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Leaching and availability of potassium in soil affected by conventional and coated fertilizer sources¹

Lixiviação e disponibilidade de potássio no solo afetadas por fontes de fertilizantes convencionais e revestidos

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HIGHLIGHTS:

The soil K concentration decreased by 26.5% in the absence of potassium fertilization.

Coated fertilizer sources increased the availability and leaching of K into the soil.

KCl coating increased the soil K availability and leaching.

ABSTRACT: The use of coated fertilizers is a strategy for improving fertilization efficiency and crop yield. However, further studies are needed to understand the dynamics of different types of coated K fertilizers in the soil. The objective of this study was to evaluate K dynamics in soil columns after the application of conventional KCl and other K sources with coating (KCl-C) and compaction (KCl-CC) combined with the use of additives and polymers. The experiment comprised four treatments, consisting of three sources of K [conventional KCl, KCl coated with additives and polymers (KCl-C), and KCl compacted and coated with additives and polymers (KCl-CC)], and a control without K application, with four repetitions. The K concentration was evaluated in the leached solution collected from the soil columns for 28 days. After this period, the K concentration in the soil was determined. The absence of K fertilization in the soil led to a 26.5% reduction in the K concentration. The coated sources had lower granule hardness and higher K leaching than conventional KCl. The amounts of K leached were 62.2%, 68.5%, and 54.0% for KCl-CC, KCl-C, and conventional KCl, respectively. However, at the end of the experiment, the soil K concentration was higher under the KCl-C treatment.

Key words: potassium fertilizers, potassium fertilization, potassium chloride, polymers

RESUMO: O uso de fertilizantes revestidos é uma estratégia para melhorar a eficiência da adubação e o rendimento das culturas. No entanto, são necessários estudos para entender a dinâmica no solo dos diferentes tipos de fertilizantes potássicos (K) revestidos. Objetivou-se avaliar a lixiviação, disponibilidade e recuperação de K em colunas de solo após aplicação de fonte convencional KCl e outras fontes de K com tecnologias de revestimento e compactação. O experimento compreendeu quatro tratamentos, constituídos por três fontes de K (KCl convencional; KCl revestido com aditivos e polímeros - KCl-C; e KCl compactado e revestido com aditivos e polímeros - KCl-CC), e um controle sem adubação, com quatro repetições. Os teores de K foram avaliados na solução lixiviada das colunas de solo por 28 dias. Após esse período, foram determinados os teores de K no solo. A ausência de adubação no solo levou a uma redução de 26,5% nos teores de K. As fontes revestidas apresentaram menor dureza de grânulos e maior lixiviação de K em relação ao KCl convencional. A quantidade de K lixiviada foi de 62,2% para KCl-CC, 68,5% para KCl-C e 54,0% para KCl convencional. No entanto, ao final do experimento, os teores de K no solo foram maiores para a fonte KCl-C.

Palavras-chave: fertilizantes potássicos, adubação potássica, cloreto de potássio, polímeros

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INTRODUCTION

The use of coated fertilizers is not a new technology, especially for nitrogen sources (Smith & Harrison, 1991). However, the technologies employed to increase the efficiency of these fertilizers are constantly being renewed, and studies are required to evaluate the effects of new technologies on the dynamics of nutrients in the soil (Tian et al., 2017; Souza et al., 2020). Studies on coated fertilizers are constantly being carried out for nitrogen (Lasisi et al., 2021; Ferreira et al., 2022), but more specific information is still lacking for potassium sources.

Although K is a cation (K^+), leaching may result in a loss of this nutrient (Prado, 2021). Mendes et al. (2016) observed that in sandy soils, K leaching can represent up to 57% of the total added fertilizer, whereas in clayey soils ($CEC \sim 70 \text{ mmol}_c \text{ dm}^{-3}$), this value is close to 8%. Using slow-release or enhanced efficiency K sources can be one way to reduce these losses (Trenkel, 2010; Yang et al., 2016; Bley et al., 2017; Guo et al., 2018).

Several compounds have been studied with the objective of changing the K release rate and increasing the period of K availability to plants (Trenkel, 2010; Timilsena et al., 2014; Bley et al., 2017; Tian et al., 2017). However, there are questions about the stability of the additives and polymers used because the products have variable efficiency depending on storage, edaphoclimatic conditions at the time of application (Cantarella, 2007), and agronomic practices (Nogueira et al., 2020; Ul-Allah et al., 2020). Considering that new technologies applied to solid fertilizers are continuously developing, there has been an increase in the number of scientific studies and more consistent results in the literature (Tian et al., 2017; Geng et al., 2020; Li et al., 2020; Chen et al., 2021).

The aim of this study was to evaluate the K dynamics in soil columns after the application of conventional KCl and other K sources with coating (KCl-C) and compaction (KCl-CC) combined with the use of additives and polymers.

MATERIAL AND METHODS

The experiment was conducted in a greenhouse (low-density polyethylene film cover) at the Agronomic Research Center of Kimberlit Agrociências ($20^\circ 43' 04'' \text{ S}$, $48^\circ 59' 50'' \text{ W}$, 550 m altitude), located in the municipality of Olímpia, São Paulo, Brazil. To set up the experiment, soil samples from the 0-0.20 m layer were collected from the Teaching, Research, and Extension Farm (Fazenda de Ensino, Pesquisa e Extensão - FEPE) of Unesp, Campus of Jaboticabal, São Paulo, Brazil, in an area cultivated with maize, without vegetation cover. In the last 10 years, this area has been cultivated with maize in the summer and, in some years, soybean in the summer and maize in the off season (second season). The chemical attributes of the sampled soils were also determined (Raij et al., 2001) (Table 1). The soil has a very high K concentration, approximately $6.0 \text{ mmol}_c \text{ dm}^{-3}$ (Raij et al., 1997). Particle size analysis of the soil (Gee & Bauder, 1986) was performed and showed values of 605, 173, and 222 g kg^{-1} of clay, silt, and sand, respectively.

The soil was classified as oxisol, with a very clayey texture, the relief slope was 6%, and the landscape was

Table 1. Chemical attributes of the soil sampled in the 0-0.20 m layer, in a maize cultivation area

Chemical attributes ⁽¹⁾	Values
pH (CaCl_2)	5.80
OM (g dm^{-3})	23.00
P (mg dm^{-3}) (resin)	75.24
Ca^{2+} ($\text{mmol}_c \text{ dm}^{-3}$)	41.25 (47.6% of CEC)
Mg^{2+} ($\text{mmol}_c \text{ dm}^{-3}$)	17.11 (19.7% of CEC)
K ($\text{mmol}_c \text{ dm}^{-3}$)	6.00 (6.9% of CEC)
H + Al	22.34
Al^{3+} ($\text{mmol}_c \text{ dm}^{-3}$)	0.41
CEC ($\text{mmol}_c \text{ dm}^{-3}$)	86.70
V%	74.23

⁽¹⁾ pH, potential hydrogen in CaCl_2 ; P, phosphorus; K, potassium; Ca, calcium; Mg, magnesium; Al, aluminum; H + Al, potential acidity; CEC, cation exchange capacity; V, base saturation; OM, soil organic matter; values in parentheses represent the participation of nutrients in soil CEC

slightly undulating. The average altitude and average annual precipitation of the soil collection site ($21^\circ 14' 59'' \text{ S}$, $48^\circ 17' 09'' \text{ W}$) were 565 m and 1,425 mm, respectively. According to Köppen's classification (Alvares et al., 2013), the climate is Aw, humid tropical, with a rainy season in summer and a dry season in winter.

The experiment was conducted in a randomized block design, with four replicates, consisting of a combination of top-dressing applications of three K sources: conventional potassium chloride (KCl), KCl coated with additives (KCl-C), and KCl compacted and coated with additive (KCl-CC); additionally, there was a control treatment without fertilizer application.

To standardize the fertilizer granules applied to the soil columns, the granules that passed through a 4-mm-mesh sieve and were retained on the 2-mm-mesh sieve were selected for the three sources studied. This procedure was performed to standardize the granule sizes of the KCl-C and KCl-CC sources with conventional KCl, avoiding a new source of variation in the experiment. In addition, the hardness of the granules was determined with a DUROControl[®] HDC-50CPD device and was equal to 8.45 kgf for KCl, 4.5 kgf for KCl-C, and 8.1 kgf for KCl-CC.

The K_2O concentrations in the K sources were 60%, 57%, and 40% K_2O for KCl, KCl-C, and KCl-CC, respectively. KCl-C was obtained by spraying additives on the surface of KCl fertilizer granules, while KCl-CC was obtained by compacting KCl powder and adding additives that act as nutrient release controls (Trenkel, 2010; Bley et al., 2017; Fu et al., 2018). Compaction was performed after conventional KCl was crushed and converted into a powder. The additives came from an acrylic polymer (Kimberlit[®]), which was applied in both enhanced efficiency fertilizers.

The soil columns were filled with 1.8 kg of the sampled soil and consisted of two 0.10-m-long sections of polyvinyl chloride (PVC) pipes that were 100 mm in diameter. At the bottom of the column, a cap with a hole in the center was connected to collect fluid percolating through the soil column. To avoid possible soil loss, a paper filter combined with a synthetic fabric was placed at the bottom of each column. To increase soil column roughness and prevent preferential water flow on the walls of the PVC sections, epoxy resin was added to the PVC walls. All the water percolated volumes were collected

in a container, and a sample was taken and analyzed for K concentration according to Raji et al. (2001). To calculate the total amount of K leached during each treatment, the percolated volume was measured at each collection time.

The fertilizers were weighed on an analytical scale with an accuracy of 0.1 mg and applied to the surface of the soil (not incorporated) contained in the PVC columns at a dose equivalent to 200 mg dm⁻³ of K₂O. This dose corresponds to 100 kg ha⁻¹ of K₂O considering the 0-0.20 m soil layer. Water was then applied to start the percolation process using drippers (one per PVC column) with a flow rate of 0.5 cm³ s⁻¹. Prior to the application of K fertilizers, all columns received a water volume equivalent to 1× field capacity (FC).

The volume of percolated water in each column was equivalent to the FC of the soil (430 mL dm⁻³ or 0.43 cm³ cm⁻³). The FC was determined based on the volume of water percolated after the addition of 100 mL of water to 100 cm³ of soil in a glass percolation pipe. In the interval between leachate collections, when necessary, moisture was re-established to keep the soil at FC, using scales to determine the water volume of the soil columns.

A total of 10 collections were performed over time to evaluate the concentration and recovery of K in the drained solution. The samples were collected at 1, 4, 7, 10, 14, 17, 21, 24, and 28 days after the fertilizers were applied in each treatment, according to the methodology described by Trenkel (2010).

Peak and sigmoidal models were fitted to study the variations in K leaching and accumulation over time in the soil columns. The fitted peak model was based on a Gaussian equation (Eq. 1) and the Hill equation was used in the sigmoidal model (Eq. 2), using SigmaPlot v. 10.0. To obtain the K leaching accumulation over time, the amount of K determined in the solution in each collection was subtracted from the amount determined in the control treatment (without K fertilization).

$$Y = Y_0 + a \cdot e^{\left[-0.5 \left(\frac{X - X_0}{b}\right)^2\right]} \quad (1)$$

where:

- Y₀ - stabilization value in Y;
- a - peak amplitude (maximum point - Y₀);
- X₀ - centroid position (X value that promotes the peak in Y);
- b - peak width parameter/maximum point.

$$Y = \frac{aX^b}{c^b + X^b} \quad (2)$$

where:

- a - Maximum point;
- b - Hill coefficient (dimensionless);
- c - inflection point (x value that promotes half the maximum value in Y).

At the end of the 10 collections (28 days after the fertilizers were applied) of the percolated fluid, the soil was collected and the K concentration was analyzed in the 0-0.10 m and 0.10-0.20 m layers (Raji et al., 2001).

The K concentration data in the two layers were subjected to analysis of variance ($p < 0.05$), and the means were compared using Tukey's test ($p < 0.05$).

RESULTS AND DISCUSSION

The coated KCl sources (KCl-C and KCl-CC) promoted higher peaks of K leaching in the soil than conventional KCl (Figure 1). This can be demonstrated by the coefficient "a" of the Gauss equation. The highest amplitudes of the K concentration in the soil were observed with KCl-C and KCl-CC (42.90 mg dm⁻³ and 40.14 mg dm⁻³, respectively) compared to conventional KCl (35.32 mg dm⁻³). Among the fertilizer-coated sources, KCl-C promoted greater K leaching than KCl-CC. K leaching peaks occurred between seven and eight days (X₀ coefficient) after K application, regardless of the source. In addition, the coated sources promoted greater K availability and leaching in the collected solution for a longer time (model-fitted variation) than conventional KCl. Additionally, the application of K increased its availability in the soil compared to the control up to 15/20 days after application; since after this period, the values of K availability were similar among the treatments.

The accumulation of K leaching through the soil columns by the evaluated sources is shown in Figure 2A. From the 200 mg dm⁻³ of K₂O applied in each treatment at the beginning of the evaluation, 108.0 mg dm⁻³ was recovered for conventional KCl, 124.3 mg dm⁻³ for KCl-CC, and 137.0 mg dm⁻³ for KCl-C. These values corresponded to relative recoveries of 54.0%, 62.2%, and 68.5%, respectively, of the total applied for conventional KCl, KCl-CC, and KCl-C (Figure 2B). Thus, it was observed that the coated sources increased K leaching by an average of 11.4 percentage points compared with conventional KCl.

After collecting 10 samples of the soil solution, it was observed that the soil K concentration in the control treatment decreased from 6.0 mmol_c dm⁻³ (Table 1) to an average of 4.41

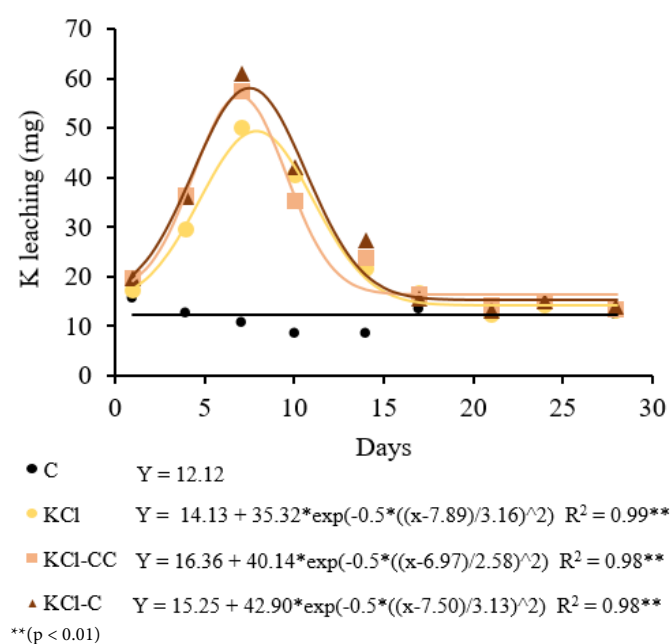
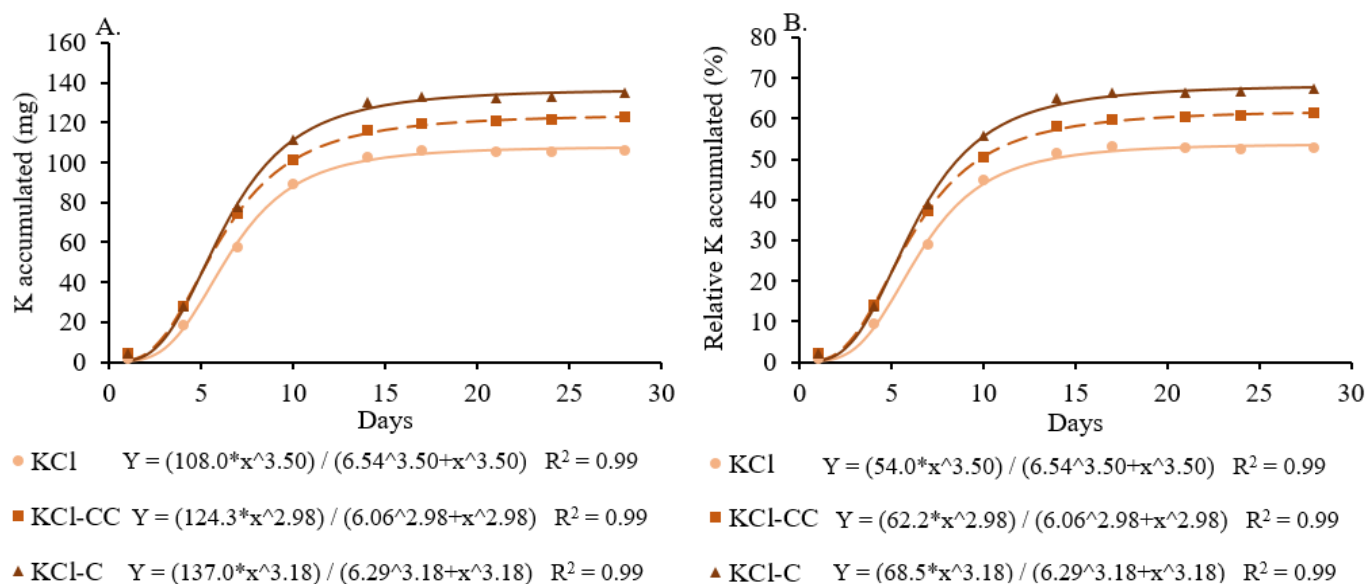


Figure 1. Potassium leaching over time in soil columns for conventional KCl, KCl coated with additives (KCl-C), and KCl compacted and coated with additive (KCl-CC)



* - Significant at $p \leq 0.05$ by F test

Figure 2. Potassium leaching accumulation (A) and relative K accumulation (B) over time in the soil columns for conventional KCl, KCl coated with additives (KCl-C), and KCl compacted and coated with additive (KCl-CC)

$\text{mmol}_c \text{ dm}^{-3}$ in the 0-0.20 m soil layer (Table 2), representing a reduction of 26.5% in the soil K concentration. In the other treatments (KCl, KCl-C, and KCl-CC), the K concentration increased, especially in the 0-0.10 m layer, with all values being higher than the K concentration in the control. The KCl, KCl-C, and KCl-CC treatments resulted in similar soil K concentrations in the 0-0.10 m soil layer. In the 0.10-0.20 m soil layer, KCl-C promoted higher K concentration compared to conventional KCl (representing an increase of 19 percentage points). This occurred because, while the coated sources resulted in greater leaching, they also resulted in greater K release from the fertilizer granules compared to conventional KCl (Figure 2). With the exception of the control, all treatments resulted in a lower K concentration in the 0.10-0.20 m layer compared to the 0-0.10 m layer. This was due to the mode of fertilizer application on the soil surface.

The participation of K in soil CEC (K%) was similar between KCl and KCl-C, with all KCl treatments resulting in higher values than the control. Only KCl-CC led to a lower K concentration in the 0-0.10 m soil layer compared to conventional KCl and KCl-C. KCl, KCl-C, and KCl-CC promoted higher K% in the 0-0.10 m soil layer, while the control treatment resulted in a higher K% in the 0.10-0.20 m layer. This occurred because, in the control treatment, K

leaching occurred from the surface layer to the deeper layer.

Contrary to our expectations, the coated potassium sources promoted greater K leaching in the soil columns than conventional KCl. Moreover, the coated sources did not alter the K release dynamics, presenting a variation model similar to that observed for conventional KCl. However, it is noteworthy that even with higher K leaching in the soil columns, the KCl-C source promoted higher available K concentration (soil solution + labile adsorbed) in the 0.10-0.20 m soil layer. By evaluating the effect of a controlled-release K source on soil and cotton yield, Geng et al. (2020) observed up to 20% higher K concentration in the 0-0.20 m soil layer for a long period in the treatment with the application of a controlled-release fertilizer, in addition to a 7% higher yield. Regarding the conventional K fertilizer (potassium sulfate), the authors observed higher K concentrations in the field with enhanced efficiency up to 200 days after fertilizer application.

The faster availability of the coated K sources evaluated in this study compared to conventional KCl may be due to the construction process of the coated fertilizers. In this process, conventional KCl granules were deconstructed and polymers were added to manufacture a new fertilizer. After all the processes, it was verified that the granule hardness of the KCl-C (4.5 kgf) and KCl-CC (8.1 kgf) fertilizers was reduced by 47% and 4%, respectively, in relation to the value observed for conventional KCl (8.45 kgf). This reduction in granule hardness likely increased the speed of solubility of the coated fertilizers, as the lower the granule hardness, the greater the availability and leaching of K in the soil columns (Guo et al., 2018).

Notably, the highest K leaching in the coated sources evaluated in this study was verified under controlled conditions in a closed system of soil columns. In this system, to obtain the soil solution, water was applied constantly and in high amounts, which was not observed under field conditions.

In medium-textured soil (160 g kg^{-1} clay), Bley et al. (2017) evaluated K availability with a K source coated with one layer

Table 2. K concentration in the soil in the 0-0.10 m and 0.10-0.20 m layers in the columns

K sources	K in soil ($\text{mmol}_c \text{ dm}^{-3}$)		K%	
	0-0.10 m	0.10-0.20 m	0-0.10 m	0.10-0.20 m
Control	4.25 bA	4.56 cA	5.00 cB	6.00 cA
KCl	12.77 aA	6.28 bB	15.00 aA	8.75 bB
KCl-CC	11.05 aA	7.05 abB	12.25 bA	9.00 abB
KCl-C	12.25 aA	7.50 aB	14.00 aA	9.75 aB
F value (Sources - S)	245.6*		369.3*	
F value (Layers - L)	156.8*		168.7*	
S × L	32.4*		67.1*	
CV (%)	2.07		2.35	

Means followed by the same letters in a column do not differ significantly according to Tukey's test ($p \leq 0.05$). *Significant at $p \leq 0.05$; K%: participation of K in soil cation exchange capacity

of elemental sulfur and another layer of organic polymer, and observed low K availability compared to the conventional source (KCl) at the beginning of the soil incubation period. According to the authors, this low K availability immediately after the application of the highly efficient source could promote the deficiency of this nutrient for crops. The authors also observed that the release of 40% of K from this source occurred only five months after the application of the nutrients in the soil. This was not verified in the present study because at the beginning of the experiment, the coated sources promoted greater availability and leaching of K in the soil compared to conventional KCl, and this effect was observed at least until 15/20 days after fertilizer application. These results demonstrate the need to evaluate different coatings to control fertilizer release. In a study by Bley et al. (2017), the authors verified that the addition of organic polymers to K sources may greatly reduce the release of K in the soil, which can result in a deficiency of this nutrient for plants; however, the polymers used were not very efficient in retarding the release of K from the fertilizer granules. This is because the organic polymer has a high surface charge and is able to retain a greater amount of K for a longer time (Trenkel, 2010), unlike the polymer used in the present study, which has a greater capacity to make K available.

The use of enhanced efficiency K sources tends to promote a higher soil K available K for a longer time, interfering with the development of plants. Tian et al. (2017) evaluated the effect of an enhanced efficiency K source on K availability in the soil and on cotton physiology and yield, as compared to conventional sources (potassium chloride and potassium sulfate), and observed that the source of enhanced efficiency fertilizer made K available for a longer period in the soil. This promoted higher net photosynthesis and, consequently, a higher yield (7-9% higher) of cotton plants compared to conventional sources.

In some cases, the combination of enhanced efficiency and conventional fertilization sources may promote greater agronomic performance in crops. Li et al. (2020) evaluated the impact of the application of controlled-release K fertilizer and a conventional source (KCl) on maize yield and soil K concentration, and verified that after fertilizer application, conventional KCl promoted higher K concentrations in the soil. However, over time, the K + concentration in the soil in this treatment decreased dramatically. In contrast, the controlled-release source promoted lower K concentrations immediately after application and increased K availability in the soil over time. According to the authors, the combination of these two sources of K fertilizers promotes an ideal condition, as it results in high K concentration immediately after the fertilizer application due to KCl, and these concentrations remain high throughout the crop cycle owing to the controlled-release source. Thus, the authors verified that the combination of these two sources of K increased maize yield by more than 15% compared with the application of KCl alone or the enhanced efficiency source.

According to the results of the present study, this combination of fertilizers would not be necessary with the KCl-C-coated source used here because this source promoted greater availability compared to conventional KCl immediately

after fertilizer application and in the soil at the end of the experiment.

In addition to the source type, factors such as the granule surface may interfere with K availability in the soil. Guo et al. (2018) highlighted that the irregular surface of KCl granules can be an obstacle to the use and manufacture of controlled-release K fertilizers because the release of nutrients at the edges and corners of the granules is very fast. Thus, the authors highlighted that the selection of granules with uniform size or the granulation of KCl powder into spherical particles with a size of 3-5 mm can be alternatives to improve the quality of the manufacture of K fertilizers coated for controlled release, as was carried out in the sources evaluated in the present study.

In the present study, the fertilizer manufacturing process may have interfered with K dissolution in the soil. The manufacturing process of the KCl-C reduced the hardness of the fertilizer granules from 8.45 kgf to 4.5 kgf. In addition, during the manufacturing process of KCl-CC, the powder from the conventional KCl was compacted and a polymer was added, affecting the original granule structure. These changes, either in hardness or in the structure of the granules, probably contributed to the greater release of K to the soil from the KCl-C and KCl-CC sources compared to conventional KCl.

CONCLUSIONS

1. The coated fertilizers reduced the granule hardness and increased K release and leaching compared to conventional KCl.
2. The KCl-C potassium source (additive spraying) increased the availability and leaching of K in the soil.
3. The KCl-C-coated fertilizer increased the participation of K in the cation exchange capacity of the 0-0.10 m soil layer compared to conventional KCl.

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