Research Article

Residual effects of polyhalite on soil fertility in ratoon cane[1]

Stella Mendes Pio de Oliveira[2], Alex Oliveira Smaniotto[2],
Cauê Vieira Furtado Santana[2], Matheus Sousa Castro[2], Gustavo Castoldi[2]

ABSTRACT

Polyhalite is a potential alternative source of potassium (K) for sugarcane cultivation. Its lower solubility, compared to potassium chloride (KCl), suggests it may act as a slow-release fertilizer, providing residual benefits to subsequent crops. This study aimed to assess the residual effects of polyhalite on the soil following two cycles of potassium fertilization in ratoon cane, in comparison with KCl. The treatments included a control (no K fertilization) and K sources applied individually (polyhalite or KCl) or in combination (polyhalite + KCl). The polyhalite performed similarly to KCl and led to the highest K levels in the 0-20 cm soil layer after two sugarcane harvests. For the sulfur (S) content, the polyhalite significantly outperformed all other treatments, with the highest concentrations in the 0-20 and 20-40 cm layers. On the other hand, the supply of calcium and magnesium from polyhalite did not result in higher soil levels of these nutrients, with no significant differences among the evaluated sources. These findings highlight the residual benefits of polyhalite application, particularly for S, which may be beneficial for sugarcane or any subsequent crops.

KEYWORDS: *Saccharum officinarum*, soil fertility, slow-release fertilizer.

RESUMO

Efeito residual no solo do uso de polihalita
na adubação de soqueira de cana-de-açúcar

A polihalita é uma potencial fonte alternativa de potássio (K) para a cultura da cana-de-açúcar e, devido à sua menor solubilidade, em comparação ao cloreto de potássio (KCl), pode atuar como fertilizante de liberação lenta e proporcionar efeito residual benéfico aos cultivos subsequentes. Objetivou-se avaliar o efeito residual no solo da polihalita, comparada ao uso de KCl, após dois ciclos de adubação potássica da soqueira da cana-de-açúcar. Os tratamentos consistiram de controle sem adubação potássica e fontes de K aplicadas de forma isolada (KCl ou polihalita) ou associadas (polihalita + KCl). A polihalita se mostrou similar ao KCl e apresentou os maiores teores de K na camada de 0-20 cm, após dois ciclos de cultivo de cana-de-açúcar. Para o teor de enxofre (S), houve diferença entre a polihalita e todos os demais tratamentos, com maior teor nas camadas de 0-20 e 20-40 cm. Já o aporte de cálcio e magnésio pela polihalita não resultou em teores mais altos desses nutrientes no solo, uma vez que não houve qualquer diferença entre as fontes avaliadas. Os resultados evidenciam o efeito residual da aplicação de polihalita, em especial para S, podendo ser benéfico para a cana-de-açúcar ou quaisquer cultivos subsequentes.

PALAVRAS-CHAVE: *Saccharum officinarum*, fertilidade do solo, fertilizante de liberação lenta.

INTRODUCTION

Sugarcane plays a vital role in the global economy, accounting for approximately 21 % of the worldwide agricultural production between 2000 and 2021 (FAO 2024).

As a long-cycle crop, sugarcane requires consistent nutrient replenishment throughout its growth, particularly during the ratoon phase (Bhatt et al. 2021). Most sugarcane-producing areas are characterized by inherently low soil fertility, making the use of fertilizers essential for achieving high and sustainable yields (Marin et al. 2016).

Among all nutrients, potassium (K) is the most absorbed and exported by sugarcane (Cavalcante et al. 2015), especially during the ratoon cycle (Korndörfer & Oliveira 2005). Potassium is involved in sugar transport (Kerbauy 2012), water uptake and translocation, enzyme activation, osmoregulation and electrical charge balance (Prado 2020). In Brazil, potassium chloride (KCl), which contains 60 % of K_2O, is the predominant K source used.

[1] Received: Feb. 18, 2025. Accepted: July 02, 2025. Published: July 31, 2025. DOI: 10.1590/1983-40632025v5581758.
[2] Instituto Federal Goiano, Campus Rio Verde, Rio Verde, GO, Brazil. *Email/ORCID*: stellamendesp@hotmail.com/0000-0002-0637-6303; aosmaniotto@gmail.com/0000-0001-8745-8935; caue.v.furtado@gmail.com/0009-0000-9715-7597; matheuscastro5200x@gmail.com/0009-0000-3467-0596; gustavo.castoldi@ifgoiano.edu.br/0000-0002-2206-2830.
Editor: Luis Carlos Cunha Junior

Polyhalite is a naturally occurring mineral fertilizer composed of K, calcium (Ca), magnesium (Mg) and sulfur (S) in the form of sulfate (SO_4^{2}-S) (Kemp et al. 2016). It contains 14 % of K_2O and can be applied alone or in combination with other sources of K, such as KCl (Yermiyahy et al. 2017, Mello et al. 2018). Polyhalite has a lower solubility than other potassium fertilizers, such as KCl (Dal Molin et al. 2020).

The nutrient release characteristics of polyhalite have been investigated in various studies. Lewis et al. (2019) evaluated different physical forms of polyhalite (powder, crushed rock and granules) alongside KCl in leaching columns and reported that, after 4,500 mm of simulated rainfall, granulated polyhalite resulted in the highest release of Ca, Mg and sulfate-S. All forms of polyhalite released more K than KCl. In another study, Huang et al. (2020) used lysimeters filled with sandy and clayey soils to compare polyhalite with soluble sulfate salts. When rainfall was sufficient, polyhalite enhanced carrot yields, primarily by increasing Ca uptake, especially in sandy soils. In both soil types, polyhalite acted as a slow-release fertilizer, with nutrient retention concentrated in the upper soil layers and minimal leaching beyond the root zone.

According to Pavinato et al. (2020), sugarcane responds positively to high K fertilization due to its substantial nutrient requirements and the low levels of exchangeable K typical of highly weathered tropical soils. Polyhalite may therefore be a promising source of K, Ca, Mg and S for sugarcane production in Brazil, given the high fertilizer demand and low native soil fertility. However, the response of sugarcane to polyhalite, in comparison with conventional sources such as KCl, remains largely unknown.

This study aimed to test the hypothesis that polyhalite may serve as an effective alternative fertilizer to supply K, Ca, Mg and S to sugarcane. Additionally, due to its lower solubility relative to KCl, polyhalite may function as a slow-release fertilizer and contribute to residual nutrient availability for subsequent crops. Thus, the objective here was to evaluate the residual effect of polyhalite on soil fertility following its application to ratoon cane, with particular emphasis on comparisons with KCl, the standard K source used in the Brazilian sugarcane production.

MATERIAL AND METHODS

The study was conducted using soil samples collected from a field experiment designed to evaluate K fertilizer sources for ratoon cane. The experiment spanned two growing seasons and was established under field conditions in Jataí, Goiás state, Brazil (17º38'37"S, 51º34'31"W and altitude of 891 m).

The region is characterized by average annual rainfall and temperature of 1,600 mm and 23 ºC, respectively. The soil in the experimental area is classified as Latossolo Vermelho Distrófico (LVd) with a clayey texture, Cerrado (Brazilian Savanna) phase (Santos et al. 2018), corresponding to Ferralsol (Caldas et al. 2021).

The sugarcane (CTC4 cultivar) was planted in 2015, at a density of 20 buds m^{-1}. Potassium fertilization treatments began in October 2019, corresponding to the fourth ratoon cycle. At the onset of the experiment, soil samples were collected in the 0-20 and 20-40 cm layers and analyzed for baseline fertility parameters (pH, organic matter, P, SO_4^-, K, Ca, Mg, Al^{+3}, H + Al and micronutrients), as well as particle size distribution (Table 1).

The underlying experiment for this study was arranged in a randomized block design, comprising four treatments and five replicates. The treatments

Table 1. Basic soil chemical and textural properties in the experimental area.

Layer	pH	P	S	K	K	Ca	Mg	Al	H + Al	CEC	V	m
cm	$CaCl_2$	mg dm^{-3}			cmol$_c$ dm^{-3}						%	
0-20	4.70	5.02	13.3	25	0.06	1.74	0.45	0	4.95	7.21	31.4	0
20-40	4.86	3.87	14.1	19	0.05	1.36	0.31	0	4.68	6.40	26.9	0

Layer	OM	Fe	Mn	Cu	Zn	B	Clay	Silt	Sand
cm	g dm^{-3}	mg dm^{-3}					g kg^{-1}		
0-20	32.7	26.2	6.94	1.63	6.68	0.27	384	85	531
20-40	28.8	15.1	2.04	1.38	1.80	0.24	369	55	576

P, K, Ca and Mg were extracted via resin; Al via KCl; S (SO_4^{2-}) via calcium phosphate; B via hot water; Fe, Mn, Cu and Zn via DTPA. CEC: cation exchange capacity; V: base saturation; m: exchangeable aluminum saturation; OM: organic matter.

included a control (no K fertilization), KCl, polyhalite and a combination treatment in which 25 % of K_2O was supplied by polyhalite and 75 % by KCl (25/75). POLY4® was the polyhalite used, a commercially available granular fertilizer derived from ground and granulated polyhalite rock, containing 19 % of S, 14 % of K_2O, 12.1 % of Ca and 3.6 % of Mg.

The potassium fertilization for ratoon cane in both growing seasons was calculated based on a nutrient replacement rate of 1.3 kg ha^{-1} of K_2O per ton of stalks harvested in the preceding cycle. The average stalk yields in the third and fourth ratoon cycles were 100 and 80 t ha^{-1}, respectively. As a result, K_2O application rates for the fourth and fifth ratoons were 130 and 104 kg ha^{-1}, respectively. The total quantities of applied fertilizer and nutrient contributions from each treatment over both cycles are detailed in Table 2.

In both growing seasons, all experimental plots received standardized phosphorus and nitrogen fertilization: 40 kg ha^{-1} of P_2O_5 (supplied as monoammonium phosphate - MAP) and 130 kg ha^{-1} of N (supplied via MAP and urea). The fertilizers were manually applied in surface bands along each row. Each experimental unit consisted of five 8-m-long rows spaced 1.5 m apart.

Soil sampling was performed after the fifth ratoon harvest, in August 2021. The samples were collected using a probe-type auger at three points within each plot (two between rows and one within the row), at depths of 0-20, 20-40 and 40-60 cm. The samples were labeled, processed and analyzed for pH, organic matter, P, SO_4^-, Al^{+3}, H + Al, K, Ca, Mg and B (Raij et al. 2001).

The soil pH was determined using a pH meter and a 0.01 mol L^{-1} calcium chloride ($CaCl_2$) solution. Exchangeable phosphorus (P) and potassium (K) were extracted using ion-exchange resin and quantified using a UV-VIS spectrophotometer and flame photometer, respectively.

Exchangeable calcium (Ca) and magnesium (Mg) were also extracted using ion-exchange resin and measured with an atomic absorption spectrophotometer, whereas the total soil acidity was determined following extraction with a 1 N $Ca(C_2H_3O_2)_2$ H_2O buffered solution at pH 7.0, using alkalimetric titration.

Exchangeable aluminum (Al^{3+}) was extracted using 1 mol L^{-1} of KCl and measured by an atomic absorption spectrophotometer. Sulfate (SO_4^{2-}) was extracted with 0.01 mol L^{-1} of calcium dihydrogen phosphate [$Ca(H_2PO_4)_2$] and quantified by a UV-VIS spectrophotometry. Boron (b) was determined colorimetrically using the azomethine-H method, whereas the organic matter content was determined via dichromate oxidation of organic carbon in a highly acidic medium, with titration of excess dichromate using Fe^{+2} ions.

The data were analyzed using descriptive statistics to assess the central tendency, dispersion and outliers. After exploratory analysis, assumptions of normality, homoscedasticity and independence were tested using the Shapiro-Wilk, Bartlett and Durbin-Watson tests, respectively ($p < 0.05$). When assumptions were met, analysis of variance (Anova) was performed. Significant treatment effects were further analyzed using the Tukey test ($p < 0.05$). The treatment means were compared within each individual soil layer and no comparisons were made between layers.

RESULTS AND DISCUSSION

After two sugarcane cultivation cycles, significant treatment effects on soil chemical fertility were limited to S content in the 0-20 and 20-40 cm layers, and to pH and K content in the 0-20 cm layer (Table 3). No significant differences were observed for the other fertility parameters, regardless of soil depth, following K fertilization in the fourth and fifth ratoon cycles.

Table 2. Fertilizer and nutrient quantities supplied by each treatment during the fourth and fifth ratoon fertilizations.

Treatments	Fertilizers		Nutrients			
	Polyhalite	KCl	K_2O	S	Ca	Mg
	kg ha^{-1}					
Control	-	-	-	-	-	-
KCl	-	390.0	234	-	-	-
Polyhalite	1,672.5	-	234	317.5	203.0	60.5
Polyhalite + KCl (25/75)	417.8	292.5	234	79.4	50.8	15.1

Table 3. Soil fertility attributes at three depths following two growing seasons of potassium (K) source application in ratoon cane.

K sources	pH	OM	P	B	H + Al	SB	CEC	m	V
0-20 cm	$CaCl_2$	g dm^{-3}	mg dm^{-3}		cmol$_c$ dm^{-3}			%	%
Combination	4.71 ab*	39.11	8.33	0.49	5.23	2.73	7.97	8.94	34.35
Control	4.78 a	36.45	13.64	0.58	4.72	3.09	7.81	6.35	39.46
KCl	4.65 b	32.60	6.64	0.48	5.04	2.63	7.68	9.50	34.35
Polyhalite	4.73 ab	40.22	9.08	0.65	5.15	3.16	8.32	6.73	38.10
20-40 cm									
Combination	4.69	29.00	3.36	0.25	4.51	1.42	5.94	16.70	24.42
Control	4.69	26.63	2.20	0.19	4.22	1.41	5.64	17.10	24.55
KCl	4.75	25.39	2.40	0.22	4.11	1.46	5.58	10.15	26.12
Polyhalite	4.80	27.88	3.12	0.28	3.96	1.47	5.44	9.71	27.20
40-60 cm									
Combination	4.90	26.03	2.00	0.15	3.25	1.09	5.27	7.15	24.70
Control	4.94	26.81	2.04	0.09	3.37	1.00	4.37	6.31	23.47
KCl	4.95	25.30	1.20	0.14	3.20	0.97	4.18	5.67	23.26
Polyhalite	4.93	23.11	2.04	0.17	3.31	1.17	4.49	6.17	26.43

* Means followed by different lowercase letters in the column and for each variable indicate a significant difference in the treatment effects according to the Tukey test ($p < 0.05$). OM: organic matter; SB: sum of bases; CEC: cation exchange capacity; m: exchangeable aluminum saturation; V: base saturation.

In the evaluation of soil pH after two cultivation cycles, exclusive K fertilization with KCl resulted in a 2.72 % decrease in pH in the 0-20 cm layer, if compared to the control treatment (Table 3). It is important to note that the pH values remained low across all treatments, since no soil amendments were applied during the experiment. This outcome is consistent with the low base saturation (V) and the presence of toxic Al^{3+} levels (m).

Figure 1 illustrates the concentrations of Ca, Mg, K and S, key nutrients supplied by polyhalite across the soil profile.

After two sugarcane cultivation cycles, there were no significant differences in Ca and Mg concentrations among the treatments at any of the three soil depths evaluated (Figures 1A and 1C). However, it is important to underscore that, at least in the surface layer, the levels of these nutrients were within the adequate range for the Cerrado region (Sousa & Lobato 2004). The K content in the 0-20 cm layer was higher in the polyhalite treatment than in the control, but did not differ significantly from the combination and KCl treatments (Figure 1D). The S concentrations in both the 0-20 and 20-40 cm layers were the highest in the treatments containing polyhalite, either alone or combined with KCl (Figure 1B).

The effectiveness of a soil-applied nutrient source largely depends on its availability for plant uptake, which, in the case of mineral fertilizers, is strongly influenced by solubility (Pavinato & Rosolem 2008). In leaching column experiments, Lewis et al. (2019) evaluated different physical forms of polyhalite (powder, crushed rock and granules) and found that the granulated form released greater amounts of Ca (183.6 µg *vs*. 153.5 µg with KCl), Mg (40.1 µg *vs*. 28.4 µg with KCl) and SO_4^{2}-S (358.4 µg *vs*. 67.3 µg with KCl). The granulated polyhalite analyzed in that study is the same product used in the present study. Similarly, Barbier et al. (2017), using leaching tests in sandy soils, reported that polyhalite released K more rapidly than potassium muriate, potassium sulfate, and potassium and magnesium sulfate.

Potassium occurs in the soil in several forms: soluble, exchangeable, non-exchangeable and mineral-bound, the last accounting for up to 90-98 % of the total soil K (Barber 1995). These forms exist in dynamic equilibrium, which determines the amount of K available in the soil solution, the form readily absorbed by plants. However, this form is also highly susceptible to leaching, particularly in soils with low cation exchange capacity (CEC), where K^+ ions have fewer binding sites on soil colloids (Bijay et al. 2004).

It is important to underscore that a greater contribution from the non-exchangeable K fraction is typically seen in soils dominated by 2:1 clay minerals, which exhibit high cation exchange capacity (CEC) (Souza Junior et al. 2007). By contrast, in highly

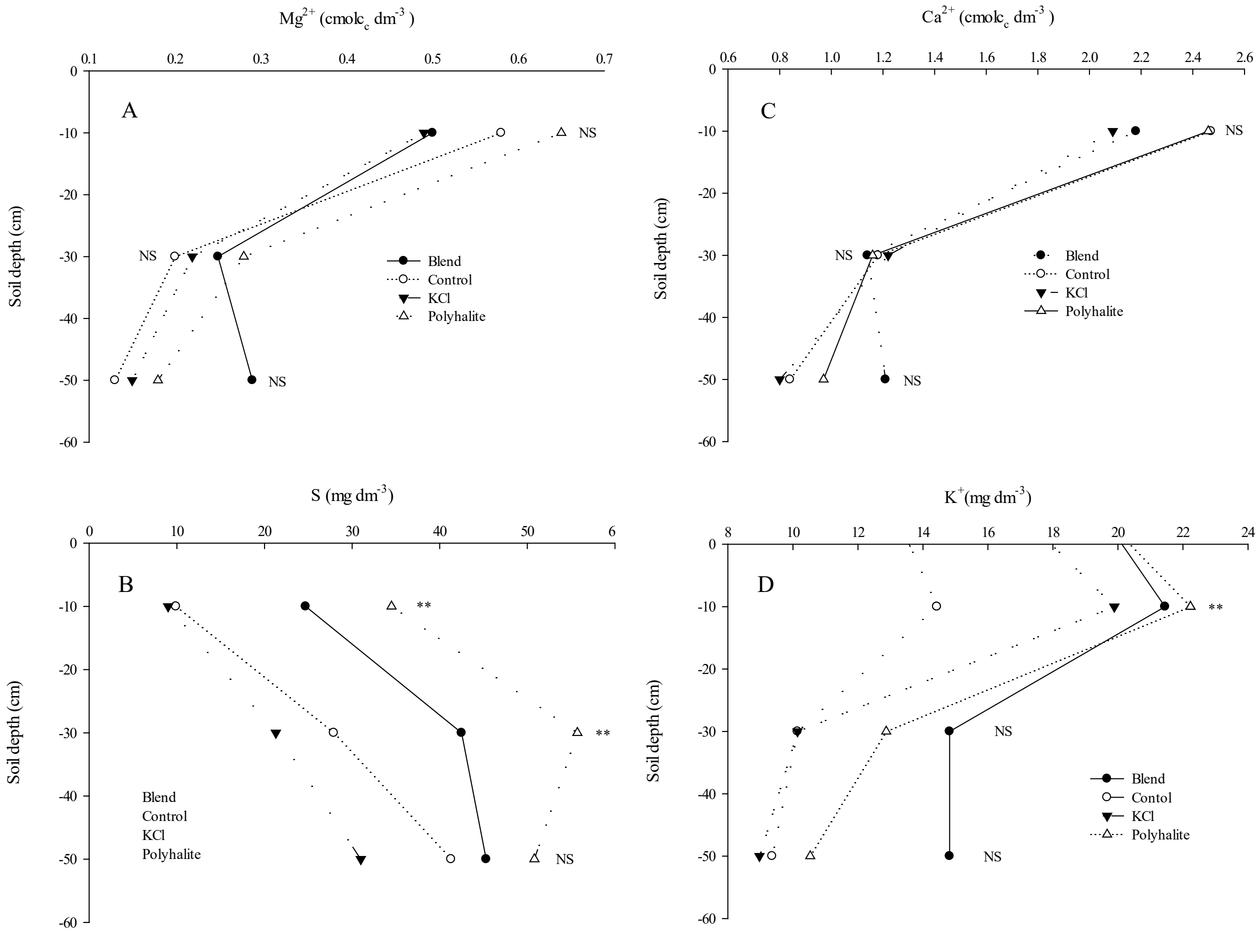

Figure 1. Exchangeable magnesium (A), sulfur (B), calcium (C) and potassium (D) concentrations across the soil profile, following two seasons of potassium source application in ratoon cane. * NS: non-significant difference; ** significant treatment effect within the soil layer according to the Tukey test ($p < 0.05$).

weathered tropical soils dominated by Fe and Al oxides and 1:1 clays such as kaolinite, with naturally low CEC, this contribution is minimal (Melo et al. 2002). Although a high soil K-supplying capacity may mask residual effects of K fertilization, this was not observed in the present study. After two years, the K content in the control treatment was significantly lower than in the fertilized treatments, at least in the 0-20 cm soil layer (Figure 1D).

Soil texture also plays a critical role in K dynamics (Brunetto et al. 2005). Sandy soils, which are more prone to water percolation, tend to lose K more readily than clay-rich soils (Lima 2001). As such, they often require higher K fertilization rates or the use of less soluble, more efficient fertilizers to ensure optimum yields and maintain a positive K balance (Rosolem & Steiner 2017). In this regard, polyhalite has been proposed as a promising K source due to its lower leaching potential and reduced salt stress risk, attributed to its low chloride content and gradual nutrient release (Yermiyahu et al. 2019). However, this potential advantage was not fully confirmed in the present study, since there were no statistically significant differences in residual soil K among the fertilizer treatments (Figure 1D). It should be noted that the soil in question was a sandy clay loam with initially low K levels (≤ 25 mg dm^{-3}) (Sousa & Lobato 2004).

The highest S content in the 0-20 and 20-40 cm layers was recorded in the treatment with polyhalite alone, when compared to the KCl and control treatments (Figure 1B). This reflects the composition of the polyhalite fertilizer used, which contains 19 % of S, as already reported by Yermiyahu et al. (2017). These authors found that polyhalite not only increased the residual S content in the soil, compared to other sulfate sources, but also resulted in lower nutrient losses by leaching and a stronger residual effect, particularly for S, on the subsequent crop (wheat, in that case).

Sulfur is known for its high leaching potential due to its retention in soils (Batista et al. 2018). Most SO^{-2}_4 in the soil can be removed through water extraction (Curtin & Syers 1990). The extent of sulfate leaching depends heavily on soil texture and water drainage volume. Jones et al. (1968) reported that up to 80 % of the S applied as gypsum to the soil was lost within a single year in soils with low adsorption capacity. Therefore, less soluble or slow-release fertilizers such as polyhalite may offer significant advantages, ensuring a steady nutrient supply over time and minimizing losses across the production cycle (Faquin 2005).

Although some researchers recommend calculating polyhalite application based on Ca and Mg needs (Yermiyahu et al. 2017, Mello et al. 2018), our findings indicate that polyhalite is particularly effective as a source of K and S. Further long-term studies are needed to understand the dynamics and distribution of K in the soil profile, which could support the development of more efficient fertilizer strategies for sugarcane cultivation.

CONCLUSIONS

1. Polyhalite fertilizer, whether used alone or in combination with potassium chloride (KCl), emerges as a promising fertilization strategy in sugarcane systems, especially due to its residual effects, which were more evident for sulfur (S);
2. After two harvests (fourth and fifth ratoons), even with very low K levels in the soil, polyhalite performed comparably to KCl and led to higher K concentrations in the 0-20 cm layer, in relation to the control treatment;
3. For S, polyhalite produced significantly higher concentrations in both the 0-20 and 20-40 cm layers, when compared to all other treatments.

ACKNOWLEDGMENTS

The authors would like to thank the Fundação de Amparo à Pesquisa do Estado de Goiás (FAPEG) for providing a doctoral scholarship to the first author, and to Cibra Fertilizantes and Anglo American for their financial support in the development of this project.

REFERENCES

BARBER, S. A. *Soil nutrient bioavailability*: a mechanical approach. 2. ed. New York: Wiley, 1995.

BARBIER, M.; LI, Y. C.; LIU, G.; HE, Z.; MYLAVARAPU, R.; ZHANG, S. Characterizing polyhalite plant nutritional properties. *Agricultural Research & Technology*, v. 6, n. 3, e555690, 2017.

BHATT, R.; SINGH, P.; ALI, O. M.; LATEF, A. A. H. A.; LAING, A. M.; HOSSAIN, A. Polyhalite positively influences the growth, yield and quality of sugarcane (*Saccharum officinarum* L.) in potassium and calcium-deficient soils in the semi-arid tropics. *Sustainability*, v. 13, n. 19, e10689, 2021.

BATISTA, M. A.; INOUE, T. T.; ESPER NETO, M.; MUNIZ, A. S. Princípios de fertilidade do solo, adubação e nutrição mineral. *In*: BRANDÃO FILHO, J. U. T.; FREITAS, P. S. L.; BERIAN, L. O. S.; GOTO, R. (org.). *Hortaliças-fruto*. Maringá: Eduem, 2018. p. 113-162.

BIJAY, S.; YADVINDER, S.; IMAS, P.; XIE, J. Potassium nutrition of the rice-wheat cropping system. *Advances in Agronomy*, v. 81, n. 1, p. 203-259, 2004.

BRUNETTO, G.; GATIBONI, L. C.; SANTOS, D. R.; SAGGIN, A.; KAMINSKI, J. Nível crítico e resposta das culturas ao potássio em um Argissolo sob sistema plantio direto. *Revista Brasileira de Ciência do Solo*, v. 29, n. 2, p. 225-234, 2005.

CALDAS, A. M.; ROLIM NETO, F. C.; RODRIGUES, A. C. F.; MOURA, A. E. S. S.; SILVA, E. R.; POSSAS JUNIOR, M. C.; SENA, J. R.; BRAGA, S. E.; SILVA, L. J. S.; RIZZI NETO, E.; PERÔNICO, A. M. B. L.; FEITOSA, T. H. S.; SANTOS, A. H. O.; SOUZA, I. A.; CORRÊA, M. M. Morphometry physical-chemical and microbiological water quality aspects and anthropic actions in a watershed in the Atlhantic Forest region. *Research, Society and Development*, v. 10, e5, 2021.

CAVALCANTE, V. S.; PRADO, R. M.; ALMEIDA, H. J.; CRUZ, F. J. R.; SANTOS, D. M. M. Gaseous exchanges, growth and foliar anatomy of sugarcane plants grown in potassium (K) deprived nutrient solution. *Australian Journal of Crop Science*, v. 9, n. 7, p. 577-584, 2015.

CURTIN, D.; SYERS, J. K. Extractability and asdorption of sulfate in soils. *Journal of Soil Science*, v. 41, n. 2, p. 305-312, 1990.

DAL MOLIN, S. J.; NASCIMENTO, C. O.; TEIXEIRA, P. C.; BENITES, V. M. Polyhalite as a potassium and multinutrient source for plant nutrition. *Archives of Agronomy and Soil Science*, v. 66, n. 5, p. 667-678, 2020.

FAQUIN, V. *Nutrição mineral de plantas*. Lavras: Ed. UFLa, 2005.

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS (FAO). *Faostat*. 2024. Available at: http://www.fao.org/faostat/en/#data. Access on: June 29, 2024.

HUANG, C.; YERMIYAHU, U.; SHENKER, M.; BEN-GAL, A. Effect of leaching events on the fate of polyhalite nutrient minerals used for crop fertilization. *Journal of Plant Nutrition*, v. 43, n. 2, p. 2518-2532, 2020.

JONES, M. B.; MARTIN, W. E.; WILLIANS, W. A. Behavior of sulfate sulfur and elemental sulfur in three California soils in lysimeters. *Soil Science Society of America Proceedings*, v. 32, n. 4, p. 535-540, 1968.

KEMP, S. J.; SMITH, F. W.; WAGNER, D.; MOUNTENEY, I.; BELL, C. P.; MILNE, C. J.; POTTAS, T. L. An improved approach to characterize potash bearing evaporite deposits, evidenced in North Yorkshire, United Kingdom. *Economic Geology*, v. 111, n. 3, p. 719-742, 2016.

KERBAUY, G. B. *Fisiologia vegetal*. 2. ed. Rio de Janeiro: Guanabara Koogan, 2012.

KORNDÖRFER, G. H.; OLIVEIRA, L. A. O potássio na cultura da cana-de-açúcar. *In*: YAMADA, T.; ROBERTS, T. L. (ed.). *Potássio na agricultura brasileira*. Piracicaba: ESALQ/USP, 2005. p. 469-490.

LEWIS, T. D.; HALLETT, P. D.; PATON, G. I.; HARROLD, L. Retention and release of nutrients from polyhalite to soil. *Soil Use and Management*, v. 36, n. 1, p. 117-122, 2019.

LIMA, V. C. *Fundamentos de pedologia*. Curitiba: Ed. UFPR, 2001.

MARIN, F. R.; MARTHA JUNIOR, G. B.; CASSMAN, K. G.; GRASSINI, P. Prospects for increasing sugarcane and bioethanol production on existing crop area in Brazil. *Bioscience*, v. 66, n. 4, p. 307-316, 2016.

MELLO, S. C.; PIERCE, F. J.; TONHATI, R.; ALMEIDA, G. S.; DOURADO-NETO, D.; PAVULURI, K. Potato response to polyhalite as a potassium source fertilizer in Brazil: yield and quality. *Hort Science*, v. 53, n. 3, p. 373-379, 2018.

MELO, V. F.; SCHAEFER, C. E. G. R.; NOVAIS, R. F.; SINGH, B.; FONTES, M. P. F. Potassium and magnesium in clay minerals of some Brazilian soils as indicated by a sequential extraction procedure. *Communications in Soil Science and Plant Analysis*, v. 33, n. 13-14, p. 2203-2225, 2002.

PAVINATO, P. S.; CORÁ, J. E.; SANTOS, A. C.; HERRERA, W. F. B.; PAVULURI, K.; PIERCE, F. J. Sugarcane response to polyhalite fertilizer in Brazilian Oxisoils. *Agronomy Journal*, v. 112, n. 6, p. 5264-5278, 2020.

PAVINATO, P. S.; ROSOLEM, C. A. Disponibilidade de nutrientes no solo: decomposição e liberação de compostos orgânicos de resíduos vegetais. *Revista Brasileira de Ciência do Solo*, v. 32, n. 3, p. 933-945, 2008.

PRADO, R. M. *Nutrição de plantas*. 2. ed. Jaboticabal: Edunesp, 2020.

RAIJ, B. V.; ANDRADE, J. C.; CANTARELLA, H.; QUAGGIO, J. A. *Análise química para avaliação da fertilidade de solos tropicais*. Campinas: Instituto Agronômico, 2001.

RAIJ, B. V.; CANTARELLA, H.; QUAGGIO, J. A.; FURLANI, A. M. C. *Recomendações de adubação e calagem para o estado de São Paulo*. 2. ed. Campinas: Instituto Agronômico, 1996.

ROSOLEM, C. A.; STEINER, F. Effects of soil texture and rates of K input on potassium balance in tropical soil. *European Journal of Soil Science*, v. 68, n. 5, p. 658-666, 2017.

SANTOS, H. G.; JACOMINE, P. K. T.; ANJOS, L. H. C.; OLIVEIRA, V. A.; LUMBRERAS, J. F.; COELHO, M. R.; ALMEIDA, J. A.; ARAUJO FILHO, J. C.; OLIVEIRA, J. B.; CUNHA, T. J. *Sistema brasileiro de classificação de solos*. 5. ed. Brasília, DF: Embrapa, 2018.

SOUSA, D. M. G.; LOBATO, E. *Cerrado*: correção do solo e adubação. 2. ed. Brasília, DF: Embrapa, 2004.

SOUZA JUNIOR, I. G.; COSTA, A. C. S. da; SAMBATTI, J. A.; PETERNELE, W. S.; TORMENA, C. A.; MONTES, C. R.; CLEMENTE, C. A. Contribution of clay fraction minerals of subtropical soils to the specific surface area and cation exchange capacity. *Revista Brasileira de Ciência do Solo*, v. 31, n. 6, p. 1355-1365, 2007.

YERMIYAHU, U.; ZIPORI, I.; FAINGOLD, I.; YUSOPOV, L.; FAUST, N.; BAR-TAL, A. Polyhalite as a multi nutrient fertilizer: potassium, magnesium, calcium and sulfate. *Israel Journal of Plant Science*, v. 64, n. 3, p. 145-157, 2017.

YERMIYAHU, U.; ZIPORI, I.; OMER, C.; BEER, Y. Solubility of granular polyhalite under laboratory and field conditions. *Electronic International Fertilizer Correspondence*, n. 58, p. 3-9, 2019.