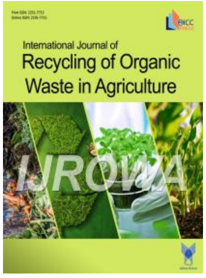

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Research Article

Response of Corn to Potassic Organomineral Fertilizer in an Oxisol

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Abstract

Purpose: Corn (*Zea mays* L.) requires an adequate supply of potassium (K) to achieve high productivity. Potassium chloride (KCl) is the main fertilizer source used, but its excessive application can increase soil salinity and production costs. Organomineral fertilizers (OMF) have emerged as an alternative, as they improve soil attributes and supply nutrients. In this study, the effects of an OMF fertilizer were compared with KCl, based on the external critical level (CL) of K for corn in a sandy loam Typic Hapludox.
Method: The experiment was conducted in a greenhouse using a randomized complete block design with five treatments and four replications. The applied K rates ranged from 40% below to 20% above the CL. Biometric and plant tissue data were evaluated.
Results: OMF showed equivalent or superior efficacy compared to KCl, especially at rates suitable for the crop. The use of OMF enhanced calcium and magnesium uptake and exhibited the highest agronomic efficiency of K use across all evaluated rates, with an average value 24% higher than that of KCl. Both fertilizers had similar K uptake efficiency, while apparent recovery efficiency ranged from 55 to 70% for OMF and 77 to 94% for KCl.
Conclusion: Both fertilizers exhibited similar efficacy, and the choice should consider availability and cost. In addition to being a viable alternative, OMF offers environmental benefits and contributes to organic waste management, promoting more sustainable agricultural practices and aligning with the United Nations Sustainable Development Objectives.

Keywords: *Zea mays,* Alternative fertilizer, Potassium chloride, Critical level of K in the soil

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1. Introduction

Corn (*Zea mays* L.) plays a significant role in the Brazilian agricultural scenario, substantially contributing to the country's economy. Brazil is positioned among the largest producers and exporters of this crop worldwide. The Brazilian corn harvest in 2022/2023 reached 126 million tons, representing an 11% increase compared to the previous harvest. Thus, it is essential to ensure adequate nutrient availability in the soil to continue achieving high yields. To produce 1 ton of grain, corn absorbs 25 kg of nitrogen (N), 5 kg of phosphorus (P), and 18 kg of potassium (K) (Schlegel and Havlin., 2017). This demand for K poses a challenge to Brazilian agriculture since a large part of Brazilian soils have reduced reserves of this nutrient (Firmano et al. 2020; Moterle et al. 2016).

Furthermore, sandy soils are widely distributed over agricultural regions and present limitations for K fertilization due to their low cation exchange capacity, low organic matter content, and high susceptibility to nutrient leaching (Šimanský et al. 2022; Barra Netto-Ferreira et al. 2023). These characteristics compromise the efficiency of the use of K and reinforce the need for fertilization strategies better suited to these conditions. In this context, the choice of K fertilizer sources used in agriculture becomes especially important. Potassium chloride (KCl) is the most commonly used potassium fertilizer in Brazilian agriculture. This fertilizer is highly soluble and furnishes nutrients readily available to plants (Li et al. 2020). However, precautions must be taken when applying it, as its continuous use has the potential to increase soil salinity and result in damage to plants and other organisms present in the soil (Soumare et al. 2023). Currently, Brazil imports about 96% of its potassium fertilizers, mainly in the form of KCl (Farias et al. 2021). In this context, it is important to improve the efficiency of the use of K and explore alternative sources that require minimal processing, such as organomineral fertilizers (OMF). Organominerals (OMFs) are physical or combined mixtures of organic material and mineral fertilizer (de Souza Alves et al. 2025; Teixeira et al. 2025; Smith et al. 2020). In addition to providing K, they also contain other important nutrients for plants, such as N and P, and contribute to improving the physical, chemical, and biological properties of the soil (Moran et al. 2021; Crusciol et al. 2020; Corrêa et al. 2018). The use of OMFs is a sustainable alternative for agriculture since these fertilizers are produced from organic materials, such as residues from animal and vegetable sources. Thus, it is possible to reduce dependence on imported fertilizers and contribute to the sustainable management of animal waste and residues. The choice of appropriate fertilizer sources and rates is a determining factor for the success of corn cultivation (Ferreira et al. 2016). The rate of K to be applied varies according to the crop and the critical level (CL) of K in the soil (Brunetto et al. 2005), and the use of OMFs may require higher rates due to the lower concentration of available K compared to KCl. Therefore, comparing rates of potassium fertilizers can provide important information on the efficiency of each fertilizer concerning the rate used and allow for the selection of the most suitable rate for each situation. Although the use of OMF is increasing, there are still few studies that evaluate its effectiveness as a source of K, especially in sandy soils. Therefore, this study aimed to compare the effects of a K-source OMF with KCl, at five rates based on the external CL of K for corn cultivation in a sandy loam Typic Hapludox. The hypothesis was that the use of OMF as a source of K shows comparable or superior efficacy to KCl, especially at appropriate rates. The careful selection of rates and fertilizer sources can contribute to the healthy development of corn plants, resulting in increased production and improved soil quality. Therefore, it is assumed that this study will provide important information in the search for more efficient and sustainable agricultural practices.

2. Materials and methods

2.1. Soil sampling and characterization

Samples were collected from the topsoil layer (0-20 cm depth) of a sandy loam Typic Hapludox, in Piracicaba, in the state of São Paulo, Brazil (22°43’5.3”S and 47°36’57.3”W), air-dried for 48 h, sieved to 4.0 mm, and stored for later use. Subsamples of this material were collected, passed through a 2.0 mm sieve, homogenized, and subjected to chemical and physical analyses.

For soil chemical characterization, pH values were determined by the potentiometric method in air-dried fine soil (ADFS) suspensions in a 0.01 mol L^{-1} $CaCl_2$ solution, with a soil-to-solution ratio of 1:2.5. Organic carbon was extracted after oxidation with $K_2Cr_2O_7$ in the presence of H_2SO_4, and the excess dichromate was titrated with 0.4 mol L^{-1} Fe $(NH_4)_2(SO_4)_2.6H_2O$ solution. Exchangeable aluminum (Al^{3+}) was extracted by 1 M KCl solution and quantified by titration. Exchangeable contents of K, P, Ca, and Mg were extracted with ion-exchange resins (Van Raij et al. 1986). Potential acidity (H^{+}+Al^{3+}) was estimated using the SMP pH method. Based on the results obtained, the base sum (BS), cation exchange capacity at pH 7.0 (CEC), and base saturation (BS) were calculated.

For soil physical characterization, organic matter was removed with 30% (v/v) H_2O_2, and particle dispersion was achieved using 0.2 M NaOH (Gee and Or 2002). Subsequently, the sand fraction was separated using a 0.05 mm-sieve, and the silt and clay fractions were collected in graduated cylinders (1 L) and separated by sedimentation (Melo et al. 2001). Soil density (ρ) was obtained using the volumetric ring method (Blake and Hartge 1986).

The sampled soil exhibited the following results from chemical and physical analyses: pH (0.01 M $CaCl_2$) = 4.4; 29 g dm^{-3} of organic matter; 13 mg dm^{-3} of P; 0.2 $mmol_c$ dm^{-3} of K; 4.4 $mmol_c$ dm^{-3} of Ca; 3.8 $mmol_c$ dm^{-3} of Mg; 2.0 $mmol_c$ dm^{-3} of Al; 24.9 $mmol_c$ dm^{-3} of H+Al; 33.3 $mmol_c$ dm^{-3} of CTC; V = 25%; 798 g kg^{-1} of sand; 57 g kg^{-1} of silt; 146 g kg^{-1} of clay; and soil density = 1.5 kg dm^{-3}.

2.2. Characterization of the organomineral fertilizer

The OMF was produced at the Embrapa Soils fertilizer laboratory in Rio de Janeiro, using commercial KCl (174.8 g) and poultry litter (825.2 g) as raw materials, in the following proportions: 10.5% (60% K_2O * 0.17476 kg) of K_2O through KCl and 1.8% (2.17% K_2O * 0.82524 kg) of K_2O through poultry litter. The mixture components were ground to a particle size less than 0.3 mm and dried in an oven at 65°C until mass stabilization. Subsequently, they were granulated using an EL-05 rotary mixing granulator from Eirich, and then 1 kg of the mixture was added to the mixer tank in powder form.

A mixing time of 1 min was established at a rotation speed of 30 Hz for dry mixing, and after this time, 220 mL of distilled water was added to the mixture, with additional mixing for another 150 s until granules of suitable size were formed. The granules were dried at 65°C for 24 hours and sieved between 2.0 and 2.8 mm. The OMF was analyzed prior to the experiment setup (Table 1), following the methodology adopted by the Ministry of Agriculture of Brazil for organomineral fertilizers. The determination of potentially toxic element content was carried out following the 3051A methodology, with a solution composed of nitric and hydrochloric acids in a 3:1 ratio (de Silva et al. 2014).

Table 1. Physical and chemical composition of organomineral fertilizer

Attribute	Results	
	Dry base (65°)	Wet base
pH (0.01 mol L^{-1} $CaCl_2$)	-	7.7
Density	-	0.5 kg dm^{-3}
Water content	-	9%
Organic matter	62%	60%
Organic Carbon	34%	33%
Total Mineral Residue	32%	31%
Nitrogen (N)	3%	3%
Phosphor (P_2O_5)	4%	4%
Potassium (K_2O)	13%	13%
Calcium (Ca)	4%	4%
Magnesium (Mg)	1%	1%
Sulfur (S)	1%	1%
C/N Ratio	-	12
Copper (Cu)	0.03%	0.03%
Iron (Fe)	0.10%	0.10%
Manganese (Mn)	0.04%	0.04%
Zinc (Zn)	0.12%	0.10%
Boron (B)	0.01%	0.01%
Sodium (Na)	3%	3%
Chlorine (Cl)	8%	8%
Cation Exchange Capacity	-	620 $mmol_c$ kg^{-1}

The maximum limits established by Brazilian Normative Instruction (NI) n. 27 of 05/06/2006 (amended by NI n. 7 of 12/04/2016) are 20 mg kg^{-1} of arsenic (As); 1 mg kg^{-1} of mercury (Hg); 70 mg kg^{-1} of nickel (Ni); 3 mg kg^{-1} of cadmium (Cd); 150 mg kg^{-1} of lead (Pb); 200 mg kg^{-1} of chromium (Cr); and 80 mg kg^{-1} of selenium (Se). The OMF presented the following analytical results: 1 mg kg^{-1} of As; <LD of Hg; 5 mg kg^{-1} of Ni; 0.1 mg kg^{-1} of Cd; <LD (limit of detection) of Pb; 12 mg kg^{-1} of Cr; and 3 mg kg^{-1} of Se.

2.3. Experiment establishment and management

The experiment was conducted under greenhouse conditions from January to March 2023. During this period, the air temperature ranged from 20°C (minimum) to 28°C (maximum) with an average of 24°C. The average relative humidity was 77%, and the maximum photosynthetic photon flux density reached approximately 1700 µmol m^{-2} s^{-1}.

The experimental design was a randomized complete block design, with four treatments (fertilizer rates) plus one control treatment (zero rate), four replicates, and two fertilizers (FOM and KCl), making a total of 36 experimental units. Each experimental unit was a polyethylene pot containing 4.5 kg of a sandy loam Typic Hapludox already corrected for base saturation (V = 70%). Drainage holes at the bottom of the pots were closed to prevent leaching. Before being weighed and placed in the pots, soil samples were air-dried and passed through a 4.0 mm mesh sieve. The fertilizer rates were applied according to the critical level (CL) of K in the soil (120 mg dm^{-3}). Therefore, the applied rates were: 65 mg dm^{-3} (40% below CL); 87 mg dm^{-3} (20% below CL); 109 mg dm^{-3} (CL); and 131 mg dm^{-3} (20% above CL), in addition to the control treatment without fertilizer. The DKB 360 PRO3 hybrid maize was grown as the test plant to evaluate agronomic parameters. Four seeds were sown per pot at a depth of 2 cm. After emergence, the plants were thinned, leaving only one plant per experimental unit. The emergence date was recorded when 90% of the pots had germinated plants. Before sowing, ammonium sulfate was applied as a source of N and S, and monoammonium phosphate was applied as a source of P, at rates of 100 mg dm^{-3} and 25 mg dm^{-3}, respectively. Potassium fertilizer was applied as a single rate before sowing. At ten days after emergence (DAE), a solution containing micronutrients [0.5 mg dm^{-3} of boron (B) as boric acid; 2.0 mg kg^{-1} of copper (Cu) as copper sulfate; 3.0 mg kg^{-1} of manganese (Mn) as manganese sulfate; and 4.0 mg kg^{-1} of zinc (Zn) as zinc sulfate] was applied. At 20 DAE, top-dressing fertilization was applied with a solution to all pots at a rate of 25 mg kg^{-1} of N, via ammonium sulfate. Plants were monitored throughout the experiment, and pots were weighed and irrigated daily with deionized water to maintain soil moisture at approximately 70% of the maximum water holding capacity (MWHC). The experiment was conducted for a 45-day cycle (V12 phenological stage).

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2.4. Biometric and plant tissue analysis of the crop

At harvest, plant height was measured, and stem diameter at 5 cm above ground level was measured using a caliper. Subsequently, leaves were counted for each plant, and the aboveground part was cut close to the ground at the stem base. Roots and aboveground parts were washed, stored in paper bags, and then dried at 60°C for 72 h in a forced-air oven. After drying, the material was weighed to determine the dry matter, then processed in a Wiley mill using a 40-mesh sieve, homogenized, stored in properly labeled polyethylene bags, and kept in a dry chamber until analysis.

For plant sample preparation, wet digestion was performed with a solution composed of nitric acid (HNO_3) and perchloric acid ($HClO_4$) in a 2:1 (v/v) ratio. Initially, 0.5 g of dried plant material was weighed using a precision digital balance.

The samples were then transferred to digestion tubes, and 6 mL of the acidic solution was added. The tubes were sealed with PVC film and left to stand at room temperature for at least 24 h. After this period, the samples were transferred to a digestion block equipped with a reflux condenser. The process started at 50°C and was gradually increased until reaching 160°C. The temperature was maintained at this level until the volume was reduced by half, and the release of brown NO_2 vapor ceased. Subsequently, the temperature was gradually increased until reaching 210°C, which was maintained until the release of white $HClO_4$ vapor ceased, and the extract began to clear and reduce in volume (Zasoski and Burau 1977).

After cooling, the extracts were transferred to sterile Falcon tubes. Next, the volume was adjusted to 50 mL using ultrapure water (Type 1 water: resistivity > 18 MΩ cm and organic carbon < 10 µg L^{-1}). All analyses were conducted in triplicate.

The determination of K, Ca, and Mg contents in both the aboveground part and roots was performed by atomic absorption spectrophotometry.

Based on the plant K contents and dry matter production, the accumulated amount of K was calculated using the formula A = C × MS, where A represents the accumulated amount, expressed in mg and µg per plant; C is the element concentration in g kg^{-1}; and MS is the dry matter mass in g per plant.

From these results and the available K content in the soil, the following parameters were calculated: i) nutrient uptake efficiency [(KUpE, mg g^{-1}) = (total accumulated nutrients in plant material, mg) / (root dry mass, g)] (Oliveira et al. 2023); ii) apparent recovery efficiency [(REK, %) = ((accumulated nutrients in aboveground part at rates - accumulated nutrients in aboveground part in control treatment) / (Amount of available K in rates) *100)] (Adaptation from Niu et al. 2011); and iii) agronomic efficiency of K use [(AKE, %) = ((aboveground dry mass at rates – aboveground dry mass in control treatment) / (total K available in rates - total K available in control treatment) *100)] (Adaptation from Neto et al. 2016).

2.5. Analysis approach

The results were subjected to statistical analyses using the RStudio statistical program. Analysis of variance was performed, and means were compared using the Tukey test (5%).

To evaluate the adequacy of the model used, normality tests (Shapiro-Wilk) and variance homoscedasticity tests (Hartley) were conducted. Significant interactions between sources and rates were analyzed using regression analysis with a significance level of 5% to assess the influence of each variable.

The choice of regression model was based on the significance of the regression coefficients, verified using the t-test for the coefficient of determination (R^2). Differences between fertilizers within each K rate were compared using the t-test (Student).

3. Results and discussion

The results showed quadratic adjustment in plant height measurements (Figure 1 A), stem diameter (Figure 1 B), aboveground dry mass (Figure 1 C), and root dry mass (Figure 1 D) as a function of fertilizer rates (Figure 2). The higher rate of KCl (>20% of the CL) reduced the development of maize plants, which can be attributed to a nutritional imbalance. Excessive K can interfere with the absorption of other nutrients, such as Ca and Mg, which can impair plant growth (Pahalvi et al. 2021; Xie et al. 2021).

The concentration (Figure 3 A) and accumulation (Figure 3 B) of K in the aboveground part of the corn plants increased as the K rate increased, following a linear model for both fertilizers. However, these values were higher in the KCl treatments, regardless of the rates applied. This difference can be attributed to the dynamics of nutrient release by fertilizers. Due to its higher solubility, KCl tends to release K more quickly and immediately, increasing its availability for plant uptake. In contrast, OMF may release K more gradually and sustainably over time.There was a higher accumulation of K in plants from treatments with KCl, but it did not translate into increased plant growth compared to OMF. This suggests that the increase in K concentration in the aboveground part of plants in KCl treatments may be related to luxury K consumption at higher rates, and thus plants absorbed more K than they actually needed for their development.

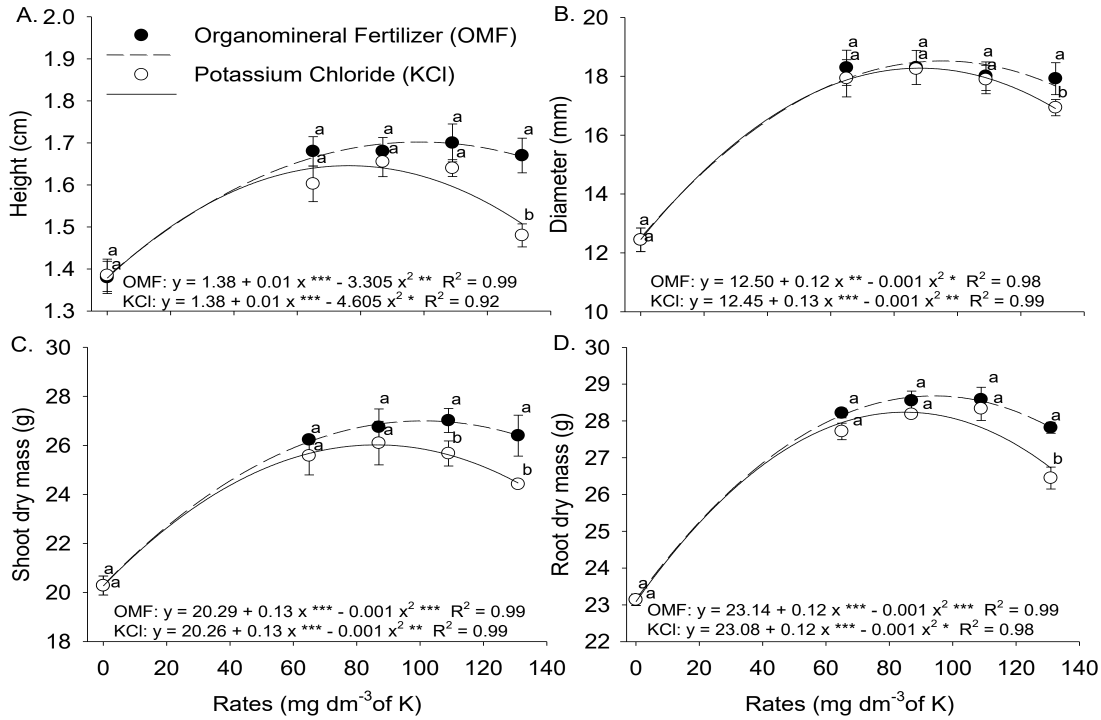

Figure 1. Growth parameters of corn plants cultivated for 45 days in an Oxisol after emergence (V12 stage) as a function of organomineral fertilizer (OMF ●) and potassium chloride (KCl ○) rates. Bars represent standard errors of the mean, n= 4. (***, **, and * – significant at 0.1%, 1%, and 5%, respectively). Comparison of fertilizer means within each rate (Student's t-test, $p \leq 0.05$)

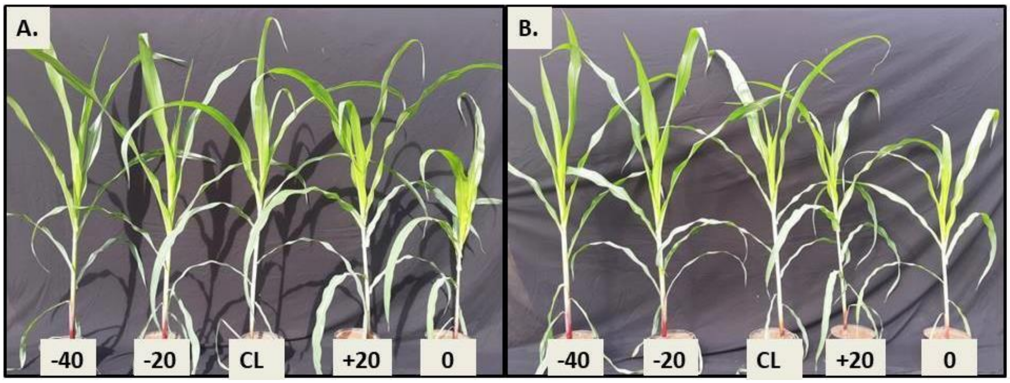

Figure 2. Corn plants at 45 days after emergence (V12 stage), cultivated in an Oxisol that received potassium fertilizers with rates applied based on the critical level (CL) of K in the soil (120 mg dm^{-3}). (a) Plants cultivated with organomineral fertilizer. (b) Plants cultivated with potassium chloride fertilizer. The applied rates were: -40% of CL = 65 mg dm^{-3}; -20% of CL = 87 mg dm^{-3}; CL = 109 mg dm^{-3}; and +20% of CL = 131 mg dm^{-3}

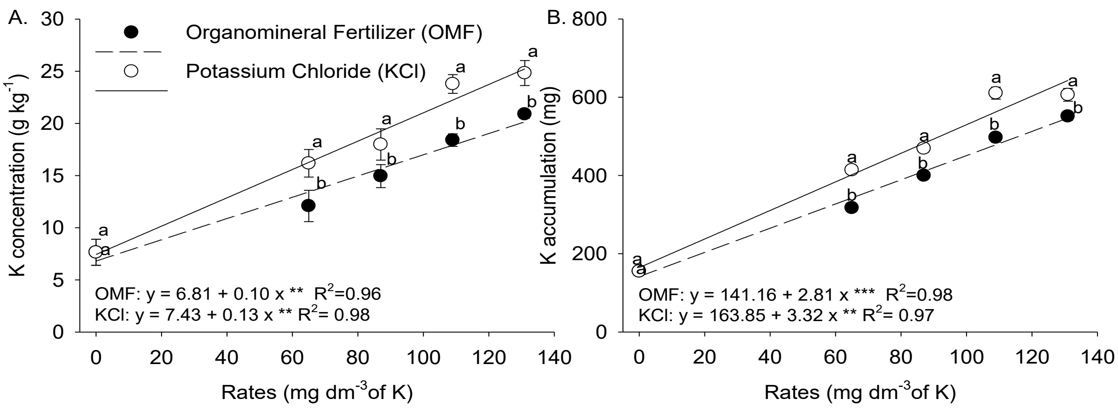

Figure 3. Potassium (K) concentration (A) and K accumulation (B) in the aboveground part of corn plants cultivated in an Oxisol as a function of organomineral fertilizer (OMF ●) and potassium chloride (KCl ○) rates. Bars represent standard errors of the mean, n= 4. (*** and ** – significant at 0.1% and 1%, respectively). Comparison of fertilizer means within each rate (Student's t-test, $p \leq 0.05$)

The treatments with FOM showed higher concentration and accumulation of Ca (Figure 4 A and B) and Mg (Figure 4 C and D) in the aboveground part of the plants compared to the treatments with KCl at all evaluated rates. There was a progressive increase in the concentration and accumulation of Ca and Mg in the OMF treatments as the rates were incremented, indicating positive correlation with the addition of OMF. On the other hand, in the KCl treatments, when increasing the rate by an additional 20% of the CL, the corn plants exhibited lower concentrations of Ca and Mg in the aboveground part, differing from all other applied rates (Table 2).

In the KCl treatments, rates 40% below the CL, 20% below the CL, and CL did not differ in Ca accumulation in corn plants ($p < 0.05$). Additionally, rates 40% below the CL and 20% above the CL also did not differ ($p < 0.05$). The plants in the control treatment showed lower Ca accumulation and differed from all other rates. Similar results were observed for Mg, where the zero rate showed lower accumulation compared to the other rates ($p < 0.05$) (Table 2).

In this study, the concentration of Ca and Mg in maize plants decreased when the rate of KCl was increased by more than 20% compared to the CL, and this effect may result from competition among K, Ca, and Mg ions at the root absorption sites (Mineo et al. 2009).

Nutrient absorption occurs through the action of proteins inserted in root membranes, which catalyze the transport of nutrients across these membranes.

Certain proteins are specific to particular nutrients, while others are less specific. For example, some families of plasma membrane transporters can transport various nutrients, such as the P3A-type H-ATPases which can transport Na^+, K^+, Ca^{2+}, Zn^{2+} (Rietra et al. 2017).

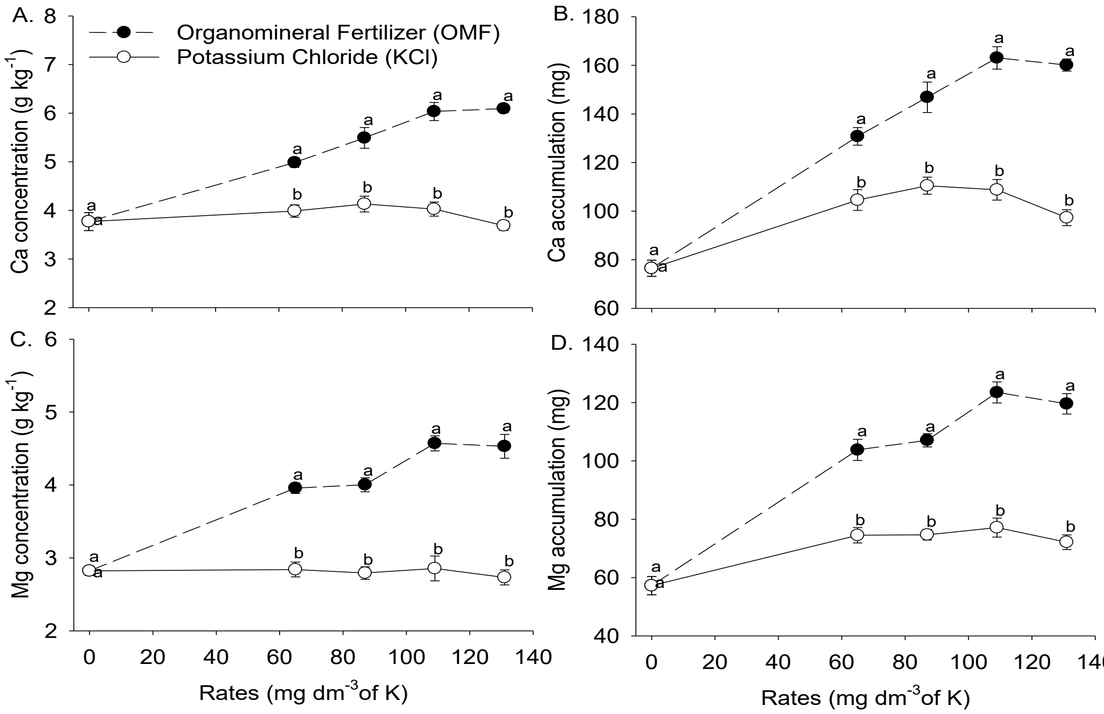

Figure 4. Calcium (Ca) concentration (A), Ca accumulation (B), magnesium (Mg) concentration (C), and Mg accumulation (D) in the aboveground part of corn plants cultivated in an Oxisol as a function of organomineral fertilizer (OMF ●) and potassium chloride (KCl ○) rates. Bars represent standard errors of the mean, n= 4. Comparison of fertilizer means within each rate (Student's t-test, $p \leq 0.05$)

Table 2. Calcium (Ca) concentration ([Ca^{2+}]), Ca accumulation (Ca*), magnesium (Mg) concentration ([Mg^{2+}]), and Mg accumulation (Mg*) in the aboveground part of corn plants cultivated at different rates of organomineral fertilizer and potassium chloride

Rate	Organomineral				Potassium chloride			
	[Ca^{2+}] g kg^{-1}	Ca* mg	[Mg^{2+}] g kg^{-1}	Mg* mg	[Ca^{2+}] g kg^{-1}	Ca* mg	[Mg^{2+}] g kg^{-1}	Mg* mg
Zero	3.7d	76.3d	2.8c	57.1c	3.7b	76.3c	2.8a	57.1c
< 40% of CL	4.9c	130.7c	3.9b	103.7b	3.9ab	104.5ab	2.8a	74.5ab
< 20% of CL	5.4b	146.7b	4.0b	107.0b	4.1a	110.4a	2.8a	74.6ab
CL	6.0a	162.9a	4.5a	129.5a	4.0ab	108.5a	2.8a	77.1a
>20% of CL	6.0a	160.7a	4.5a	123.4a	3.6c	97.2b	2.7b	72.1b

K is absorbed by plants through specific high-affinity channels as well as by nonspecific low-affinity channels, while Ca and Mg are absorbed by nonspecific channels only. Increased K concentrations in the soil may lead to greater competition between these ions in nonspecific channels. Consequently, there may be increased K absorption at the expense of Ca and Mg, which reduces the amount of these nutrients absorbed by plant roots (Yadav and Sidhu 2016; Shabala and Pottosin 2014). Results similar to those of our study were observed by Garcia et al. (2022) and Veloso et al. (2001) when investigating the relationship of Ca, Mg, and K in maize dry matter production. They also used KCl as a K source and found that increasing K rates resulted in reduced Mg concentration in the aboveground part of maize plants. The same was observed by Volf et al. (2022) when studying nutrient uptake dynamics by soybeans grown in sandy soil under K rates applied via KCl. Volf et al. (2022) observed a linear decrease in foliar concentrations of Ca and Mg with increasing K rate. Fertilizers showed comparable results regarding plant growth at rates below and at the CL, and this indicates that organomineral sources are as efficient as mineral sources, which corroborates the findings of other researchers (Mumbach et al. 2020; Frazão et al. 2019; Corrêa et al. 2018). At the highest K rate (>20% of the CL), OMF outperformed KCl in plant development compared to KCl, suggesting that its composition or nutrient release form may be more efficient in preventing nutritional imbalances. Additionally, OMF showed positive correlation between rate and Ca and Mg absorption by plants, which may have contributed to its better performance compared to KCl in plant growth. These results are attributed to the organic matrix of OMF, which contains Ca and Mg in its composition.

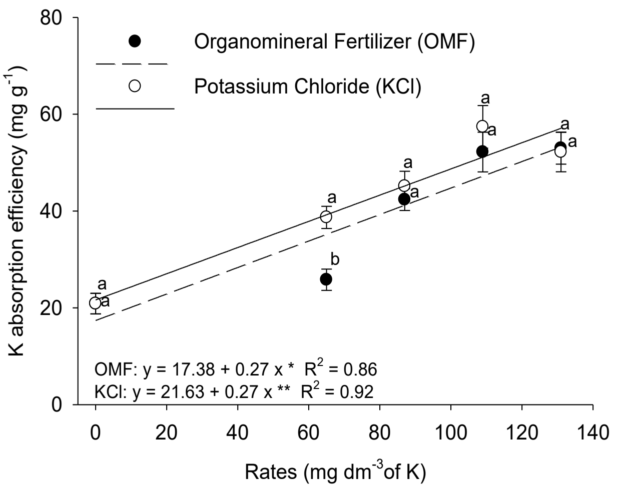

Figure 5. Potassium (K) uptake efficiency by corn plants cultivated at different rates of organomineral fertilizer (OMF ●) and potassium chloride (KCl ○). The bars indicate standard errors of the mean, n=4. (** and *– significant at 1% and 5%, respectively). Comparison of means between fertilizers within each rate (Student's t-test, $p \leq 0.05$)

Therefore, as rates increased, there was a linear increase in the concentration of these nutrients in the soil.

KCl and OMF had similar results in terms of potassium uptake efficiency (KUpE) by corn plants in most of the applied rates (< 20% of the CL, CL, and > 20% of the CL) (Figure 5). The exception occurred at the rate corresponding to 40% below the CL, where KCl had superior efficiency compared to OMF. This higher efficiency of KCl at the lowest applied K rate is due to the dynamics of K release, as KCl is highly soluble and provides K^+ more quickly compared to OMF. Therefore, in situations where plants have an urgent demand for K due to nutritional deficiency, KCl proves to be more efficient.

Apparent recovery efficiency (REK) ranged from 55% to 70% for OMF, while KCl showed a higher REK than OMF, with variations from 77% to 94% (Figure 6 A). The highest REK occurred at the CL for both fertilizers. Conversely, the lowest REK in the OMF treatments was at the rate of 40% below the CL, while for KCl it was at the rate of 20% above the CL ($p < 0.05$).

REK is defined as the percentage of added K that was recovered in plant biomass (Niu et al. 2011). The difference in REK between OMF and KCl is related to higher accumulation of K in the aboveground part of plants when KCl was added. There was a nonlinear pattern in REK, indicating that extreme rates can impair fertilizer efficiency. The lower REK in OMF at the lowest K rate (<40% of the CL) was related to the slow release of K in OMF. Therefore, at very low rates, the available amount of K may not be sufficient to meet plant needs, resulting in low REK. On the other hand, in KCl, the lower REK at the highest K rate (>20% of the CL) may be related to the fact that it provides K immediately to plants.

Excessive K saturation in the root environment can create problems of ionic competition and nutritional imbalance. Additionally, high levels of K can negatively affect specific physiological processes within the plant, such as water absorption and transpiration (Weksler et al. 2021), which can affect plant growth and development, making it less efficient in terms of nutrient recovery. The application of high rates of KCl also results in the addition of high amounts of chloride, which can lead to plant toxicity (Parker et al. 1983). The highest REK occurred in treatments with CL of K in the soil, meaning that supplying K through fertilizers may be more effective when aligned with the actual needs of plants. This highlights the importance of optimizing fertilizer rates to maximize REK while maintaining the balance between supplying necessary nutrients and minimizing costs and potential environmental impacts. The agronomic potassium uses efficiency (AKE) (Figure 6 B) followed a linear model for both fertilizers, with AKE decreasing as the potassium rate increased.

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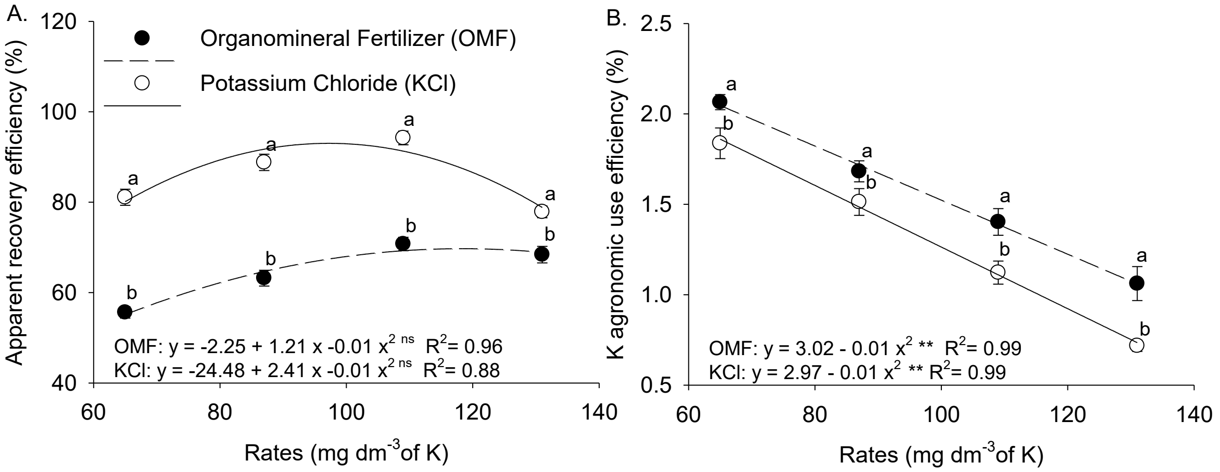

Figure 6. Apparent recovery efficiency (A) and agronomic potassium use efficiency (B) by maize plants grown under different rates of organomineral fertilizer (OMF ●) and potassium chloride (KCl ○). Error bars represent the standard error of the mean, n = 4. (** - significant at 1% and ns - not significant). Comparison of means of fertilizers within each rate (Student's t-test, $p \leq 0.05$)

OMF exhibited higher AKE compared to KCl at all evaluated rates. AKE is used to evaluate the increase in plant biomass production relative to the amount of K applied. The higher the AKE, the more efficient the potassium fertilizer is in improving maize crop yield, given the amount of K available in the soil and experimental conditions. For the two fertilizers evaluated, AKE decreased as the applied K rate increased. In other words, the more K applied, the lower the proportional increase in aboveground dry matter production, as has also been observed by Li et al. (2020) and Niu et al. (2011). The result is consistent with Mitscherlich's "Law of Diminishing Returns" in agriculture, which suggests that after a certain point, increasing the application of a nutrient, such as K, will not result in proportional increases in production. This may happen because other factors such as the availability of other nutrients or soil conditions may limit the additional benefit of applying more K (Ferreira et al. 2017). OMF had a higher AKE compared to KCl at all evaluated rates. Thus, under the conditions of this study, OMF was more effective in improving maize plant yield in relation to the amount of K applied compared to KCl. Li et al. (2020) and Fachini et al. (2022) associate higher AKE with slow fertilizer release, as gradual release of K provides more time for plants to absorb the nutrient, resulting in more efficient absorption over time and less losses due to leaching. Although OMF gradually releases nutrients, we cannot state that the higher AKE observed with OMF in our study was directly related to the dynamics of release and more efficient absorption of K, since there were no differences in KUpE between OMF and KCl. While the hypothesis that gradual release of K in OMF may have influenced AKE is plausible, our results indicate that other factors may be involved, including soil interactions, availability of other nutrients such as Ca and Mg, the effect of the organic matrix on soil microbial community, and other mechanisms that deserve further investigation to elucidate the underlying factors of AKE. Recent incubation studies have shown that granulated organomineral fertilizers tend to release K more steadily over time in sandy soils, which can improve synchronization with plant demand and enhance nutrient use efficiency (Barra Netto-Ferreira et al. 2023).

Unlike mineral fertilizers, organic and organomineral sources release nutrients more gradually, as they depend on the decomposition and mineralization of organic residues by soil microorganisms (de Morais et al. 2023; Viana et al. 2025).

Additionally, the application of poultry litter-based OMF alter the composition of bacterial and fungal communities in humid tropical soils, and favor microbial groups associated with nutrient cycling and organic matter decomposition (Oliveira et al. 2025). These findings indicate that, beyond the chemical properties of the fertilizer, the interaction between OMF and the soil microbiota may also contribute to the gains observed in agronomic efficiency, especially in low-fertile soils. Although the results demonstrate the efficiency of the OMF compared to KCl under controlled greenhouse conditions in sandy soil, some limitations must be considered.

The short experimental cycle and the absence of field conditions may not fully represent the long-term behavior and nutrient release patterns of OMF in field situations. Furthermore, the results may vary depending on the organic matrix of the fertilizer. Additional field studies conducted over multiple growing seasons and under different environmental conditions are necessary to validate these findings and to better understand the long-term agronomic and environmental impacts of organomineral potassium sources.

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4. Conclusion

The organomineral fertilizer had comparable or superior efficacy compared to potassium chloride, especially at rates close to the critical level of the element. Moreover, rates above the critical level of potassium in the soil did not result in production gains, regardless of the fertilizer used. The organomineral fertilizer and potassium chloride had similar level of efficacy. However, the use of organomineral fertilizer presents environmental benefits and contributes to the management of organic residues from agriculture and animal production, which cannot only improve productivity but also promote the achievement of global sustainable development goals.

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Authors Contribution

The authors confirm the conception and design of the study: Caroline de Figueiredo Oliveira, Tiago Tezotto, Vinícius de Melo Benites, Luís Reynaldo Ferracciú Alleoni; data collection and analysis: Caroline de Figueiredo Oliveira; interpretation of results: Caroline de Figueiredo Oliveira, Tiago Tezotto, Vinícius de Melo Benites, Luís Reynaldo Ferracciú Alleoni; manuscript writing: Caroline de Figueiredo Oliveira; critical review and editing: Tiago Tezotto, Vinícius de Melo Benites, Luís Reynaldo Ferracciú Alleoni. All authors reviewed the results and approved the final version of the manuscript.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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