied at soybean emergence did not affect K concentration in crop leaves (Table 1). The reduced effect of K fertilizer rates on K concentration in soybean leaves may be related to the average K concentration in the soil (Raij et al., 1997), the release of K by straw mineralization (Rosolem et al., 2003), and the reduced K uptake by the crop up to the flowering stage (Gaspar et al., 2017). For the K1 and K2 sources, the leaf K concentrations, considering the average of the rates, were below the lower limit of 17–25 g kg⁻¹ reported by Raij et al. (1997) as suitable for the soybean crop (Table 1). Machado (2016), in a study on arabica coffee, did not observe any effect of the application of ground phonolite and thermopotash on leaf K concentration. In corn grown in succession to soybean and wheat crops, K concentration in leaves was affected only by K rates, not sources (Table 1). Applying increasing K rates to soybean in the 2007/2008 growing season led to a linear residual effect on K concentration in the leaves of corn cultivated in 2008/2009 (Figure 2B); however, except for control, the leaf K concentrations for both treatments were within the range of 17–35 g kg⁻¹ considered suitable for the crop (Raij et al., 1997). According to Bender et al. (2013), for grain yields of ~12,000 kg ha⁻¹, the uptake of the corn crop is of ~167 kg ha⁻¹ K; 75% of that amount is taken up until the flowering stage.

An interaction between K sources and rates was found between the studied factors for Si concentration in soybean (Table 1). The increasing rates of the KCl fertilizer slightly increased Si concentration (Figure 2 A). In addition, at the rate of 50 kg ha⁻¹ K₂O, K2 resulted in a higher Si concentration, whereas, at the rates of 25 and 100 kg ha⁻¹ K₂O, KCl promoted the highest concentrations. Although large amounts of SiO₂ were applied through the K1 (51.7%) and K2 (52.5%) sources, they were not enough to affect

Si concentration in soybean leaves. However, when compared with KCl, the residual effect of K1 and K2 on Si concentrations in corn leaves was higher (Table 1). Regardless of the used K sources, Si concentrations in corn leaves were increased by the residual effect of K fertilizer application (Figure 2 C).

Soybean grain yield was affected only by the main factors (Table 1). When applied at emergence at the estimated rate of approximately 80 kg ha⁻¹ K₂O, K1 provided a higher grain yield than K2 and KCl (Table 1 and Figure 2 D). The highest grain yields were found for the wheat crop grown in succession to soybean due to the residual effects of sources K2 and KCl (Table 1); however, the highest wheat grain yield was obtained with the estimated rate of 60 kg ha⁻¹ K₂O applied at soybean crop emergence, regardless of the used source (Figure 2 D). A residual effect of K fertilizer rates was observed on corn yield (Table 1), with increases up to

the estimated rate of 65 kg ha⁻¹ K₂O, also regardless of the sources (Figure 2 D).

In experiment II, with the corn/millet/soybean crop rotation, K and Si concentrations in corn leaves were affected by the interactions between the K sources and rates applied just after seedling emergence (Table 1). Both alternative K sources increased the nutrient concentrations in corn leaves, with the highest values found at the highest rates (Figure 3 A). Furthermore, at the recommended rate of 100 kg ha⁻¹ K₂O, K2 provided higher K concentrations in corn leaves than the other sources, whereas, at the highest rate of 200 kg ha⁻¹ K₂O, greater values were observed for KCl and K2. A greater K concentration in corn leaves under increasing K rates was also reported by Nogueira et al. (2021) when using nepheline syenite, phonolite, and KCl in soils containing a very low concentration of K, which indicates that, not only the used source but also K availability can affect fertilization efficiency. At the

Table 1. Potassium and silicon concentrations in soybean (*Glycine max*) and corn (*Zea mays*) leaves, as well as grain yields of soybean, wheat (*Triticum aestivum*), and corn, and shoot dry matter yield of millet (*Pennisetum glaucum*), as affected by sources and rates of K fertilizer applied to the first crop in two experiments with different crop successions⁽¹⁾.

Variable	K source			Source of variation (P < F)			CV (%)
	K1 ⁽²⁾	K2 ⁽³⁾	KCl	Source (S)	Rate (D)	S × D	
Experiment I – K fertilizers applied at soybean emergence (soybean/wheat/corn rotation)							
Soybean							
Leaf K concentration (g kg ⁻¹)	16	16	17	0.621	0.187	0.225	8.6
Leaf Si concentration (g kg ⁻¹)	2.4	3.0	3.3	<0.001	<0.001	<0.001	17.6
Grain yield (kg ha ⁻¹)	2,624a	2,392 b	2,455b	0.011	0.008	0.192	8.5
Wheat – residual effect							
Grain yield (kg ha ⁻¹)	2,265b	2,450a	2,535a	0.001	<0.001	0.124	7.9
Corn – residual effect							
Leaf K concentration (g kg ⁻¹)	17	17	17	0.185	<0.001	0.595	6.4
Leaf Si concentration (g kg ⁻¹)	7.6a	7.9a	7.0b	0.009	<0.001	0.188	9.6
Grain yield (kg ha ⁻¹)	8,209	8,103	8,133	0.886	0.049	0.486	7.7
Experiment II – K fertilizers applied at corn emergence (corn/millet/soybean rotation)							
Corn							
Leaf K concentration (g kg ⁻¹)	24	26	26	<0.001	<0.001	<0.001	3.5
Leaf Si concentration (g kg ⁻¹)	24	26	26	0.003	0.007	0.001	4.6
Grain yield (kg ha ⁻¹)	8,106	7,971	8,152	0.590	<0.001	0.057	6.4
Millet – residual effect							
Shoot dry matter yield (kg ha ⁻¹)	3,772	3,817	3,642	0.351	<0.001	0.052	9.3
Soybean – residual effect							
Leaf K concentration (g kg ⁻¹)	20	19	20	0.962	0.380	0.538	5.7
Leaf Si concentration (g kg ⁻¹)	2.1	2.0	2.0	0.155	0.324	0.822	7.0
Grain yield (kg ha ⁻¹)	2,593	2,570	2,456	0.464	<0.001	0.822	7.7

⁽¹⁾Means followed by equal letters in the rows do not differ by the LSD test, at 5% probability. ⁽²⁾K1, molten and ground alkaline K-silicate rocks. ⁽³⁾K2, ground phonolite rock.

recommended rate, no significant differences were found between the used sources for Si concentration in corn leaves, and, at the rates of 50 and 200 kg ha⁻¹ K₂O, K2 and KCl performed better than K1 (Figure 3 B), indicating an efficient short-term release of Si when using K2.

The highest Si concentrations were obtained with the estimated rates of 130, 145, and 170 kg ha⁻¹ K₂O, respectively, for K1, K2, and KCl (Figure 3 B). However, leaf K and Si concentrations in soybean

cultivated after corn and millet were unaffected by the residual effects of the application of K fertilizers, regardless of the used rate (Table 1). Despite the large amounts of Si applied via K1 and K2 (soybean in experiment I and corn in experiment II, respectively), the availability of the element did not exceed that provided by KCl, which is not a Si source. In the case of soybean, even in long-term assessments, alternative fertilizers produced from alkaline K-silicate rocks (K1 and K2) did not affect Si concentrations in the

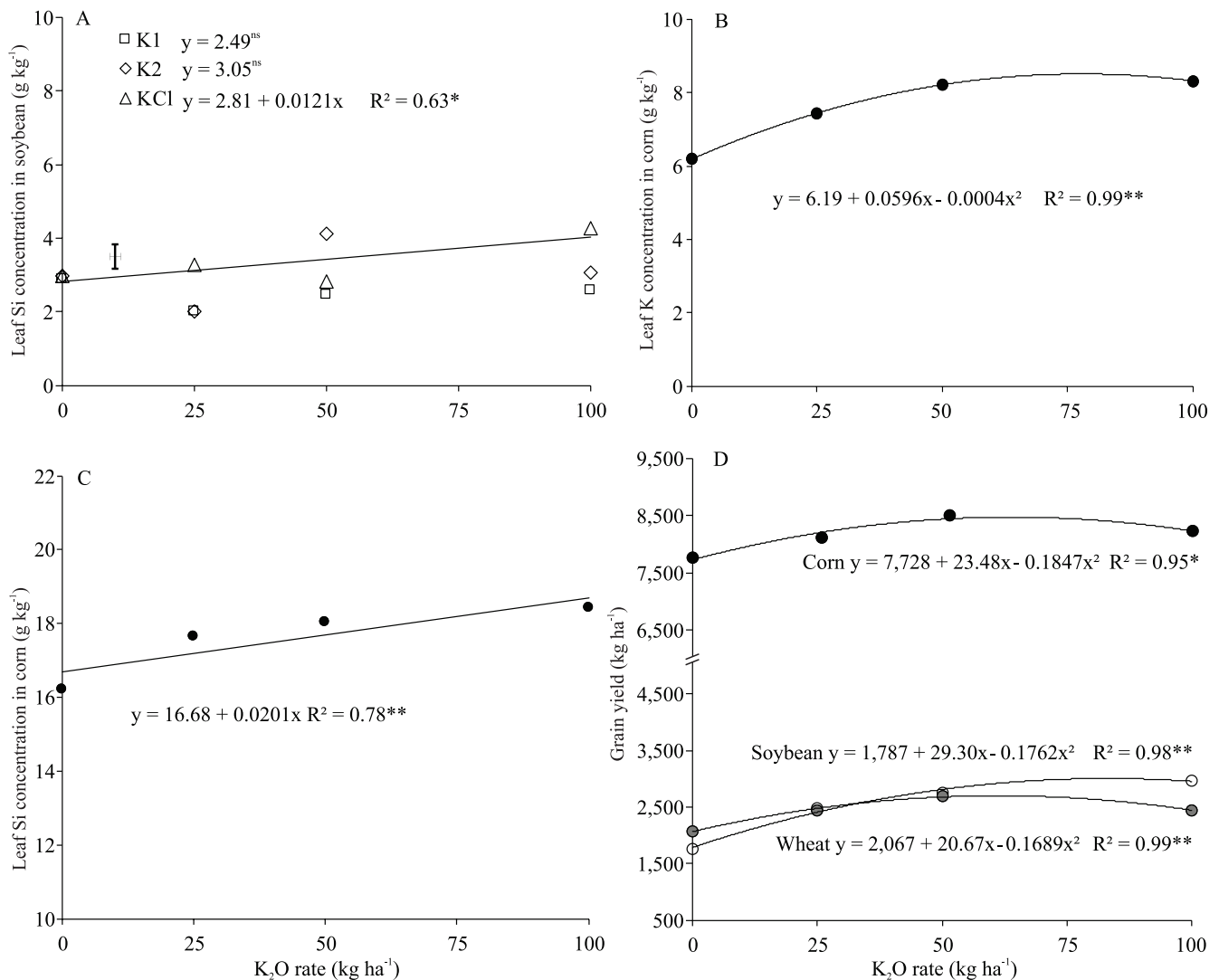


Figure 2. Effect of K fertilizer sources and rates on leaf Si concentration in soybean (*Glycine max*) (A), as well as leaf K (B) and Si (C) concentrations in corn (*Zea mays*), and grain yield of soybean, wheat (*Triticum aestivum*), and corn (D) in experiment I. K fertilizers were applied at soybean emergence in the soybean/wheat/corn rotation. Circles represent average of three K sources. K1, molten and ground alkaline K-silicate rocks; and K2, ground phonolite rock. * and **Significant by the t-test, at 5 and 1% probability, respectively. Vertical bars indicate the least significant difference to separate K sources in a same K rate by the LSD test, at 5% probability.

leaves of the crop (residual effect in experiment II), which, unlike corn, is not considered to accumulate Si (Guntzer et al., 2012). Machado (2016) and Mancuso et al. (2014) also found similar results for K and Si leaf concentrations in *Brachiaria decumbens* Stapf and arabica coffee after phonolite, thermopotash, and KCl application.

Regardless of the fertilizer source, corn grain yield increased linearly with increasing K rates (Table 1 and Figure 3 C). For millet grown in succession to the corn crop, shoot dry matter yield was also influenced only by the residual effect of the K fertilizers, increasing up to the highest K rate (Table 1 and Figure 3 C). Likewise, the grain yield of soybean grown in succession to millet was affected only by the K fertilizer rates (Table 1). The residual effect of K increased soybean grain yield up to the estimated rate of 130 kg ha⁻¹ K₂O (Figure 3 C).

Potassium fertilization affected the yield of both crops to which the fertilizer was directly applied, increasing corn grain yield to a higher K rate (linear effect) in experiment II, when compared with soybean in experiment I (Figures 2 D and 3 C). This result was expected due to the higher and earlier K demand of corn (Bender et al., 2013; Gaspar et al., 2017) – in soils with a low exchangeable K concentration of 0.8–1.5 mmol_c dm⁻³, the recommended rate of K fertilizer is approximately 100 kg ha⁻¹ K₂O for corn yielding 7.0–10 Mg ha⁻¹ and 50 kg ha⁻¹ K₂O for soybean yielding 2.0–3.0 Mg ha⁻¹ (Raij et al., 1997). Moreover, the slightly lower exchangeable K concentration in experiment II explains the higher response of corn to the application of K fertilizers immediately after seedling emergence. Lacerda et al. (2015) also reported a higher corn susceptibility to fertilization, in comparison with soybean, even under suitable soil fertility conditions. It should be noted that the soybean sowing date in January was not the most adequate, which may have limited crop grain yield and response to the treatments.

The countless roles of K have been well documented in the literature, showing it is a fundamental element for plant metabolism, which explains its high demand by most species (Malavolta et al., 1997, Raij et al., 1997; Hasanuzzaman et al., 2018). In the present study, regardless of the sources used in both experiments, the residual effect of the applied K rates was positive on the grain yield of the two crops cultivated in succession (Table 1 and Figures 2 D and 3 C).

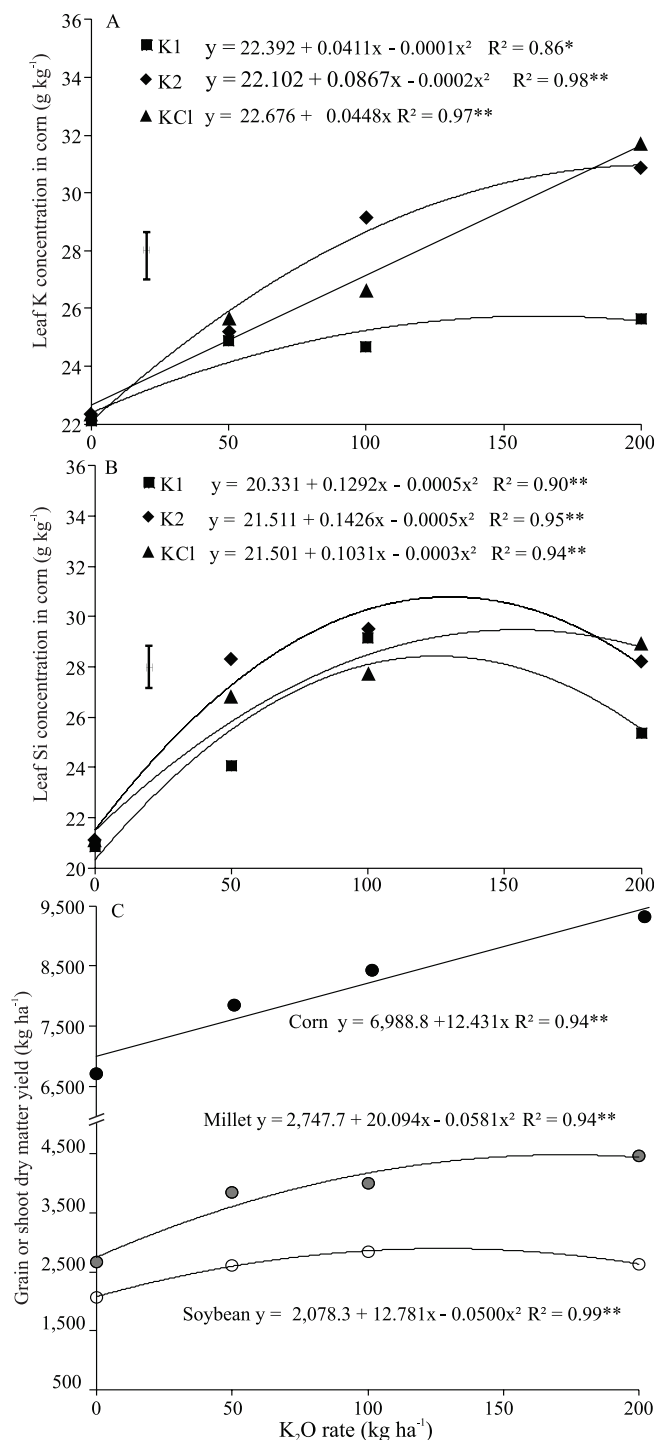


Figure 3. Effect of K fertilizer sources and rates on leaf K (A) and Si (B) concentrations in corn (*Zea mays*) and shoot dry matter yield of millet, as well as grain yields of corn and soybean (*Glycine max*) (C), in experiment II. K fertilizers were applied at corn emergence in the corn/millet/soybean rotation. Circles represent average of three K sources. K1, molten and ground alkaline K-silicate rocks; and K2, ground phonolite rock. * and **Significant by the t-test, at 5 and 1% probability, respectively. Vertical bars indicate the least significant difference to separate K sources in a same K rate by the LSD test, at 5% probability.

Although the interaction of sources and rates was not significant (Table 1), K1 promoted a greater soybean grain yield than K2 or KCl in experiment I, leading to a higher AEI, regardless of the applied K rates (Table 2). For corn in experiment II, a higher AEI was observed for K2 at 50 and 100 kg ha⁻¹ K₂O, whereas K1 was more efficient at 200 kg ha⁻¹ K₂O. When compared with KCl, a short-term agronomic efficiency was found for ground phonolite rocks in other crops, showing both positive and negative plant responses (Pádua, 2012; Nogueira et al., 2021).

In experiment I, KCl promoted a higher grain yield for the wheat crop grown in succession to

soybean at nearly all K rates (Table 2). The K1 and K2 alternative sources led to greater grain yields and AEI in comparison with the KCl traditionally used for the corn crop grown after wheat, especially at the highest K₂O rate and particularly K1. In experiment II, the increase of millet shoot dry matter yield indicated a greater residual effect of K1 and K2, but only at the rates of 50 and 100 kg ha⁻¹ K₂O (Table 2). For the soybean crop grown after millet, the AEIs of K1 and K2 were similar and both were higher than that of KCl, mainly at the rates of 100 and 200 kg ha⁻¹ K₂O. Pádua (2012) also observed that the application of phonolite rocks, compared with KCl, showed a greater agronomic

Table 2. Increased soybean (*Glycine max*), corn (*Zea mays*), wheat (*Triticum aestivum*), and millet (*Pennisetum glaucum*) yields as affected by K sources and rates of fertilizer applied to the first crop of each experiment, as well as the agronomic efficiency index (AEI) of three rates of K1 and K2 compared with KCl.

K ₂ O rate (kg ha ⁻¹)	Increased yield (kg ha ⁻¹) ⁽¹⁾			AEI (%) ⁽²⁾	
	K1 ⁽³⁾	K2 ⁽⁴⁾	KCl	K1 ⁽³⁾	K2 ⁽⁴⁾
Experiment I – K fertilizers applied at soybean emergence (soybean/wheat/corn rotation)					
Soybean					
25	787	757	651	111	105
50	1,298	839	846	144	91
100	1,445	1,050	1,126	122	88
Mean	-	-	-	125	95
Wheat – residual effect					
25	104	372	639	16	58
50	509	605	751	68	81
100	137	511	441	31	116
Mean	-	-	-	38	85
Corn – residual effect					
25	271	74	702	39	11
50	634	973	628	101	155
100	887	320	168	528	190
Mean	-	-	-	223	119
Experiment II – K fertilizers applied at corn emergence (corn/millet/soybean rotation)					
Corn					
50	907	1,667	1,134	80	147
100	1,556	2,002	1,830	85	110
200	2,814	2,097	2,582	109	81
Mean	-	-	-	91	113
Millet – residual effect					
50	1,047	1,599	898	117	178
100	1,677	1,304	1,043	161	125
200	1,725	1,728	1,988	87	87
Mean	-	-	-	122	130
Soybean – residual effect					
50	585	481	534	110	90
100	771	860	686	112	125
200	724	648	313	232	207
Mean	-	-	-	151	141

⁽¹⁾Increased yield relative to the mean yield in the zero-K control. ⁽²⁾Agronomic efficiency of the K1 and K2 alternative sources relative to the traditional source (KCl). ⁽³⁾K1, molten and ground alkaline K-silicate rocks. ⁽⁴⁾K2, ground phonolite rock.

feasibility in the sunflower crop and a residual effect on the soybean crop. These results are indicative that less soluble slow-releasing sources, presenting a greater residual effect than KCl, are important for supplying the K demand of the subsequent crops in production systems. In a study on the effect of the application of K-silicate sources containing K on soil chemical attributes, Martins et al. (2015) reported increased K levels as a function of the applied rates after 45 days of incubation by the chemical fractionation of K in the soil (exchangeable fraction – Mehlich 1). For KCl, with the high solubility and rapid release of K, the residual effect may also be related to millet use as a winter crop in experiment II (Table 2). Millet is highly efficient in nutrient recycling, with a high capacity to extract leached nutrients, mainly K, from the soil subsurface layers and to release them again in the straw (Costa et al., 2016), which decreased the residual AEI values in experiment II.

However, some cautions must be taken regarding the continuous use and high rates of K₂, especially due to its high content of Na (Machado, 2016), an element that, when in excess, can cause damage in seedlings via salt stress (Shrivastava & Kumar, 2015). Moreover, since high rates of K₁ and K₂ are necessary to meet the K requirements of the crop because of their lower K₂O concentrations in comparison with those of KCl, transportation costs could be a barrier to the use of both alternative sources in regions distant from the fertilizer production site (Martins et al., 2008).

Conclusions

1. Potassium fertilization, regardless of the used sources, increases the yield of all evaluated crops.

2. The alternative K sources – molten and ground alkaline K-silicate rocks and ground phonolite rock – present suitable agronomic efficiencies equivalent to that reached by the traditional KCl source, besides causing residual effects greater than those of KCl, especially on crops grown about one year after their application and under higher K rates than those recommended for the crops.

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