http://doi.org/10.1590/1678-992X-2021-0266

ISSN 1678-992X

Scientia Agricola

Research Article

Do enhanced efficiency potassium sources increase maize yield in soil with high potassium content?

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Edited by: Mohammad Bagher Hassanpouraghdam

Received November 16, 2021

Accepted February 02, 2022

ABSTRACT: Enhanced efficiency potassium fertilizers can be a management tool that is crucial to crop sustainability in maize (*Zea mays* L.). However, there is a need for studies aimed at validating the use of these fertilizers in different production environments. This study aimed to evaluate the performance of maize under sources and rates of K through conventional and enhanced efficiency fertilizers in soil with high available K content. The experiment was carried out for two years in an Oxisol (605 g kg^{-1} of clay) with high K content (6.7 $mmol_c$ dm^{-3}). Three sources were used, one conventional (KCl), one obtained by additives sprayed on the fertilizer surface (KCl-C), and one obtained by compacting KCl powder and adding additives (KCl-CC), associated with three K_2O rates as top-dressing (50, 100, 150 kg ha^{-1}) and a control without K_2O. In all treatments, 48 kg ha^{-1} of K_2O was applied in the sowing furrow. In the first year, maize yield increased linearly for both the KCl and KCl-C sources. The maximum yield (7,967 kg ha^{-1}) for the KCl-CC was obtained at 88 kg ha^{-1}. In the second year, the maximum yields for the KCl (7,553 kg ha^{-1}) and KCl-C (8,166 kg ha^{-1}) were obtained with 20 and 67 kg ha^{-1} K_2O, respectively, while for the KCl-CC maize yield did not change. Enhanced efficiency K sources promote increases in maize yield ranging from 4.3 % to 7.1 %. Top-dressing K fertilization in high-fertility soils is a viable alternative for producers focused on increasing maize yield, mainly when enhanced efficiency sources are used.

Keywords: *Zea mays* L., potassium chloride, compacted source, slow release, grain yield

Introduction

Potassium (K) is the second most absorbed nutrient by maize (*Zea mays* L.) (Ray et al., 2020), playing a fundamental role in enzymatic activation and osmotic adjustment (Hawkesford et al., 2012; Raij, 2011; Prado, 2021). As suggested by Cantarella et al. (1997), when the K_2O recommendation on maize sowing exceeds 50 kg ha^{-1}, the application should be divided between top-dressing and pre-sowing for clay soils. However, whereas official recommendations for fertilizing maize date back to the late 1990s (Cantarella et al., 1997), currently many producers have been applying high rates of K_2O as top-dressing in maize crops even after the application of up to 50 kg ha^{-1} of K_2O in the sowing furrow and in soils with high available K content. Given this context, studies are necessary to test the effect of high K_2O rates in top-dressing so as to recommend potassium fertilization in maize under these conditions and thereby assist in decision- making.

Although K is a cation, K losses by leaching are relevant and may represent up to 57 % of the total applied in sandy soil (Mendes et al., 2016). Thus, the application of high rates of K_2O in maize crops can lead to nutrient loss by leaching, especially in the summer season, when high rainfall events are recurrent. These factors can reduce the efficiency of applying this nutrient and, thus, may not promote increases in crop yield.

The rational and balanced use of enhanced efficiency K sources can be a viable alternative for achieving balance in the management and efficient use of K in maize, and avoid nutrient losses by leaching and maintaining K contents in the soil at adequate levels (Geng et al., 2020; Li et al., 2020). This technology acts by changing the rate of nutrient release thereby contributing significantly to the environmental and economic protection of the fertilizer production and consumption chain (Trenkel, 2010; Timilsena et al., 2015; Al Shamaileh et al., 2018). Although the benefits of using enhanced efficiency fertilizers are known, uninterrupted studies are needed to validate this technology, given the high variability both in the production of this fertilizer source and in the maize cultivation over the years.

The hypotheses are that the application of high K_2O rates as top-dressing does not increase maize yield in clay soil with high available K content and that enhanced efficiency sources increase maize agronomic performance. Thus, the aim was to evaluate maize agronomic performance under the application of K sources and rates through conventional and enhanced efficiency fertilizers in soil with high available K content.

Materials and Methods

The study was carried out in the Jaboticabal municipality, São Paulo, Brazil (21°14′33″ S, 48°17′10″ W, altitude 570 m). The experiment was conducted in the first season (summer) of 2018/2019 and 2019/2020. The average annual rainfall at the site is 1,425 mm. According to Köppen's classification, the climate is Aw, humid tropical with a rainy season in summer and a dry season in winter (Alvares et al., 2013).

Chemical attributes and particle size of the soil in the experimental area were evaluated in the 0-0.20 m layer (Raij et al., 2001) before the experiment was set up (Table 1). For this, 20 random points were collected from the experimental area, forming a pooled sample that was sent for analysis. Physical analysis showed clay, silt and sand contents of 605, 173 and 222 g kg^{-1}, respectively. The soil is a heavy clayey Oxisol (*Latossolo Vermelho eutrófico*, in Brazilian classification), and the relief has slope of 6 %, characterized as gently undulating. Soil is also classified as kaolinitic and oxidic, with low non-exchangeable K contents in its structure.

The experiments were conducted in randomized blocks, with four replicates, in a 3 × 3 + 1 factorial scheme, consisting of the combination of the top-dressing application of three K sources, namely KCl, KCl-C and KCl-CC, and at three increasing rates (50, 100 and 150 kg ha^{-1} of K_2O), plus an additional treatment without top-dressing K_2O.

The sources and concentrations of K_2O were KCl (60 % K_2O), KCl-C (57 % K_2O) and KCl-CC (40 % K_2O, 1.6 % Ca, 3.9 % Mg and 1.3 % S). KCl-C was obtained by spraying the additives on the surface of the KCl fertilizer, and KCl-CC was obtained by compacting KCl powder and adding nutrients and additives. The additives come from an acrylic polymer, an ingredient applied in both fertilizers, and act in the control of nutrient release. For top-dressing fertilization and respective application of the treatments, the nutrients Ca, Mg and S were added to the sources KCl and KCl-C to balance all sources and rates of fertilizer.

Throughout the two years, the experiments were set up in the same experimental units, i.e, the plots remained in the same place in order to evaluate as to whether the residual effect occurred between the sources. Fertilizers were applied at 35 (V6 stage) and 18 (V4 stage) days after sowing in the first and second years, respectively. The fertilizers were applied manually to the soil surface in a continuous strip, 0.10 m away from the maize row. The plots were composed of five 6m long rows, and the usable area of three central rows, extending to 1 m from the borders.

Table 1 – Soil chemical attributes of the experimental area evaluated in the 0-0.20 m layer, before setting up the experiments in the 2018/2019 and 2019/2020 seasons.

Chemical attributes[1]	2018/2019 season[2] Year 1	2019/2020 season[2] Year 2
pH ($CaCl_2$)	5.6	5.7
OM (g dm^{-3})	21.5	17.3
P (mg dm^{-3}) (resina)	56.0	55.0
Ca^{2+} ($mmol_c$ dm^{-3})	38.0	32.2
Mg^{2+} ($mmol_c$ dm^{-3})	16.5	11.9
K ($mmol_c$ dm^{-3})	6.7	6.7
H+Al	23.5	23.7
Al^{3+} ($mmol_c$ dm^{-3})	0.0	0.0
CEC ($mmol_c$ dm^{-3})	84.7	74.5
V %	72.3	68.1

[1]pH = hydrogen potential in $CaCl_2$; P = phosphorus; K = potassium; C = calcium; Mg = magnesium; Al = aluminum; H+Al = potential acidity; CEC = cation exchange capacity; = base saturation; OM = organic matter. [2]Summer crop season.

Sowing in both seasons was carried out with spacing of 0.45 m interrow and three plants per meter, generating a population density of 66,666 plants per hectare. The hybrid used in the two years was P4285 VYHR, which is recommended within the environmental zone of lowlands (< 700 m).It shows characteristics of good leaf health, early cycle (~ 130 days), high tolerance to lodging and breakage, tolerance to late harvests, being an excellent option for silage, with excellent grain quality, low reproduction factor for the nematode *Pratylenchus brachyurus*. Under adequate management conditions, it displays high tolerance to the complex of stunting and viral diseases. In addition, sowing in areas of low fertility or with compacted soil should be avoided.

The crop preceding the beginning of the experiment (2018/2019) was first-season maize, followed by fallow. Prior to the sowing of the 2018/2019 season |(first year), minimum tillage was applied with chiseling, intermediate harrowing and leveling harrowing. After the harvesting of the experiment in the first year, the area was kept fallow. The spontaneous vegetation present in the experimental area was desiccated through systemic herbicides before the experiment sowing in the 2019/2020 season (second year). For this, glyphosate (1,800 g of active ingredient per ha) and clethodim (60 g of active ingredient per ha) were used. Ten days after weed desiccation, maize was sown under no-tillage on 30 Nov 2018, in the 2018/2019 season, and on 05 Dec 2019, in the 2019/2020 season.

Based on the results of the soil analysis for sowing in the 2018/2019 season, the maize received sowing fertilization according to the recommendations of Cantarella et al. (1997), using 300 kg ha^{-1} of the 08-28-16 fertilizer + 0.5 % of Zn in the sowing furrow (0.05 m to the side and below the seeds), supplying 20, 84 and 48 kg ha^{-1} of N, P_2O_5 and K_2O, respectively. All treatments, including the control, received this sowing fertilization. As highlighted above, the distinction between treatments refers to top-dressing. The same fertilization was carried out in the 2019/2020 season.

For both years, 140 kg ha^{-1} of N were applied in top-dressing, with nitrogen fertilization divided into two time periods. In the 2018/2019 season, the first fertilization of 80 kg ha^{-1} of N, was carried out at the V6 stage (35 days after planting; dap) and the second application of 60 kg ha^{-1}, at the V8 stage (45 dap). In the 2019/2020 season, the first N fertilization of 80 kg ha^{-1}, was carried out at the V4 stage (18 dap) and the second application of 60 kg ha^{-1}, at the V8 stage (50 dap). The N source was urea and the fertilizer was applied to the soil surface, in a continuous strip, 0.10 m away from the maize cultivation row.

Data on rainfall and the minimum and maximum temperatures recorded during the experiments are shown in Figure 1. In the first year (Figure 1A), the average minimum and maximum temperatures were 19.6 and 31.0 °C, respectively, with accumulated rainfall of 758 mm. In the second year (Figure 1B), the average minimum and maximum temperatures were 18.9 and 30.2 °C, respectively, with accumulated rainfall of 801 mm.

At the time of female flowering (R1), at 56 dap in the 2018/19 season and 57 dap in the 2019/20 season, the following measurements were taken: stem diameter (SD), using a caliper, at 5 cm height from the soil surface; plant height (PH), using a graduated ruler, and the relative chlorophyll index (RCI) in the diagnostic leaf, using a SPAD 502 Plus chlorophyll meter. In ten plants per plot, the central third of ten leaves opposite to and below the first ear was collected for leaf K concentration (LKC) (Malavolta et al., 1997). When the crop reached physiological maturity, ten ears were collected from each plot to count the number of rows per ear (NRE) and the number of grains per row (NGR) and determine the thousand-grain weight (1,000-GW) on a precision scale (0.01 g), correcting moisture to 13 %. In addition, grain K concentration (GKC) was determined according to Malavolta et al. (1997). Grain yield (GY) was estimated in the usable area of each plot by harvesting all ears, threshing the grains and adjusting the moisture content to 13 %.

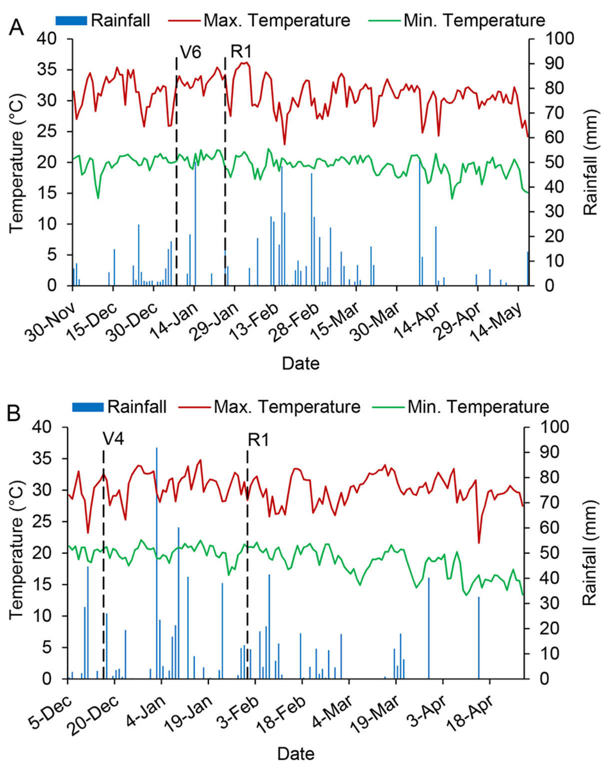

Figure 1 – Daily data of rainfall and air temperature (maximum and minimum), during the experiments in the years 2018/2019 (A) and 2019/2020 (B).

At the end of each cultivation cycle, to evaluate the residual effect of the sources and rates of K applied, five soil samples were collected to form a pooled sample per plot to determine the K contents in the soil, in the 0-0.10 m and 0.10-0.20 m layers (Raij et al., 2001). The soil samples were continuously collected in the maize interrow, randomized within each plot. This method extracts the potassium in the soil by the ion exchange resin. The resin simulates the action of plant roots and extracts only exchangeable K from the soil. After extracting exchangeable K from the soil, K content was determined by flame photometry.

Agronomic efficiency (kg kg^{-1}) was determined according to the equation described by Fageria and Baligar (2005) (Eq. 1):

$$AE = \frac{GYwf - GYwof}{QKhr - QKlr} \quad (1)$$

where AE = agronomic efficiency (kg kg^{-1}), $GYwf$ = grain yield with fertilizer; $GYwof$ = grain yield without fertilizer; $QKhr$ = quantity of K applied at the high rate (kg); and $QKlr$ = quantity of K applied at the low rate (kg).

Statistical analyses were carried out using the AgroEstat statistical program (Barbosa and Maldonado Júnior, 2015), based on a factorial experimental design with two factors and additional treatment (3 × 3 + 1). Before the analysis of variance, the homoscedasticity test of variances by Levene (Gastwirth et al., 2009) and data normality by the Shapiro-Wilk test (Royston, 1995) for each variable were applied. Meeting the principles of homoscedasticity and normality, the data were subjected to analysis of variance, using the F test ($p < 0.05$), and the means were compared by Tukey test ($p < 0.05$). Where the effects of rates and the source versus rate interaction were significant in the analysis of variance, regression analyses were carried out. The regression model choice complied with the parsimony principle, i.e., the simplest models were chosen where precision did not increase satisfactorily (> 5 %) compared to the model with a superior polynomial. Due to differences in soil tillage between years and time of application of potassium fertilizers, the years were analyzed independently in the statistical analysis.

Results and Discussion

An effect of sources on LKC was observed in the two years investigated (Table 2). The leaf K concentration values for the KCl and KCl-C sources did not differ from each other, but responded to the use of KCl-CC in the second year. Interaction between sources and rates was observed only in year 1 (Figure 2A). The effect of rates was observed only in year 2 (Figure 2B). At the lowest rates (up to 50 kg ha^{-1}), the enhanced efficiency source KCl-CC promoted higher LKC compared to the

Table 2 – Leaf potassium concentration (LKC) and grain potassium concentration (GKC) in maize grown under sources and rates of K_2O in two years.

Study factors	LKC		GKC	
K Sources (S)	Year 1	Year 2	Year 1	Year 2
	g kg^{-1}			
KCl	23.2 ab	23.6 a	4.3	3.5
KCl – C	23.6 a	23.1 a	4.1	3.6
KCl – CC	22.3 b	20.9 b	4.2	3.5
Mean rate 0	22.5	23.6	4.3	3.7
F test				
S	5.7**	19.5**	1.9	0.3
K_2O rates (R)	1.9	4.2**	0.4	1.0
S × R	5.9**	0.3	0.2	0.8
Factorial	4.8**	6.1**	0.7	0.7
Additional * Factorial	1.1	3.1	0.2	1.0
Treatments	4.4**	5.7**	0.6	0.8
CV (%)	4.1	5.0	5.4	10.1

Data were submitted to analysis of variance (Test F $p < 0.05$); Lowercase equals, in the column, do not differ from each other by the Tukey test ($p < 0.05$); $*p < 0.05$; $**p < 0.01$. KCl = potassium chloride; KCl-C = potassium chloride coated with additives; KCl-CC = potassium chloride compacted and coated with additives; CV = coefficient of variation.

conventional source, while at the highest rates (> 100 kg ha^{-1}), the conventional source generated LKC values higher than those obtained with KCl-C and KCl-CC (Figure 2A). For the LKC of KCl-C and KCl-CC sources, the mean was the parameter that best explained the variation of this variable as a function of the K_2O rates. This demonstrates that the application of these two K sources neither increases nor reduces the maize LKC, regardless of the applied rate.

For the first year only the KCl source increased LKC with the increase in K_2O rates, which was not observed in the other sources (Figure 2A). This fact can be justified on the basis that KCl is a source of high solubility and rapid availability of the nutrient. KCl-C and KCl-CC, due to the use of additives and polymers, present themselves as sources of slower release of K. According to Bley et al. (2017), compared to fertilizers with K release control technology, KCl has rapid solubilization which facilitates the process of making K available in the soil profile, i.e., after application this source generates high availability of the nutrient in the soil solution, resulting in rapid availablability for absorption by plants. This differs from other sources of slow or controlled release (KCl-C and KCl-CC), from which K is released gradually. As the leaf analysis of K was carried out at the beginning of the maize flowering, in treatments with controlled-release sources, probably all the K was not yet available in the soil solution, while in treatments with KCl, greater availability of exchangeable K in the soil solution was expected compared to the other sources.

The combination of potassium fertilizers from conventional (KCl) and enhanced efficiency sources compared to the isolated application of each source may increase maize yield. Li et al. (2020) observed that combining the two types of sources was the best management as it better met the demand throughout the maize cycle. According to the authors, conventional KCl promoted a rapid release of K in the soil and failed to meet the late crop demand, while the enhanced efficiency source had low initial release and did not satisfactorily meet the initial maize demand.

The K uptake by maize over time follows a sigmoidal model, where initially there is low demand. Subsequently, this demand grows linearly, and at the end of the cycle, the demand decreases (Bender et al., 2013). Maximum maize K demand is reached close to the female flowering stage (R1), and up to this stage, maize absorbs approximately 60 % of the total amount. The remaining 40 % is absorbed after stage R1 (Bender et al., 2013). This demonstrates that even after flowering, maize demand for K is still significant, emphasizing the importance of the availability of this nutrient in the soil throughout the entire crop cycle.

Changes in K release rate are verified when comparing enhanced efficiency K fertilizer sources and conventional sources (Ballotin et al., 2020). It is essential to highlight that, regardless of the treatments tested, LKC was within the range from 17 to 35 g kg^{-1}, which are values established as adequate for leaf analysis of K in maize (Cantarella et al., 1997).

Maize exports are in the order of 5 kg of K per t of maize produced (Cantarella et al., 1997). When analyzing the exporting of K by eight municipalities in the state of São Paulo, an average of 3.2 kg of K per t of maize exported was observed (Duarte et al., 2018). From a broader perspective, results referring to the mass of data from 197 samples indicate variations in the exporting of K from 2.1 to 4.3 kg t^{-1} of maize, thus reaching a proposition of new reference values for K exported, with 3.7 kg t^{-1} of maize produced. In this context, in the evaluation of K exported based on GKC, although no effect was observed as a function of the sources or rates tested (Table 2), for the two years, the K exported range, was similar to the data presented above. For the hybrid P4285 VYHR, K exported in the order of 3.9 kg t^{-1} was observed. Although the absorbed amount of K is high, only 20 % on average is exported by the grains, and the rest returns to the soil by crop remains (Silva et al., 2018).

In the present study, considering a relative export of 3.9 kg of K per t of grains produced (4.7 kg t^{-1} of K_2O), the average total export in the two years was 31.6 kg ha^{-1} of K_2O for the rate 0, 35.7 kg ha^{-1} for the rate 50, 36.2 kg ha^{-1} for the rate 100 and 35.5 kg ha^{-1} for the rate 150. For the control, considering the losses by leaching and the fertilization efficiency, the theoretical amount extracted per year is close to the amount applied at sowing (48 kg ha^{-1} of K_2O). Thus, the soil K content would remain constant over time if maize yield remained at the levels obtained in this study. For the other treatments, a soil K content increase is expected over time, since in addition to the application at sowing, K was also added in the top-dressing. This effect may already be seen in the second year when the soil K content increases as a function of rates (Figure 2C).

Corroborating the results found by Sokal et al. (2020), in the analysis of vegetative development components, in both seasons evaluating K sources, there was no effect on SD, PH and relative RCI (Table 3). For SD, there was an effect only from the K_2O rates (Figure 2D and E). When the effect of interactions was analyzed in year 2, there were responses to the rate increment for plant height.

In the first year, SD showed linear increments, with increases of 0.11 mm for every 10 kg ha^{-1} of K_2O applied, while in the second year, the variation was quadratic, with a maximum value (26.0 mm) obtained at the rate of 143 kg ha^{-1} (Figure 2D and 2E). With regard to PH, the KCl and KCl-C sources did not promote increments as a function of the K_2O rates, while for the KCl-CC source the variation was quadratic, with a maximum value (222.4 cm) obtained at the rate of 135 kg ha^{-1} (Figure 2F).

Fertilization management combining the use of conventional and enhanced efficiency sources promoted higher values of SPAD index in leaves compared to the two sources separately (Li et al., 2020). According to the authors, the combination of the two types of sources promotes the high availability of K immediately after application due to the rapid availability of K from KCl. The content remains high throughout the crop cycle due to the constant availability of K from the enhanced efficiency source. Potassium is the primary enzyme activator in plants and is not part of any structural compound. In grasses K activates the nitrate reductase enzyme (Prado, 2021), allowing plants to assimilate nitrate into molecules such as chlorophyll, increasing the green color index in the plant, a factor that increases the SPAD index values.

In the present study, for both seasons, in the analysis of the yield components NRE, NGR 1,000-GW, no differences were observed for any of the factors studied (Table 4). The overall mean of 1,000-GWwas 337.8 g for the 2018/2019 season and 324.7 g for the 2019/2020 season. However, as regards GY, there was source versus rate interaction for the two years.

Table 3 – Stem diameter (SD), plant height (PH) and relative chlorophyll index (RCI) of maize grown under sources and rates of K_2O in two years.

Study factors	SD		PH		RCI	
K sources (S)	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
	—— mm ——		—— cm ——		-	
KCl	24.5	25.5	215.6	216.7	58.7	58.8
KCl-C	25.0	26.0	214.4	215.4	57.7	57.9
KCl-CC	24.7	25.7	217.2	216.8	57.1	57.6
Mean rate 0	23.8	24.6	212.7	213.8	56.9	58.9
F test						
S	0.6	0.7	0.4	0.1	1.4	1.3
K_2O rates (R)	4.2*	4.3*	0.1	0.6	0.2	0.1
S × D	1.9	1.9	2.1	3.0*	0.1	0.1
Factorial	2.1	2.2	1.2	1.7	0.5	0.4
Additional * Factorial	3.0	3.7	0.6	0.5	0.5	0.7
Treatments	2.2	2.4*	1.1	1.5	0.5	0.4
CV (%)	4.2	4.2	3.4	3.3	4.0	3.5

Data were submitted to analysis of variance (Test F, $p < 0.05$); Lowercase equals, in the column, do not differ from each other by the Tukey test ($p < 0.05$); *$p < 0.05$. KCl = potassium chloride; KCl-C: = potassium chloride coated with additives; KCl-CC = potassium chloride compacted and coated with additives; CV = coefficient of variation.

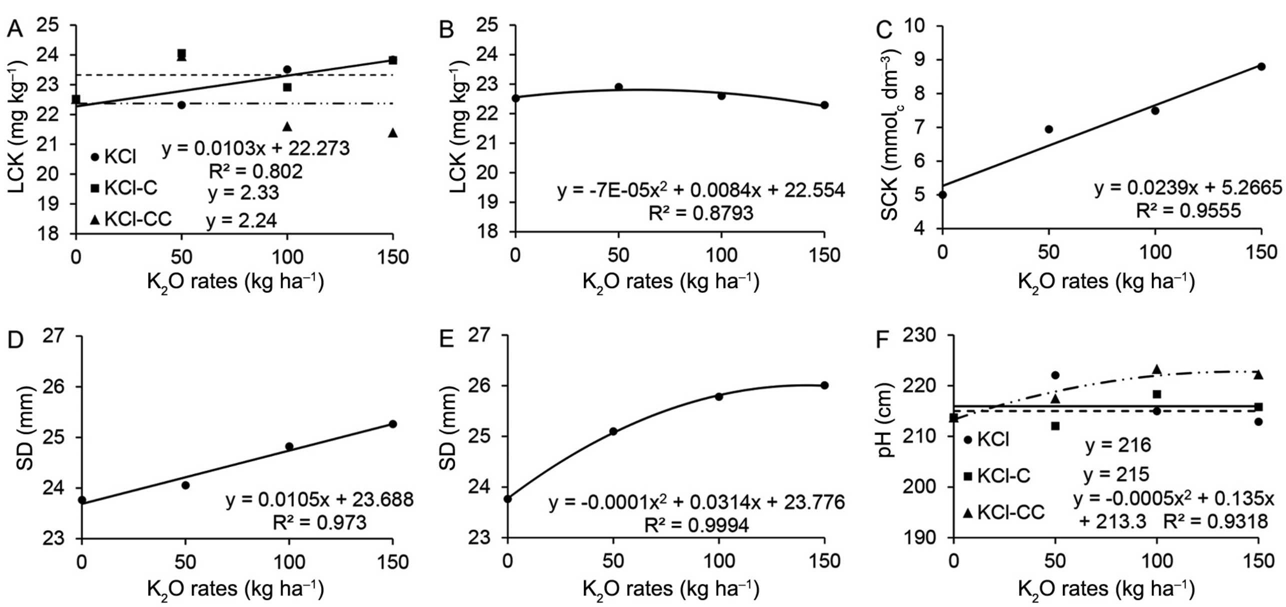

Figure 2 – Regression analysis for leaf potassium concentration (LKC); stem diameter (SD); soil K content in the 0-0.10 m layer (SKC) and plant height (PH) as a function of K_2O rates applied in the first (A and D) and in the second (B, C, E and F) years.

Maize GY increased linearly in the first year, having KCl and KCl-C as sources (Figure 3A). Among them, the enhanced efficiency source KCl-C generated a higher response of maize in the increase of GY, since for every 10 kg ha^{-1} of K_2O applied using this source, GY increased by 92 kg ha^{-1}, while for conventional KCl this value was 71 kg ha^{-1}. For the KCl-CC source, the behavior was quadratic, with maximum GY (7,967 kg ha^{-1}) obtained at 87.6 kg ha^{-1}. In the second year (Figure 3B), the sources KCl and KCl-C promoted quadratic increments in GY. The maximum GY (7,553 kg ha^{-1}) for the KCl source was observed at a rate of 19.9 kg ha^{-1} and the maximum GY (8,166 kg ha^{-1}) for the KCl-C source at a rate of 66.9 kg ha^{-1}. In that same year, the source KCl-CC did not promote increases in GY as a function of the K_2O rates applied, with an average GY of 7,702 kg ha^{-1}.

Two factors that directly interfere with nutrient dynamics are water availability in the system and temperature. According to Du et al. (2006), there is an increasing linear response in the nutrient release rate due to an increase in temperature. After applying the top-dressing K_2O rates, high temperatures were found with values above 25 °C in both years (Figure 1).

Although the amount of rainfall was similar in the two years the distribution was different after the application of the treatments. In the 2018/2019 season, 15 days after application of the treatments there were four days of rainfall, totaling 80.9 mm, with an interval between rainfall events of four days and another that reached five days. This resulted in the sourcs and rates interaction for GY (Figure 3A), particularly for the enhanced efficiency source KCl-CC, followed by KCl-C. Thus, under adverse environmental conditions, the technologies embedded in the fertilizers were efficient, corroborating the results observed in the literature (Du et al., 2006); Trenkel, 2010).

Table 4 – Number of grain rows per ear (NRE), number of grains per row (NGR), 1,000-grain weight (1,000-GW) and grain yield (GY) of maize cultivated under sources and rates of K_2O in two years.

Study factors	NRE		NGR		1,000-GW		GY	
K sources (S)	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
	-		-		g		kg ha^{-1}	
KCl	13.8	14.1	33.4	34.2	338.4	331.1	7,413	7,306 b
KCl-C	13.8	14.1	33.7	33.9	333.7	323.6	7,654	7,822 a
KCl-CC	13.6	14.1	33.4	33.8	341.3	317.6	7,735	7,659 ab
Mean rate 0	13.5	14.5	32.5	34.1	338.3	330.5	6,731	7,482
F test								
S	1.3	0.1	0.1	0.1	1.3	1.2	1.9	5.9**
K_2O rates (R)	0.9	1.4	2.7	0.4	0.2	0.1	2.3	2.9
S × R	0.3	0.6	0.3	2.2	0.7	0.1	3.9*	13.7**
Factorial	0.7	0.7	0.8	1.2	0.7	0.4	3.0*	9.1**
Additional * Factorial	1.5	1.9	1.4	0.1	0.1	0.3	15.8**	0.3
Treatments	0.8	0.8	0.9	1.9	0.6	0.4	4.5**	8.1**
CV (%)	2.9	3.3	4.9	5.0	3.5	6.6	5.5	4.9

Data were submitted to analysis of variance (Test F, $p < 0.05$); Lowercase equal, in the column, do not differ from each other by the Tukey test ($p < 0.05$); *$p < 0.05$; **$p < 0.01$; KCl = potassium chloride; KCl-C = potassium chloride coated with additives; KCl-CC = potassium chloride compacted and coated with additives; CV = coefficient of variation.

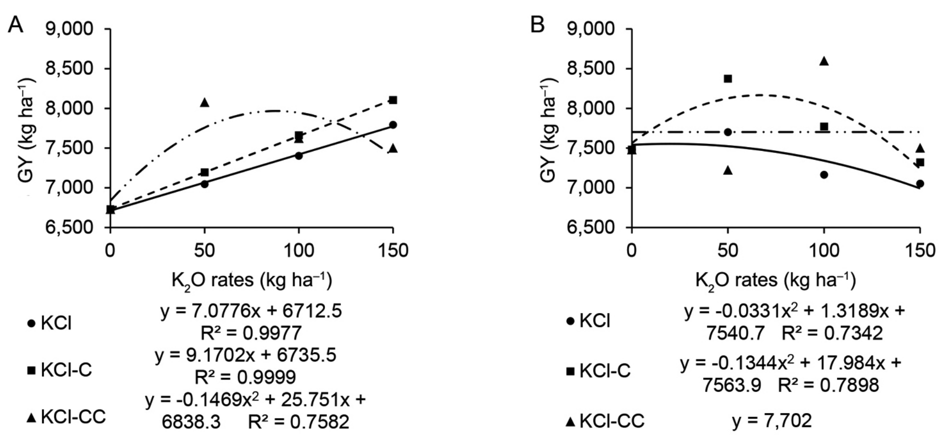

Figure 3 – Regression analysis for grain yield (GY) as a function of sources and rates of K_2O applied in the first (A) and second (B) years.

In the 2019/2020 season, 15 days after the application of the treatments, there were seven days of rainfall, totaling 140.3 mm, with an interval of up to seven days without rainfall. This resulted in a difference in the enhanced efficiency source KCl-C, which led to maximum GY. There was source and rate interaction for K fertilizers (Figure 3B).

Conventional KCl showed rapid K release, generating very high K concentrations in contact with soil moisture, leading to short-term losses in tomato crop growth (Qu et al., 2020). This may have occurred in the present study in the second year, in which the low amount of rainfall after fertilization promoted high availability of K from the KCl source and, due to the absence of adequate soil moisture subsequently, this generated a high concentration of K in the soil, interfering in maize growth. This fact was not as pronounced for enhanced efficiency fertilizers since these sources have a lower K release rate compared to conventional sources, not leaving the soil solution with a very high amount of K. This phenomenon justifies, for example, the GY of maize having decreased in the second year after the application of only 19.9 kg ha^{-1} of K_2O, using KCl. In contrast, for the enhanced efficiency sources, this was not verified.

Although there were no differences between sources and rates for the maize yield components in the present study, it should be emphasized that maize yield is formed by the interaction between all yield components (Tucker et al., 2020; Mingotte et al., 2021). It is worth pointing out, within the yield components, that NRE has high genetic heritability, being little affected by agricultural management (Tucker et al., 2020). Thus, the absence of the effect of the study factors on the yield components does not mean that, for GY, there will also be no differences. This same result was also reported by Mingotte et al. (2021), who evaluated the effects of intercropping of maize with *Urochloa ruziziensis* on the agronomic performance of the crop and verified that the intercropped system did not interfere in maize yield components, but GY was reduced compared to maize monoculture.

The means of the maximum yields achieved in the 2018/2019 season were 7,735 kg ha^{-1} for KCl-CC and 7,654 kg ha^{-1} for KCl-C, while for the conventional source (KCl), the mean yield was 7,413 kg ha^{-1}. In the 2019/2020 season, the means were 7,822 kg ha^{-1}, 7,659 kg ha^{-1} and 7,306 kg ha^{-1} for KCl-C, KCl-CC and KCl, respectively (Table 4). In a general analysis, for the two years, where there was statistical difference for the source or for the source versus rate interaction, the enhanced efficiency fertilizers with the technology to change the K release rate led to increased yield, corroborating results found in the literature (Tian et al., 2017); Li et al., 2020).

In a comparison of the trend and agronomic response for yield in both seasons, the enhanced efficiency sources showed better results. In the 2018/2019 season, the maximum GY was obtained with KCl-CC, with a 322 kg ha^{-1} higher mean compared to that found with KCl, and in the 2019/2020 season, the maximum GY was obtained with KCl-C, which led to an average increment of 516 kg ha^{-1} of maize compared to KCl. These factors are attributed to the balanced, rational, and efficient use of enhanced efficiency fertilizers.

The agronomic efficiency (AE) of K use in the first year was influenced by the rates applied, with 50 kg ha^{-1} being the rate of highest AE (Table 5). For the cultivation of maize in the second year, AE was influenced by the interaction between sources and rates of K. The KCl-C source had the highest AE at K_2O rates of 50 and 100 kg ha^{-1} and KCl-CC the highest AE at the K_2O rate of 150 kg ha^{-1}. This demonstrates that the enhanced efficiency K sources promote greater fertilization efficiency than the conventional source, i.e., they increased the amount of maize produced per unit of K applied.

It was also observed that the enhanced efficiency K source promoted more significant AE in the cotton crop compared to conventional KCl (Pelá et al., 2020). According to the authors, this demonstrates the capacity of enhanced efficiency fertilizers to increase fertilization efficiency, which assists in more sustainable management.

When analyzing the availability of K in the soil prior to cultivation in the two years (Table 1), the exchangeable contents remained in the order of 6.7 mmol$_c$ dm^{-3} (261 mg dm^{-3}) in the 0-0.20 m layer. After the maize harvest in both seasons, no differences in soil K contents (SKC) were observed between sources or rates in the first year in the 0-0.10 m and 0.10-0.20 m layers (Table 6). This exchangeable SKC is classified as very high (Cantarella et al., 1997) and that for a kaolinitic and oxidic Oxisol, such as the one in the experimental area this value represents most of the total K in the soil. Diniz et al. (2007) observed for an Oxisol that the non-

Table 5 – Agronomic efficiency (AE) of K use in maize crop cultivated under sources and rates of K_2O in two years.

Study factor	AE			
K sources (S)	Year 1	Year 2		
KCl	8.1	3.6 b		
KCl-C	10.1	10.1 a		
KCl-CC	13.7	3.8 b		
Rates (kg ha^{-1} K_2O) (R)		KCl	KCl-C	KCl-CC
50	16.8 a	10.1 Aa	23.5 Aa	0.7 Bb
100	8.6 ab	0.6 Bb	5.7 Ba	1.3 Bb
150	6.6 b	0.2 Bb	1.0 Cb	9.3 Aa
F test				
S	1.5	10.4**		
R	3.6*	9.3**		
S × R	1.3	17.6**		
CV (%)	51.5	141.5		

Data were submitted to analysis of variance (Test F, $p < 0.05$); Lowercase equals, in the column, and uppercase equal, in the line, do not differ from each other by the Tukey test $p < 0.05$); *$p < 0.05$; **$p < 0.01$; KCl = potassium chloride; KCl-C = potassium chloride coated with additives; KCl-CC = potassium chloride compacted and coated with additives; CV = coefficient of variation.

Table 6 – Soil K content (SKC) in the 0-0.10 m and 0.10-0.20 m layers in areas cultivated with maize under sources and rates of K_2O in two years.

Study factors	Year 1 - SKC		Year 2 - SKC	
K sources	0.10	0.20	0.10	0.20
	m			
KCl	8.4	6.1	7.7 a	6.1
KCl-C	7.0	5.3	7.4 a	5.6
KCl-CC	7.6	5.8	8.2 a	5.6
Mean rate 0	7.1	5.5	5.00	5.2
F test				
S	3.1	1.8	0.7	0.8
K_2O rates (R)	0.5	0.5	4.2*	2.1
S × R	0.5	0.2	0.9	1.2
Factorial	1.1	0.6	1.7	1.3
Additional * Factorial	0.2	0.2	10.4**	1.4
Treatments	1.0	0.6	2.6*	1.3
CV (%)	17.8	19.2	21.6	17.6

Data were submitted to analysis of variance (Test F, $p < 0.05$). Lowercase equals, in the column, do not differ from each other by the Tukey test ($p < 0.05$); *$p < 0.05$; **$p < 0.01$; KCl = potassium chloride; KCl-C = potassium chloride coated with additives; KCl-CC = potassium chloride compacted and coated with additives; CV = coefficient of variation.

exchangeable K content in the 0-0.20 m layer is less than 30 % compared to the total K.

In the second year, the sources had no effect on SKC, when the two layers were analyzed. However, a relative analysis of the exchangeable K distribution between the first and second soil layer, under the different sources, showed that the application of KCl, KCl-C and KCl-CC led to 27, 31 and 45 % more SKC in the first soil layer compared to the 0.10-0.20 m layer, respectively. When the rate effect was analyzed, there was a linear response in the increase of SKC (Figure 2C) for the first layer in the second year, although the soil had high exchangeable K contents (Table 1). For every 10 kg ha^{-1} of K_2O applied, there was an increase of 0.24 $mmol_c$ dm^{-3} in the SKC in the 0-0.10 m layer.

The K movement varied with soil type and increased with K_2O rate increment (Neves et al., 2009). After seven days, with the highest rate of KCl being applied, K movement was lower in the clay-textured *Latossolo Vermelho distrófico* (Oxisol) (567 g kg^{-1} of clay), although this is a soil with high exchangeable K content (11.9 $mmol_c$ dm^{-3}). This indicates that studies contemplating K fertilization in soils with high exchangeable K availability are necessary in order to better understand its dynamics in the soil-plant system.

When evaluating the effects of enhanced efficiency and conventional K sources on exchangeable K availability in soil throughout the cotton cycle, Geng et al. (2020) observed higher K availability in the soil throughout the crop cycle under treatments with enhanced efficiency sources. However, after the harvest, despite the higher exchangeable K contents in the soil under the enhanced efficiency sources, the difference from the content observed in the soil under conventional source was less. It is worth pointing out that the soil evaluated by the authors initially had lower exchangeable K and clay contents (16 %) compared to the values observed in the present study. Thus, the higher exchangeable K contents in the soil evaluated by the authors with the enhanced efficiency sources after the cotton harvest can be explained by the lower natural fertility of the soil compared to the soil in the present study.

Similar behavior was observed by Li et al. (2020) when assessing the effects of long-term K application on exchangeable K content in the soil. The authors verified that, by the end of the maize cycle, the treatments with application of enhanced efficiency K fertilizer had promoted higher SKC compared to the conventional source (KCl). However, the soil evaluated by the authors also had, at the beginning of the cycle, lower availability of natural exchangeable K and lower clay content (10.6 %) than the values observed in the present study.

Although the experimental area soil is very clayey (60 % clay), leaching is a process of significant K loss in the soil, especially in seasons of very intense precipitation events, such as the summer in Brazil. Therefore, the responsiveness of maize to potassium fertilization in soils with high SKC is associated with the genotype responsiveness and climatic conditions of the summer season (high photoperiod and precipitation). These conditions promote more significant plant growth, demand for nutrients and leaching, thereby demonstrating the importance of potassium fertilization management in the summer season in Brazil.

Conclusions

Maize yield is affected by the K source vs rate interaction. In the first year, maize GY increased linearly for the KCl and KCl-C sources at the rate of 71 and 92 kg ha^{-1} for every 10 kg ha^{-1} of K_2O added in top-dressing, respectively. The maximum GY (7,967 kg ha^{-1}) for the KCl-CC was obtained at the rate of 88 kg ha^{-1}. In the second year, the maximum GY for the KCl (7,553 kg ha^{-1}) and KCl-C (8,166 kg ha^{-1}) were obtained with 20 and 67 kg ha^{-1} of K_2O, respectively, while for the KCl-CC maize GY did not change. Enhanced efficiency potassium sources promote increments in fertilizer use efficiency and maize GY, with average increases of 4.3 % and 7.1 % in the first and second years, respectively. Top-dressing K fertilization in high-fertility soils is a viable management approach which increase maize agronomic performance for producers, and this effect is more pronounced when enhanced efficiency sources are used.

Authors' Contributions

Conceptualization: Ribeiro, B.N.; Gissi, L.; Lemos, L.B. **Data acquisition**: Ribeiro, B.N.; Roms, R.Z.; Batista-Silva, W. **Data analysis**: Ribeiro, B.N.; Coelho, A.P.;

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