Research Findings

Photo 1. Evaluating polyhalite on orange crop in Brazil.

Evaluation of Polyhalite Fertilizer on the Yield and Quality of Orange Crop in Brazil

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Abstract

Polyhalite is a new, natural, multi-nutrient fertilizer which contains 48% SO_3 as sulfate, 14% K_2O as sulfate of potash, 6% MgO as magnesium sulfate, and 17% CaO as calcium sulfate. The objective of this study was to evaluate polyhalite as a partial replacement for potassium chloride (KCl) fertilizer in orange plantations in Brazil. The experiment took place in 2017-2018 at Colorado farm, in Mogi Guaçu, São Paulo state, Brazil. The treatments included fertilizer blends with increasing proportions of polyhalite at the expense of KCl, at 0, 23, 39, 51, 60, and 68% polyhalite (0, 140, 280, 420, 560, and 700 kg ha^{-1}, respectively) while using KCl to maintain a constant total K_2O dose of 300 kg ha^{-1}. The experiment was designed in four random blocks. Leaf Ca, Mg, and S concentrations increased significantly with the rising polyhalite application rate. Fruit counts and size increased significantly in response to the rising polyhalite rate from 0-280 kg ha^{-1}, no further response was detected at higher polyhalite rates. While fruit and juice quality parameters were unaffected by the fertilizer treatments, the overall sugar yield rose to

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2,537 kg ha^{-1}, 42% greater than the KCl control, mainly due to the yield increase. Curve fitting elucidated that the optimum polyhalite application rate was from 300-500 kg ha^{-1}. Unequivocally, the partial replacement of KCl with polyhalite displayed significant advantages to industrial orange production under tropical conditions in Brazil. The Ca, Mg and S nutrient status in the trees was enriched with polyhalite application. Overall crop performance was significantly improved, including fruit and TSS yields. However, it remains open whether the potential of this fertilizer has been fully exploited in the present study, or just partially unraveled. Further research is required to explore the actual nutrient limitations to orange production in Brazil, emphasizing aspects of Ca and Mg uptake efficiency under various polyhalite application rates and their synchronization with the annual precipitation pattern.

Keywords: Calcium; *Citrus sinensis* L. Osb., var. Natal; magnesium; orange juice; polyhalite; Polysulphate; potassium.

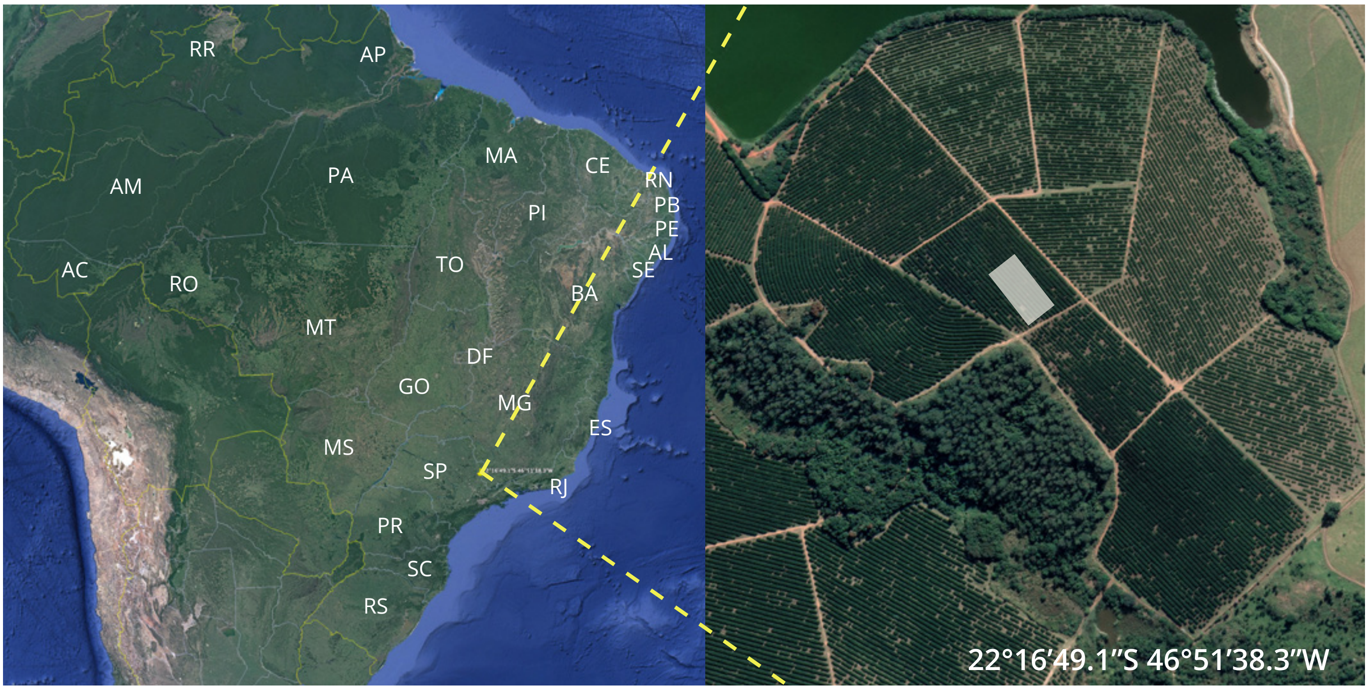
Introduction

Brazil is the world's leading citrus producer (FAOstat, 2020). The industry is especially concentrated in the 'citrus belt region', which includes municipalities in São Paulo State, but also in Minas Gerais in the Triângulo Mineiro and the Southwest regions of this state that altogether produced 11.7 million tonnes of fresh orange fruit in the 2020/2021 season (PES, 2020). Within this context, the investment in agricultural inputs, aiming at greater productivity and competitiveness in the citrus market, is steadily increasing. Fertilizer is a major input in the local citrus production; on the unfertile tropical soils of Brazil, consistent soil amendments and fertilization are fundamental to provide essential nutrients to ensure productive citrus tree development.

Calcium (Ca), nitrogen (N), and potassium (K) are the dominant mineral constituents of the citrus tree biomass. Phosphorus (P), magnesium (Mg), and sulfur (S) represent a smaller proportion (~10%), followed by micronutrients (<1%). However, the proportion of individual nutrients may vary among different cultivars, tree age, and horticultural practices in the orchard (Mattos Jr. *et al.*, 2003).

Citrus tree fruit yield and quality depends largely on the application of N and K (Cantarella *et al.*, 2003; Alva *et al.*, 2006), elements that also account for the largest nutrient removal by the trees between harvests (Bataglia *et al.*, 1977; Mattos Jr. *et al.*, 2003). Excess K nutrition has adverse effects on the external fruit characteristics; the peel grows bigger and coarser and the desired balance between peel and pulp is disrupted. Conversely, K deficiency reduces fruit number and size of all citrus varieties while decreasing the total soluble solids (TSS) content in the juice (Alva *et al.*, 2006). Therefore, optimization of fruit quality for either fresh consumption or the production of frozen concentrated orange juice can be managed by ensuring adequate nutrient supply (Quaggio *et al.*, 2005; Obreza *et al.*, 2008).

Potassium chloride (KCl) is the major fertilizer used as the source of potash (K_2O), even though other fertilizers such as potassium sulfate (K_2SO_4) and potassium nitrate (KNO_3) are also available for agricultural use. The latter are usually more expensive but are



Map 1. Experiment located near Mogi Guaçu city, São Paulo, Southeast region, Brazil. *Source:* Google Maps.

preferred for chloride sensitive crops, such as citrus, or when there is a risk of salt accumulation in soils (Bañuls and Primo-Millo, 1992). All three fertilizers are rapidly dissolved in water and hence, most of the K^+ ions supplied find their way to the soil solution shortly after application. In addition to the considerable risk of an osmotic stress immediately after application due to a transient excess salt index in the soil solution. Additionally, the upsurge in K^+ concentration in the soil solution might compete with other essential cations, such as Ca^{2+} and Mg^{2+}, on the ion absorption sites in the roots, consequently decreasing the root uptake of these nutrients. Indeed, lower Ca and Mg contents were detected in the spring flush leaves collected from fruiting terminals in a commercial grove with six-year-old 'Murcott' tangor trees growing on a sandy loam Oxisol. In that research, high rates of K applied during several years of fertilization resulted in the occurrence of stem dieback and reduced fruit yield (Mattos Jr. *et al.*, 2004). Alternatively, when applied during a heavy rainy season, the rapidly dissolved K might be washed away from the rhizosphere soon after application, before any nutritional benefits occur in the trees. These effects must be considered in fertilizer recommendations to prevent possible nutritional imbalances in the grove that are likely to cause fruit yield losses.

In recent years, a new supplementary fertilizer, polyhalite, was introduced to Brazil. Polyhalite is a natural mineral comprised of four nutrients: K, Ca, Mg, and S, in the form of 48% SO_3 as sulfate; 14% K_2O as sulfate of potash; 6% MgO as magnesium sulfate; and 17% CaO as calcium sulfate. Due to reduced levels of sodium and chloride, this fertilizer has a lower salinity rate compared to KCl (Fried *et al.*, 2019), in addition to gradual nutrient solubility (Yermiyahu *et al.*, 2017; Yermiyahu *et al.*, 2019). Studies have demonstrated the effect of applying polyhalite to several crops (Vale and Serio, 2017; Bernardi *et al.*, 2018; Pittelkow *et al.*, 2018).

The aim of the present research was to evaluate the efficiency of polyhalite as a fertilizer for Natal sweet orange (*Citrus sinensis* L. Osb.) crop in Brazil, the potential to replace KCl as the K_2O source, and the contribution of Ca, Mg and S supply through polyhalite to the fruit yield and quality.

Materials and methods

The field trial was conducted at Colorado farm, near the city of Mogi Guaçu, São Paulo state, Brazil, in a field located at the geographic coordinates 22°16'49.1"S - 46°51'38.3"W, with an average altitude of 594 meters (Map. 1). The experiment took place in a commercial orchard of 9-year-old Natal sweet orange (*Citrus sinensis* L. Osb.), grafted on Rangpur lime (*C. limonia* Osb.) variety planted in 2007 at a density of 357 plants ha^{-1}. The trial was established in January 2017 and lasted two seasons, 2017 and 2018.

Table 1. Physical and chemical properties of soil prior to trial installation.

Soil property	Quantity	Units
Sand	465	g kg^{-1}
Silt	75	g kg^{-1}
Clay	460	g kg^{-1}
pH ($CaCl_2$)	5.2	
Organic matter	25.0	g dm^{-3}
Cation exchange capacity (CEC)	7.2	$cmol_c$ dm^{-3}
Basic saturation (V%)	32.0	%
Phosphorus, as $P_{Mehlich}$	14.5	mg dm^{-3}
Potassium (K)	0.18	$cmol_c$ dm^{-3}
Calcium (Ca)	2.2	$cmol_c$ dm^{-3}
Magnesium (Mg)	0.5	$cmol_c$ dm^{-3}
Sulfur (S)	15.0	mg dm^{-3}
Boron (B)	0.3	mg dm^{-3}
Cooper (Cu)	1.5	mg dm^{-3}
Iron (Fe)	112.0	mg dm^{-3}
Manganese (Mn)	8.0	mg dm^{-3}
Zinc (Zn)	1.8	mg dm^{-3}

The region is part of the Atlantic Rainforest biome and its predominant climate is Cfa (Humid subtropical) type according to the Köppen-Geiger classification (Peel *et al.*, 2007), characterized by hot and temperate climate, with significant rainfall throughout the year, on average 1,480 mm $year^{-1}$ and average annual temperature of 21.6°C.

The soil where the experiment was conducted was Ultisol, or a dystrophic red-yellow Argisol in the Brazilian system of soil classification (Dos Santos *et al.*, 2018). The physical and chemical properties of the soil before the installation of the experiment are given in Table 1. The interpretation of soil fertility with respect to citrus requirements was characterized according to a set of critical levels, which indicated that phosphorus (P), copper (Cu), iron (Fe), and zinc (Zn) contents were classified as high; organic matter, S, Ca, and manganese (Mn) contents were classified as medium; and K, Mg, and boron (B) contents were classified as low, showing potential response to polyhalite fertilization (Quaggio *et al.*, 2005).

A tissue test was made before the installation of the experiment in order to characterize the nutritional status of the trees (Table 2). Nitrogen, Cu and Fe levels were considered high, while P, Ca and B were medium, and K, Mg, S, Mn, and Zn levels were lower than the recommended thresholds and restrictive for a sound yield (Quaggio *et al.*, 2005).

Table 2. Orange trees nutritional status prior to trial installation.

Nutrient	Quantity	Units
Nitrogen (N)	40.13	g kg^{-1}
Phosphorus (P)	1.45	g kg^{-1}
Potassium (K)	8.63	g kg^{-1}
Calcium (Ca)	37.25	g kg^{-1}
Magnesium (Mg)	2.69	g kg^{-1}
Sulfur (S)	0.94	g kg^{-1}
Boron (B)	83.2	mg kg^{-1}
Cooper (Cu)	90.5	mg kg^{-1}
Iron (Fe)	220.0	mg kg^{-1}
Manganese (Mn)	20.5	mg kg^{-1}
Zinc (Zn)	39.5	mg kg^{-1}

The experiment was designed in complete randomized blocks, with six treatments distributed in four replicates. With planting spaces of 7×4 m, each plot consisted of 15 trees standing in 3 rows (5×3) on an area of 420 m^2, and 1,680 m² per treatment. However, only the three central plants of each plot were evaluated, while the others functioned as borders.

All fertilizer treatments were designed to a similar potassium application rate of 300 kg K_2O ha^{-1}, while modifying the relationship between different K sources, and allowing increasing application rates of Ca, Mg, and S (Table 3). Two K sources were used: KCl (60% K_2O) and polyhalite, a natural fertilizer which contains 14% of K_2O, 19% of S, 12% of Ca, and 3.6 % of Mg.

The first fertilizer application took place in January 2017 and included all nutrient sources corresponding to each treatment (Table 3), with additional 200 kg N ha^{-1}, using urea. The first harvest took place in December 2017, and it was considered as a 'white harvest', without yield evaluation as a function of treatments, thus leveling the nutritional status of the trees at the beginning of the trial.

In January 2018, all plots were fertilized again according to the treatments indicated in Table 3, including the urea. In September 2018, samples were taken for chemical analyses of leaf K, Ca, Mg, and S and the evaluation was compared to the common standards in citriculture (Quaggio *et al.*, 2005).

Fruit maturation and yield assessments were carried out in December 2018. The number of fruits from each of the three central trees of each plot were counted. Twenty fruits from each tree were randomly sampled and the average fruit weight and fruit diameter were determined. Total fruit yield per treatment was calculated from fruit count and mean fruit weight.

The 20-fruit samples were sent to the industrial unit of Sucorrico (an international producer of frozen concentrated orange juice, FCOJ, located at Araras, São Paulo State, Brazil), where quality parameters were calculated, including juice percentage (% of fruit fresh weight), total soluble solid (TSS, expressed as °Brix), titratable acidity (TA), and sugar/acidity ratio (°Brix/TA) in the juice. The yield of TSS (kg TSS ha^{-1}) was calculated from fruit yield, juice percentage, and TSS (Redd *et al.*, 1986).

Data were tested for significant differences among treatments using the analysis of variance (ANOVA) by applying the F test ($P < 0.05$); means were then compared by the t-test - LSD ($P < 0.05$), and variables were adjusted by regression and correlation model analyses using the statistical analysis program Sisvar 5.6 (Ferreira, 2011).

Results and discussion

Effects of polyhalite rate on leaf nutrient concentration

Partially replacing KCl with polyhalite while keeping K_2O application rate consistently equal at 300 kg ha^{-1} brought about significant changes in the nutrient status of the orange trees (Table 4; Fig. 1). Interestingly, the effect on leaf K status was statistically insignificant (Table 4); nevertheless, when polyhalite rate exceeded 400 kg ha^{-1} and 50% of the K_2O dose, leaf K rose above the minimum threshold of K optimum range in citrus leaves (Quaggio *et al.*, 2005). These results can be attributed to the prolonged availability of nutrients

Table 3. Detailed description of the fertilizer treatments evaluated in the orange experiment at Mogi Guaçu, São Paulo state, Brazil.

Treatments	Fertilizer blend	Source		Nutrients			
		KCl	Polyhalite	K_2O	S	Ca	Mg
		kg ha^{-1}					
T1	100% KCl	500	0	300	0	0	0
T2	77% KCl / 23% polyhalite	467	140	300	27	17	5
T3	61% KCl / 39% polyhalite	434	280	300	54	34	10
T4	49% KCl / 51% polyhalite	402	420	300	81	50	15
T5	40% KCl / 60% polyhalite	369	560	300	108	67	20
T6	32% KCl / 68% polyhalite	336	700	300	134	84	25

Table 4. Effects of increasing KCl replacement rates by polyhalite on leaf nutrient concentration (K, Ca, Mg, and S) in Natal orange trees.

Treatment	Fertilizer mixture	Polyhalite	Nutrients in leaves			
			K	Ca	Mg	S
		kg ha^{-1}	------------ *g kg^{-1}* ------------			
T1	100% KCl	0	9.69a	22.05b	2.59b	2.64a
T2	77% KCl / 23% polyhalite	140	9.87a	23.36ab	2.68ab	2.89a
T3	61% KCl / 39% polyhalite	280	9.81a	23.85ab	2.71ab	2.68a
T4	49% KCl / 51% polyhalite	420	11.94a	23.70ab	2.73ab	2.80a
T5	40% KCl / 60% polyhalite	560	11.87a	24.98ab	2.79a	3.20a
T6	32% KCl / 68% polyhalite	700	11.09a	26.35a	2.77ab	3.57a
	F		1.17^{ns}	1.06*	1.21*	0.52^{ns}
	CV%		18.24	11.87	4.85	33.50
	Average		10.71	22.31	3.02	7.32
	LSD		2.90	4.24	0.19	1.47

^{ns} non-significant; *significant at p = 0.05; means followed by different letters in the column are different (t-test, p < 0.05).

when applied using polyhalite, compared to KCl, due to its lower solubility (Yermiyahu *et al.*, 2017; Yermiyahu *et al.*, 2019). This also reduces the risk of K leaching under rainy conditions.

In Brazil's tropical climate and soils, uptake of Ca and Mg by roots normally declines as an immediate response to KCl application (Jakobsen, 1993). However, in spite of the high and even K application dose practiced in the present study, the rising polyhalite rates gave rise to significant increases in leaf Ca and Mg concentrations (Table 4). Yet, leaf nutrient concentrations did not reach the adequate ranges, 35-50 and 3.5-5.0 g kg^{-1} DM, for Ca and Mg, respectively (Quaggio *et al.*, 2005), even under the highest polyhalite rates. Furthermore, a comparison with the leaf nutrient status at the beginning of the trial (Table 2) shows that Ca concentration declined during the season, while Mg remained stably low (Table 4).

In all treatments, leaf S concentration was within the optimum range of 2-3 g kg^{-1} DM (Quaggio *et al.*, 2005). In fact, the rising polyhalite application rates resulted in considerable increases in leaf Ca, Mg, and S, as indicated by the significant regression curves (Fig. 1). Obviously, polyhalite application demonstrated considerable ability to function as a Ca, Mg, and S donor, displaying positive relationships between application rate and leaf nutrient concentration (Fig. 1). It is still questionable whether higher polyhalite rates could further and adequately enhance the nutrient status of orange trees under the given circumstances. Alternatively, a different synchronization between the annual precipitation pattern and fertilizer application time should be

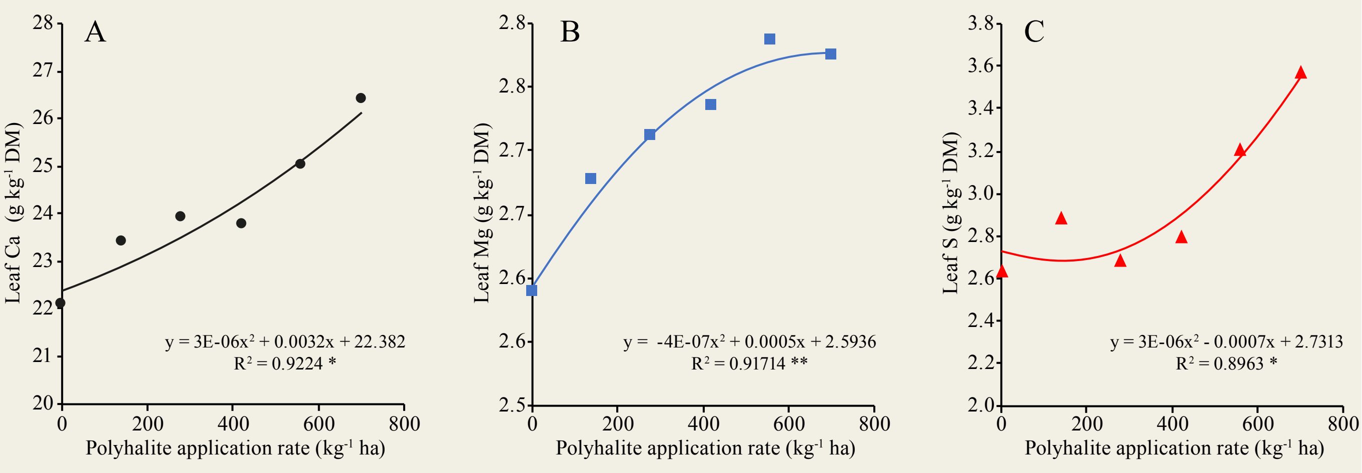


Fig. 1. Effects of polyhalite application rate on leaf calcium (A), magnesium (B) and sulfur (C) concentration in Natal orange trees, expressed through binomial regression curves. *, and ** indicate significance of the regression curve at P < 0.05, and P < 0.01, respectively.

Table 5. Effects of increasing KCl replacement rates by polyhalite on fruit count, fruit diameter and weight, and on fruit yield of Natal orange trees in Brazil.

Treatment	Fertilizer mixture	Polyhalite	Fruit count	Fruit diameter	Fruit weight	Yield
		kg ha^{-1}	*Fruit tree^{-1}*	*cm*	*g*	*Mg ha^{-1}*
T1	100% KCl	0	553.3b	7.41a	233b	36.8b
T2	77% KCl / 23% polyhalite	140	635.0ab	7.43a	235ab	42.9ab
T3	61% KCl / 39% polyhalite	280	705.0a	7.47a	241ab	48.6a
T4	49% KCl / 51% polyhalite	420	671.3ab	7.56a	252ab	48.1a
T5	40% KCl / 60% polyhalite	560	653.8ab	7.57a	245ab	45.6ab
T6	32% KCl / 68% polyhalite	700	657.5ab	7.69a	257a	48.0a
Statistical analyses	F		1.05*	0.77^{ns}	1.43*	2.17*
	CV%		15.45	3.17	6.43	13.8
	Average		645.9	7.52	244	45
	LSD		148.3	0.35	23.3	9.18

^{ns} non-significant; *significant at $p = 0.05$; means followed by different letters in the column are different (t-test, $p < 0.05$).

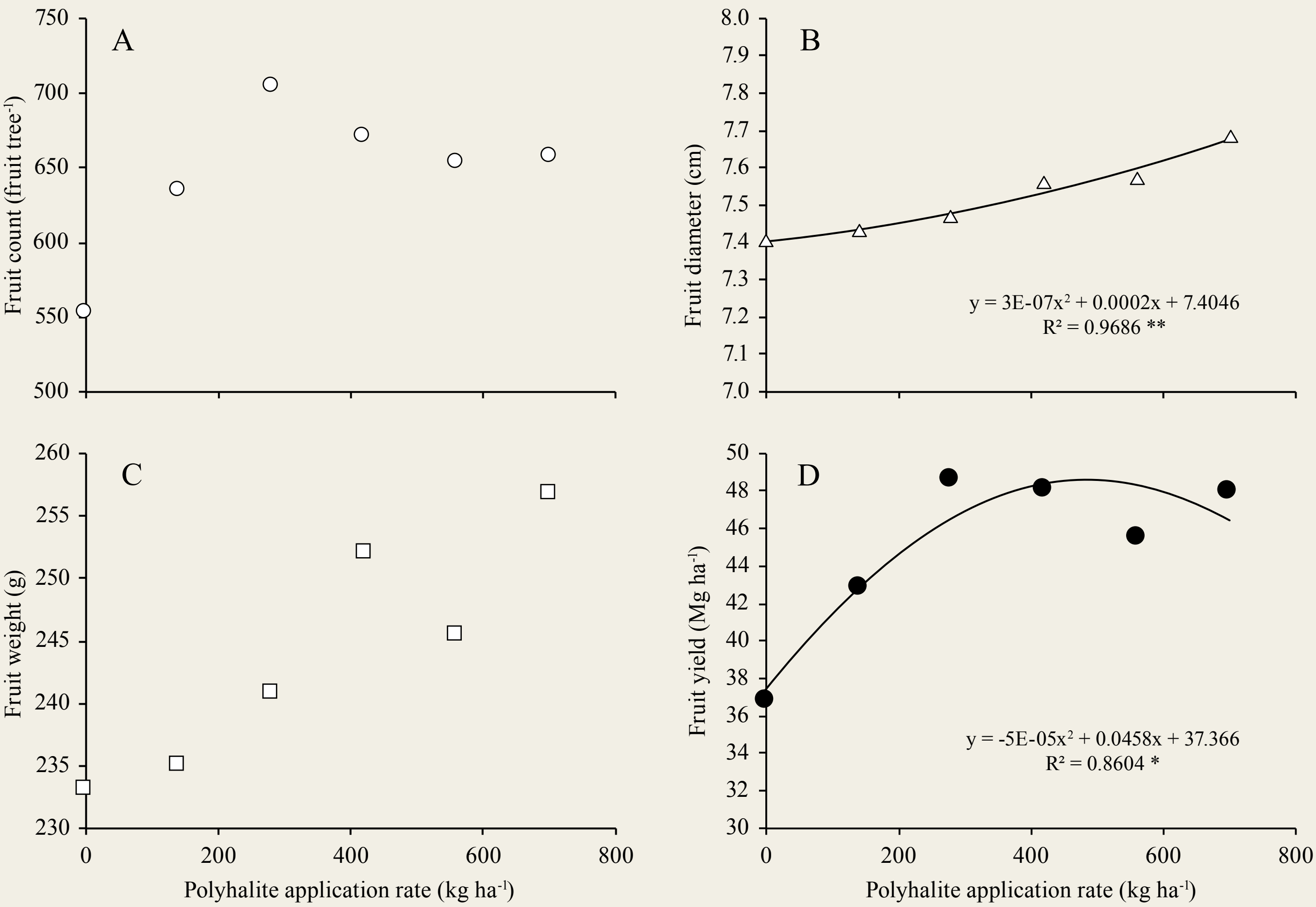


Fig. 2. Effects of polyhalite application rate on number of fruit per tree (A), fruit diameter (B), fruit weight (C), and fruit yield (D) of Natal orange trees in Brazil.

Table 6. Effects of increasing KCl replacement rates by polyhalite on fruit quality parameters of Natal orange trees in Brazil.

Treatment	Fertilizer mixture	Polyhalite	Juice content	TSS	°Brix/TA	TSS yield
		kg ha^{-1}	*%*	*°Brix*		*kg ha^{-1}*
T1	100% KCl	0	54.60a	9.13a	14.3a	1,779b
T2	77% KCl / 23% polyhalite	140	53.18a	9.16a	13.6a	2,103ab
T3	61% KCl / 39% polyhalite	280	55.75a	9.38a	14.9a	2,537a
T4	49% KCl / 51% polyhalite	420	54.68a	9.05a	14.0a	2,449a
T5	40% KCl / 60% polyhalite	560	53.23a	9.23a	14.4a	2,321ab
T6	32% KCl / 68% polyhalite	700	57.28a	9.15a	14.4a	2,526a
Statistical analyses	F		0.91^{ns}	0.95^{ns}	0.54^{ns}	2.55*
	CV%		5.98	2.45	8.68	16.20
	Average		54.78	9.18	14.30	2,286
	LSD		4.87	0.33	1.84	186

^{ns} non-significant; *significant at p = 0.05; means followed by different letters in the column are different (t-test, p < 0.05).

considered; fertilizer application during the less humid seasons may reduce nutrient leaching, thus improving the chances of uptake by the trees.

Effects of polyhalite rate on fruit yield parameters

Fruit count exhibited a significant increase in response to polyhalite application, increasing by 27%, from 550 to 700 fruit tree^{-1}, in response to the polyhalite application rate of 280 kg ha^{-1} (Table 5; Fig. 2A). However, further increases of the polyhalite proportion at the expense of KCl showed no additional influence. The effect of the partial KCl replacement by polyhalite had a very small impact on fruit diameter, which grew from 7.41-7.69 cm. While the differences between fertilizer treatments in the fruit diameter were insignificant due to the large variability (Table 5), the positive trend of the rising polyhalite portion was significant (Fig. 2B).

Fruit weight tended to rise as the polyhalite share increased, but significant differences of about 10% only occurred between the control and the maximum polyhalite rate (Table 5). Although the relationship between the polyhalite rate and fruit weight seemed quite clear, there was no significant regression line (Fig. 2C).

Consequent to these effects, the mean fruit yield surged by 32%, from 36.8 to 48.6 Mg ha^{-1}, in response to the polyhalite application rate of 280 kg ha^{-1} (replacing 39% of the normal KCl dose) but remained quite constant with any further rise in polyhalite rate (Table 5). It appears that the effect of the fertilizer treatments on the fruit count was much more dominant than the effect on fruit size, as indicated by the response pattern of the yield (Fig. 2D). The significant rise in fruit yield clearly suggests that the replacement of KCl by polyhalite, while keeping a constant K_2O application dose, fills certain gaps in the orchard nutrient status and reveals a greater productivity. The increase in leaf Ca, Mg, and S (Table 4; Fig. 1) must have had positive effects on the foliar functions that, in turn, boosted vegetative as well as reproductive development. Lessening chlorine (Cl) uptake might present another reason for this improvement, since excess Cl is found to be toxic to many citrus species, varieties, and rootstocks (Lloyd *et al.*, 1989; Syvertsen *et al.*, 1993; Ruiz *et al.*, 1997; García-Sánchez *et al.*, 2003; Fried

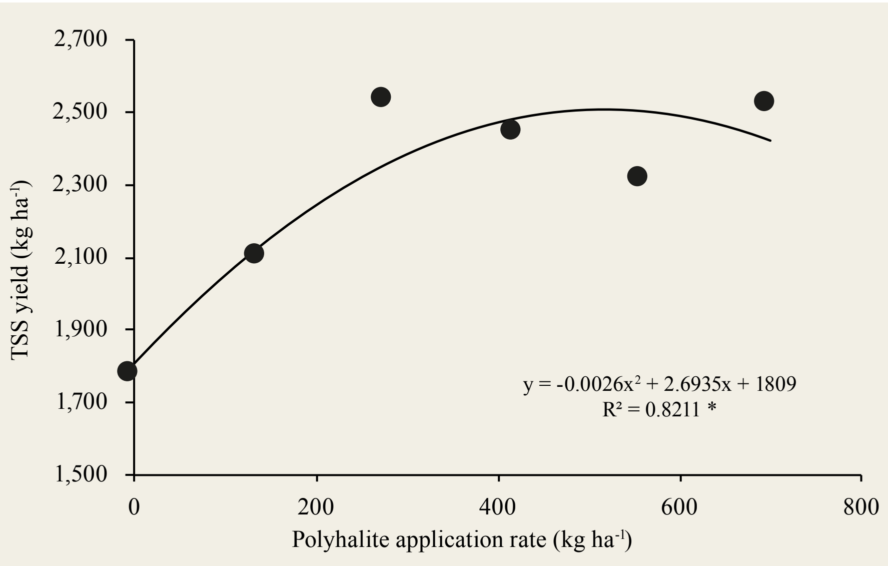


Fig. 3. Effects of polyhalite application rate on the TSS yield of Natal orange trees in Brazil, expressed through a binomial regression curve. * indicates significance of the regression curve at P < 0.05.

et al., 2019). Nevertheless, this point would require further research, as leaf Cl status was not examined in the present study.

Nevertheless, the polyhalite effect seems to be saturated at 300 kg ha^{-1}, supplying about 40% of the K_2O dose (120 kg K_2O ha^{-1}), 36 kg Ca ha^{-1}, 10.5 kg Mg ha^{-1}, and 57 kg S ha^{-1} to the orchard soil. Questions may arise regarding the sufficiency and the efficiency of that nutrient supply. It may well be that greater uptake of all, or some, of these nutrients could have further improved crop performance and yield. Polyhalite is relatively less soluble than KCl and some other fertilizers (Yermiyahu *et al.*, 2019), but under the rainy conditions in São Paulo State in January, the retention of this fertilizer would be quite limited, and consequently, the efficiency of the tested fertilizer practice would be low.

Effects of polyhalite rate on fruit quality parameters

The higher the juice content in fruit (% of fruit weight) the greater the juice yield as an industrial produce. Juice quality is primarily determined by its sugar content, expressed as TSS or °Brix, and the ratio between TSS and titratable acids (TA). This ratio indicates the balance between sweetness and sourness in the juice. During fruit maturation, the ratio increases as sugars are formed and organic acids degrade. Both parameters, °Brix and °Brix/TA, determine fruit ripening and the optimum time of harvest. In extracted juice, the concentration of sugar typically varies from 9 °Brix for early season varieties to 12 °Brix for fruit harvested late in the season. Maturity standards for oranges in Florida require a minimum °Brix of 8.0 and a minimum °Brix/TA ratio of 9. However, consumers usually prefer a higher ratio of about 15, and hence, it is often necessary delay the harvest (Redd *et al.*, 1986).

The partial KCl replacement by polyhalite, keeping the K_2O rate at 300 kg ha^{-1}, did not have any significant effect on the juice content, °Brix, or °Brix/TA ratio (Table 6). The mean °Brix value was 9.18, at the lower threshold of the desired range. The mean °Brix/TA ratio was 14.26, at the higher edge of the desired range. These values indicate that at harvest, fruit were quite low in sugar content, but the juice produced was pleasant for drinking and acceptable from the industrial perspective. However, the most important industrial evaluation of orange orchard performance is the TSS yield, which integrates fruit yield, juice content, and °Brix, and expressed in kg TSS ha^{-1}. As expected, this parameter followed the response curve of the fruit yield to the fertilizer treatments, exhibited significant differences between treatments, and peaked at 2,537 kg TSS ha^{-1}, 42% higher than the KCl control, at an input of 280 kg polyhalite ha^{-1} (Table 6). As for the fruit yield, the response curve indicated saturation of the TSS yield beyond 300 kg polyhalite ha^{-1} (Fig. 3). The increase in TSS yield was greater than that of the fruit yield, conveying significant advantages in using polyhalite as a substitute for KCl.

In conclusion, the partial replacement of KCl by polyhalite displayed unequivocal advantages for industrial orange production under tropical conditions in Brazil. The nutrient status of trees was enhanced, especially enriched by Ca, Mg, and S that are essential to citrus productivity. Overall crop performance was significantly improved, including fruit and TSS yields. However, it remains open whether the potential of this fertilizer has been fully exploited in the present study, or just partially unraveled. Further research is required to explore the actual nutrient limitation of orange production in Brazil, including aspects of nutrient uptake efficiency under various application rates and schedules.

Acknowledgements

The authors acknowledge the field technicians of the Monterra Consultants for their support in setting up and conducting the experiment; and the International Potash Institute (IPI) for the financial support.

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The paper "Evaluation of Polyhalite Fertilizer on the Yield and Quality of Orange Crop in Brazil" also appears on the IPI website.