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Editorial

Dear readers,

Synergy between partners is so satisfying. Not just to the collaborators involved but also to the many more who benefit from the output of the productive partnership or teamwork. That is certainly true of the research themes and teams in this latest edition of the *e-ifc* which illustrate the synergy between science and farming, for different crops and across continents, and the potential for us all to benefit from additions to our knowledge of how to optimize productivity.

Let's begin in Brazil, South America, the location for the first paper. The research team show how production of juicy, vitamin-packed citrus oranges is enhanced, in fruit number and size, by polyhalite application.

Next stop, Asia. This paper focusses on an equally colorful crop, pepper in China, where complementing the usual NPK fertilizer with polyhalite increased productivity by up to about 40%.

The last stop is North America, in Mexico, where the powerful synergy, respected since ancient times, between corn and beans is investigated to measure the extent to which polyhalite - added to the usual NPK fertilizer regime - contributes to better roots, shoots, cobs, and pods.

Running through all these studies we find the synergy or combined efforts between researchers and the farming communities their studies serve to benefit. There is great unity of purpose to plan, plant, treat, measure, monitor, and gather results to the highest standards. By sharing with you the results from these three papers we hope you can harvest the synergism between them and even be inspired for your own investigation for best practice.

As we welcome in another new year, may this latest edition's selection of excellent science provide you with some essential and enjoyable reading.

Stay safe.

Dr. Patricia Imas
IPI Scientific and Communications Coordinator

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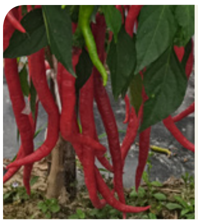

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Photo cover page: Almond trial. Photo by N. Cohen Kadosh.

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

Silva, R.A.[(1)], and F. Vale[(2)*]

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

[(1)]Monterra Agricultural Research and Advisory Services Ltda, Piedade, São Paulo state, Brazil
[(2)]IPI Coordinator for Latin America, International Potash Institute, Zug, Switzerland
*Corresponding author: fabio.vale@icl-group.com

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.

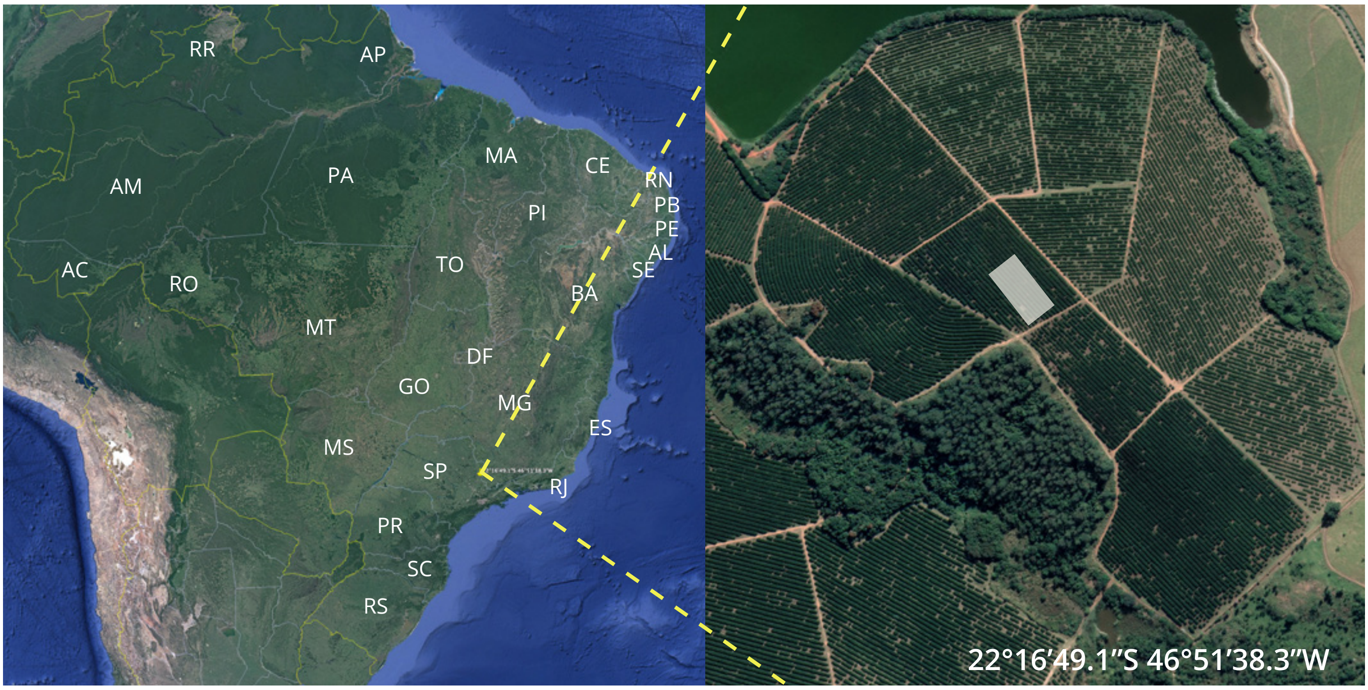
Introduction

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

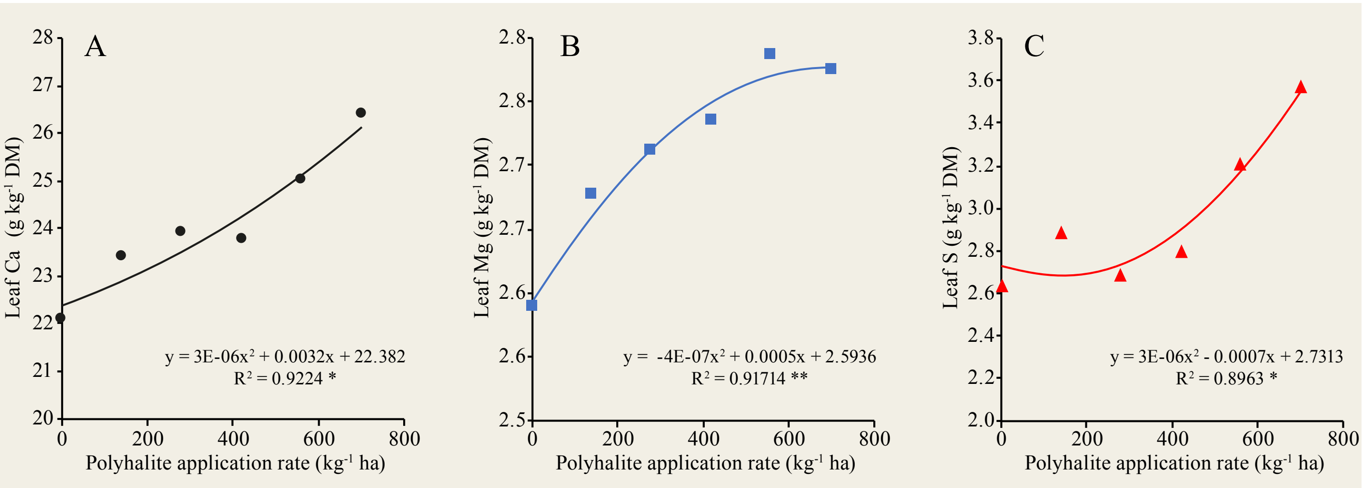


Fig. 1. Effects of polyhalite application rate on leaf calcium (A), magnesium (B) and sulfur (C) concentration in Natal orange trees, expressed through binomial regression curves. *, and ** indicate significance of the regression curve at P < 0.05, and P < 0.01, respectively.

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, $p < 0.05$).

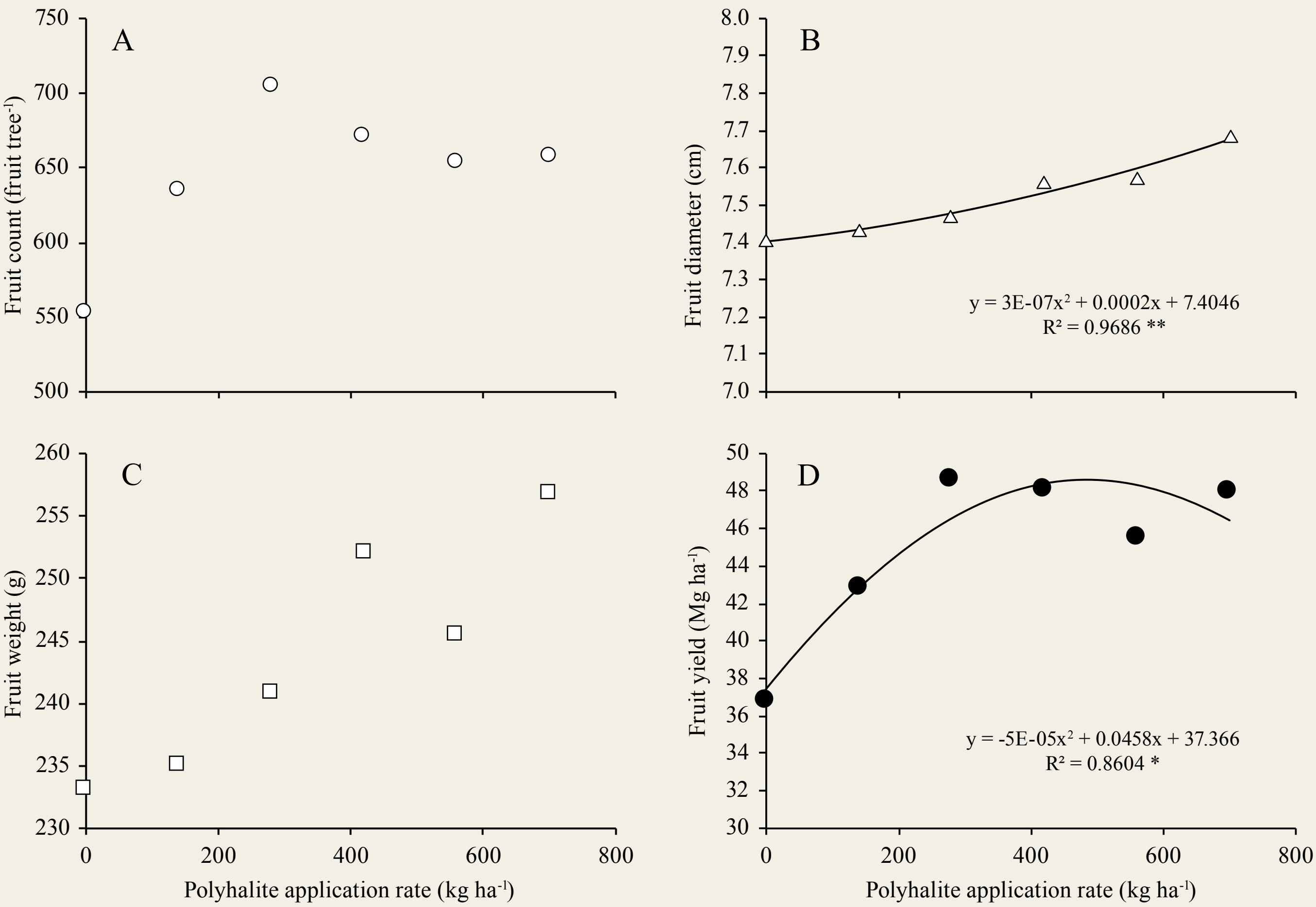


Fig. 2. Effects of polyhalite application rate on number of fruit per tree (A), fruit diameter (B), fruit weight (C), and fruit yield (D) of Natal orange trees in Brazil.

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

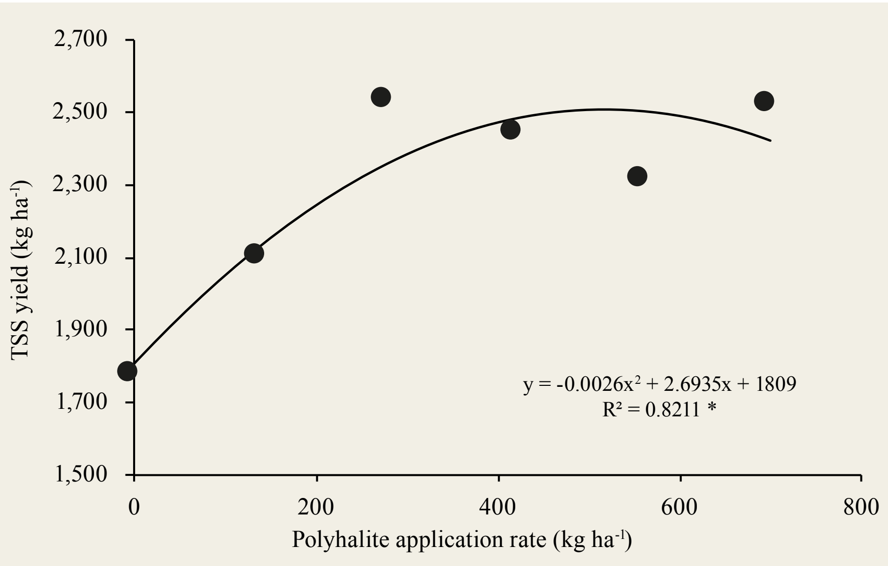


Fig. 3. Effects of polyhalite application rate on the TSS yield of Natal orange trees in Brazil, expressed through a binomial regression curve. * indicates significance of the regression curve at P < 0.05.

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

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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.

Research Findings

Photo 1. Pepper plants grown on yellow soil in China. Photo by the authors.

Enrichment of Compound NPK Fertilizer with Polyhalite Enhances Pepper *(Capsicum annuum)* Yield and Quality on Poor Yellow Soils in Southwest China

Yi, L.[(1)], L. Ming[(1)], Y. Zhi[(1)], C. Xin-ping[(1)], G. Li[(2)], and L. Dun-yi[(1)*]

Abstract

Pepper (*Capsicum annuum*) is one of the major vegetable crops grown on the yellow soils of southwest China. While the vegetable crops in the area are intensively fertilized with a uniform compound nitrogen (N), phosphorus (P), and potassium (K) fertilizer at a composition ratio of 15-15-15 (N-P_2O_5-K_2O), secondary macronutrients such as calcium (Ca) and magnesium (Mg) are usually ignored. Under the rainy subtropical climate of the region, soil Ca and Mg are rapidly depleted, crops suffer from imbalanced mineral nutrition, and consequently, farmers fail to realize the economic potential of the crop. Two principal steps were examined in the present study: adjustment of the NPK ratio according to pepper crop requirements; and, adding polyhalite to the compound NPK blend, as a supplementary Ca and Mg fertilizer. Two experiments

[(1)]College of Resources and Environment, Southwest University, Chongqing Key Laboratory of Efficient Utilization of Soil and Fertilizer Resources, Chongqing, 400715, China

[(2)]IPI Coordinator for China, International Potash Institute (IPI), Zug, Switzerland

*Corresponding author. E-mail: liudy1989@swu.edu.cn

were conducted at two sites: Chongqing and Guizhou. Each experiment included four treatments: T1 – farmer's practice, applying compound NPK fertilizer at 15-15-15; T2 – NPK 15-15-15 with supplementary polyhalite; T3 – NPK 16-8-18; and T4 – NPK 16-8-18 with polyhalite. In all treatments, the seasonal N and K_2O doses were kept quite similar at 248-260, and 248-284 kg ha^{-1}, respectively, while P_2O_5 dose was 248 or 164 kg ha^{-1}, in treatments T1 and T3, or T2 and T4, respectively. Polyhalite comprised 19-23% of the total fertilizer blend of T2 and T4, and provided 63-68, and 23-28 kg ha^{-1} of CaO and MgO, respectively. The adjustment of the NPK ratio alone gave rise to a substantial increase in the agronomic P use efficiency without having much impact on pepper productivity or yield. However, the addition of supplementary polyhalite increased the aboveground biomass and fruit yield, and significantly enhanced the agronomic use efficiency of both N and P. In addition, polyhalite increased crop Ca and Mg uptake and their distribution to plant organs, while replenishing the soil reserves of these nutrients. Polyhalite application also increased fruit K, Mg, and vitamin C contents, thus enhancing the produce quality. All economic parameters were improved dramatically as a result of polyhalite application, with the return on investment (ROI) ranging from 15-27. The supplementary application of polyhalite, which provides four essential nutrients gradually released over a prolonged period, demonstrates the principles that should dominate the required modification of the fertilization approach in vegetable cultivation on the yellow soils: balanced soil nutrition; adjustment to crop requirements; and, use of slow- or controlled-release fertilizers.

Keywords: Capsicum annuum; magnesium; nutrient use efficiency; Polysulphate; vitamin C.

Introduction

Pepper (*Capsicum annuum*) cultivation area in China is steadily expanding. With the second largest production area for vegetables in China, after Chinese cabbage (China Agricultural Yearbook, 2015), pepper is a key crop in agricultural and rural economic development. As one of the dominant production areas for pepper cultivation, Southwest China has the largest cultivation area, accounting for 29.3% of the national total pepper cultivation area and 19.5% of the national total pepper production. However, the average regional yield is only 79.3% of the national average yield (National Vegetable Industry, 2014). In addition, the southwest region is also a major consumer of peppers, and spiciness is one of the characteristics of the region's food culture (He and An, 2004). Therefore, it is important to conduct research on improving pepper quality and yield in southwest China in order to increase regional production and economic benefits to farmers.

For a long time, driven by economic considerations, excessive application of macronutrient fertilizers has been very common in vegetable production. Currently, the total amounts of nitrogen (N), phosphorus (P), and potassium (K) applied to open field vegetables are 2.7, 5.9 and 1.5 times higher than recommended (Huang *et al.*, 2017). Over-reliance on compound NPK fertilizers and the absence of other essential nutrients may often lead to a disrupted nutrient allocation ratio (Zhu *et al.*, 2005; Yu *et al.*, 2013). Ti *et al.* (2015) concluded that fertilizer use efficiency in Chinese open field vegetables was extremely low, with an N use efficiency of only 25.9%, seriously upsetting the sustainable development of agroecosystems (Vitousek *et al.*, 2009; Zhang *et al.*, 2015). In addition, long-term deficient input of secondary macronutrients, such as calcium (Ca), magnesium (Mg), and others, has extremely interfered with the crop-soil balance of these nutrients (Liu *et al.*, 2005; Cakmak and Yazici, 2010). Yellow soil, one of the typical soil groups in southwest China (China Soil Science Database http://vdb3.soil.csdb.cn/), is characterized by rapid weathering rates, high acidity, and poor capacity for fertilizer retention. Due to heavy rainfalls in the region, soils are very susceptible to Ca^{2+} and Mg^{2+} depletion by leaching (Gransee and Fuhrs, 2013). Li *et al.* (2018) found that Mg losses to leaching on a yellow soil ranged from 105-244 kg ha^{-1}, 2-3 times higher than on red soils. Therefore, the crop biomass Mg content is generally lower (Li, 1994), and in a similar way, vegetable Ca content is low (Zhang *et al.*, 2011). This has become a primary limiting factor of pepper crop yield and its nutritional quality (Brodowska and Kaczor, 2009; Ma *et al.*, 2015).

Previous studies demonstrated that Mg fertilizer application on Mg-deficient soils can significantly increase the yield and mineral nutrient content in Chinese cabbage and onion, adding up to 20.4% and 38.0% to the yield, respectively (Klelber *et al.*, 2012; Huang *et al.*, 2016). In addition, Yang Yang and Tao (1994) found that Ca and Mg fertilization not only significantly increases tomato yield, but also strongly improves the fruit vitamin C and mineral nutrients contents. Similar to tomato, pepper belongs to the Solanaceae family of cash crops, which is characterized by high biomass and, consequently, high Ca and Mg requirements (Zhang, 2007). In a field study at He County, Anhui Province, Liu *et al.* (2017) revealed that pepper requirements throughout the reproductive period were 135 kg CaO ha^{-1} and 74.9 kg MgO ha^{-1}, respectively, higher than the requirement for the primary macronutrient P, which was 61 kg P_2O_5 ha^{-1}. Therefore, in terms of fertilizer management, pepper cultivation on yellow soils would require attention not only to the optimization of macronutrient formulations, but also to the adequate application of secondary macronutrients, such as Ca and Mg.

Polyhalite is a new natural fertilizer containing four essential nutrients: K, Ca, Mg, and S in sulfate forms (K_2SO_4, $CaSO_4$, and $MgSO_4$), and is composed of SO_3 (48%), K_2O (14%), CaO (17%), and MgO (6%). Polyhalite is adequately water soluble to release its mineral nutrients to the crop rhizosphere, but the rates of mineral release are more prolonged than commonly used fertilizers (Yermiyahu *et al.*, 2017; Yermiyahu *et al.*, 2019; Huang *et al.*, 2020). In addition, polyhalite has negligible chloride and sodium contents, and hence any risk of salt stress or salinization are considerably

Map 1. Location of the experiment sites in Hongming Village, Chongqing and Sanhe Village, Guizhou, China. *Source*: Google Maps.

lessened. These advantages make polyhalite a promising candidate as a complementary fertilizer for a wide range of crops and countries (Zhuo *et al.*, 2019; Bhatt *et al.*, 2021).

Matching nutrient supply to crop roots with the aboveground requirements and ensuring high efficiency and, subsequently, high productivity of the soil-crop system, necessitates a scientific approach (Chen *et al.*, 2011). At present, there are a few studies aimed at composing fertilizer formulae containing Ca and Mg for pepper production. In the present study, an NPK formula was adjusted to the estimated pepper crop requirements. This formula was enriched with polyhalite in order to supply the crop with Ca, Mg, and S. The two new formulae were examined compared with the usual NPK fertilizer, with and without polyhalite. The objective was to provide theoretical basis for high-yield and high-efficiency cultivation of pepper based on two field experiments, and to demonstrate the advantages of balanced fertilization on two typical yellow soils in southwest China.

Table 1. Basic physical and chemical properties of the soils at the two experiment sites.

Soil property	Units	Shizhu, Chongqing	Jinping, Guizhou
Soil type		Purpli-Udic Cambosols	Ultisol, fine
Clay (<2 µm)	%	13.8	45
Silt (2-20 µm)	%	26.7	43.5
Sand (20-2,000 µm)	%	59.5	11.5
pH		4.51	4.87
Organic matter	g kg^{-1}	13.1	23.2
Exchangeable Ca	mg kg^{-1}	279	945
Exchangeable Mg	mg kg^{-1}	31.3	48.8
Available K	mg kg^{-1}	65.0	91.0
Available N	mg kg^{-1}	208	268
Phosphorus (Bray)	mg kg^{-1}	31.9	24.9

Materials and methods

Location of field experiments

The first experiment was located at Hongming Village, Sanhe Town, Shizhu County, Chongqing (N 30°04′, E 108°10′). The second experiment was located at Sanhe Village, Dunzhai Town, Jinping County, Qiandongnan Miao and Dong Autonomous Prefecture, Guizhou Province (N 26°15′, E 109°15′). Both sites belong to the central subtropical humid monsoon climate zone, and the soil types are subclasses of the yellow soil group. The basic physical and chemical properties of the soils are given in Table 1. Soils at both experimental sites exhibited deficient or extremely deficient levels of exchangeable Ca and exchangeable Mg (Li, 1994; Zhang *et al.*, 2011).

Fertilizer formulae and treatments

Based on previous findings on pepper requirements of N, P and K (Liu *et al.*, 2017), a fertilizer formula was designed for pepper, with NPK ratio of 16-8-18 and supplementary K, Ca, Mg, and S in the form of polyhalite (Polysulphate®, ICL, Israel). The specific raw materials, fertilizers' composition, and application doses, are given in Table 2.

The two experiments similarly included four fertilizer treatments: T1 – the commonly used NPK fertilizer; T2 – the commonly used NPK fertilizer mixed with additional polyhalite; T3 – a specially

Table 2. Detailed description of the fertilizer treatments: nutrient application rate, fertilizer ratio, and the formulas of the fertilizer nutrient composition.

Treatment	Nutrient application rate					Fertilizer ratio				Fertilizer composition ratio
	N	P_2O_5	K_2O	MgO	CaO	Urea	Mono-ammonium phosphate	Potassium sulfate	Polyhalite	$N-P_2O_5-K_2O-MgO-CaO$
	-----------------*kg ha⁻¹*-----------------					----------------------%----------------------				
T1	248	248	248	–	–	28	38	34	–	15-15-15-0-0
T2	248	248	248	23.1	62.7	26	30	25	19	15-15-15-3.8-1.4
T3	260	164	284	–	–	36	21	43	–	16-8-18-0-0
T4	260	164	284	27.9	67.5	31	16	30	23	16-8-18-4.2-1.8

designed NPK fertilizer formulation for pepper; and T4 – the pepper NPK fertilizer mixed with polyhalite (Table 2). The experiments were planned in a random block design with four replicates. Each plot included border rows and was surrounded by a drainage ditch. The fertilizer dose was divided into four equal portions applied as a pre-planting base, and as a side dressing at bloom, early fruiting, and full fruiting stages. Field management practices were strictly consistent for all experimental treatments except for the difference in fertilizer application.

In Chongqing, pepper seedlings of the cultivar 'Jing Zhi Cui Mei' were planted on 27 April 2018, at spacing of 0.55×0.4 m. Experiment plot size was 5×2 m (10 m^2). Harvest took place on 18 August 2018. In Guizhou, pepper seedlings of the cultivar 'Xinxiang No. 8' were planted in May 2018, the experimental plot size was 5×4 m (20 m^2), and harvest took place on 26 August 2018. In both sites, the planting pattern was single-ridge mulching, and field management was carried out according to local farmers' practice.

Measurements

Soil samples were collected before tilling according to the S-shaped sample plan, air-dried and sieved. The basic physicochemical properties of the soil samples were determined according to conventional agrochemical analysis methods (Lu, 2000). Crop sampling area was set at 1.6×2.2 m (16 plants), and the commercial fruit yield was measured in three fixed plots from the time of fruiting to the time of crop harvest. Plant sampling was carried out during the pepper crop harvest period. Four representative plants were randomly selected from each plot, divided into stems, leaves, and fruits. After deionization and washing, the samples were dried in an oven at 105°C for 30 min, and then at 70°C until a constant weight was reached. Samples were then crushed with a stainless-steel grinder. A sample of 0.2 g was weighed and digested using HNO_3-H_2O_2. The concentrations of K, Ca, and Mg were then determined using ICP-OES (5110, Agilent, USA). Fruit vitamin C content was determined by the 2, 6-dichloroindophenol method (Lu, 2000).

Table 3. Effects of the fertilizer treatments on the dry biomass of leaves, stems, and fruit of pepper plants at harvest, and on the harvest index (HI). Values present are means of 4 replicates ±SD.

Test site	Treatment, $N-P_2O_5-K_2O-MgO-CaO$	Dry matter weight			HI
		Leaves	Stems	Fruits	
		---------------------------*kg ha⁻¹*---------------------------			
Shizhu, Chongqing	T1, 15-15-15-0-0	363 ± 6b	249 ± 27b	1,683 ± 138b	0.733
	T2, 15-15-15-3.8-1.4	397 ± 9a	397 ± 23a	2,541 ± 49a	0.762
	T3, 16-8-18-0-0	392 ± 14ab	315 ± 52ab	2,011 ± 47b	0.740
	T4, 16-8-18-4.2-1.8	416 ± 4a	364 ± 49ab	2,489 ± 202a	0.762
Jinping, Guizhou	T1, 15-15-15-0-0	386 ± 11b	530 ± 11b	1,446 ± 13b	0.612
	T2, 15-15-15-3.8-1.4	578 ± 61a	750 ± 55a	2,044 ± 46a	0.606
	T3, 16-8-18-0-0	488 ± 32ab	600 ± 50b	1,530 ± 54b	0.584
	T4, 16-8-18-4.2-1.8	596 ± 32a	813 ± 32a	2,156 ± 19a	0.605

Similar letters indicate no significant differences within an organ and site at P<0.05.

Calculations and data analyses

SAS 8.1 software was used for statistical analysis and significance of variances test, and Excel 2016 software was used for data processing and graphs.

Results

Yield and dry matter accumulation

Polyhalite, when added to the compound NPK fertilizer, the commonly used one or the one formulated for pepper (T2 and T4), gave rise to significant increases in the dry biomass of leaves, stems, and fruit (Table 3). These differences were highly significant compared to the common NPK fertilizer (T1), and a bit less pronounced compared to the improved NPK fertilizer (T3). Subsequently, the aboveground dry biomass at both experiment sites increased by 42-51% in response to the NPK+polyhalite mixtures, compared to T1, while improving the NPK formula alone resulted in biomass rise of only 11-18% (Fig. 1A). Notably, leaf biomass, but particularly stem biomass, were greater at Guizhou than at Chongqing (Table 3).

The NPK+polyhalite fertilizers brought about 42 and 36% increase in fresh pepper fruit yield in Chongqing, and 41 and 52% increase in Guizhou, compared to the common NPK treatment (Fig. 1B). The improved NPK formula (T3) gave rise to only 14.5%, and to less than 2% yield increase in Chongqing and Guizhou, respectively. Interestingly, pepper fruit yields were considerably higher at Chongqing than at Guizhou in all treatments (Fig. 1B), while no such differences were observed in the aboveground biomass (Fig. 1A). In addition, polyhalite application enhanced the harvest index (HI) at Chongqing but not at Guizhou (Table 3).

Nutrient uptake and distribution

Generally, the different fertilizer treatments had various effects on the nutrient concentration and distribution among major pepper plant organs at harvest (Fig. 2). First, substantial differences occurred in K concentrations between the two sites, which were much higher at Chongqing in all three plant organs (Fig. 2A,B). Leaf K concentration that ranged from 30-36 g kg^{-1} DM at Chongqing, and from 17-20 g kg^{-1} DM at Guizhou, tended to be greater than in the two other organs, however, fruit K concentration was considerably high, ranging from 22-28 g kg^{-1} DM at Chongqing, and at about 14.5 g kg^{-1} DM at Guizhou. The direct effect of the fertilizer treatments on organ K concentration seemed quite weak and inconsistent, although some statistical differences were observed (Fig. 2A,B).

While leaf Ca concentrations were generally similar at both sites, ranging from 14-23 g kg^{-1} DM, stem Ca concentrations were much lower at Guizhou than at Chongqing, 1.5-2 vs. 9-13 g kg^{-1} DM, respectively (Fig. 2C,D). At both sites, fruit Ca concentrations were much lower than in the two other plant organs, ranging from 0.39-0.61 g kg^{-1} DM. Unexpectedly, polyhalite application reduced leaf Ca concentrations at both sites, a trend that was also observed in the stems. Similar to Ca, leaf Mg concentrations were quite similar at both sites (3.3-4.2 g kg^{-1} DM), while stem Ca concentrations were substantially higher at Chongqing than at Guizhou, 3.5-4.4 vs. 1.2-1.7 g kg^{-1} DM, respectively (Fig. 2E,F). Contrary to what was measured for Ca, fruit Mg concentrations were relatively high at both sites and ranged from 1.85-2.08 g kg^{-1} DM. The fertilizer treatments had very small effects on the organs' Mg concentration, excluding a tendency of polyhalite to reduce leaf and stem Mg concentrations,

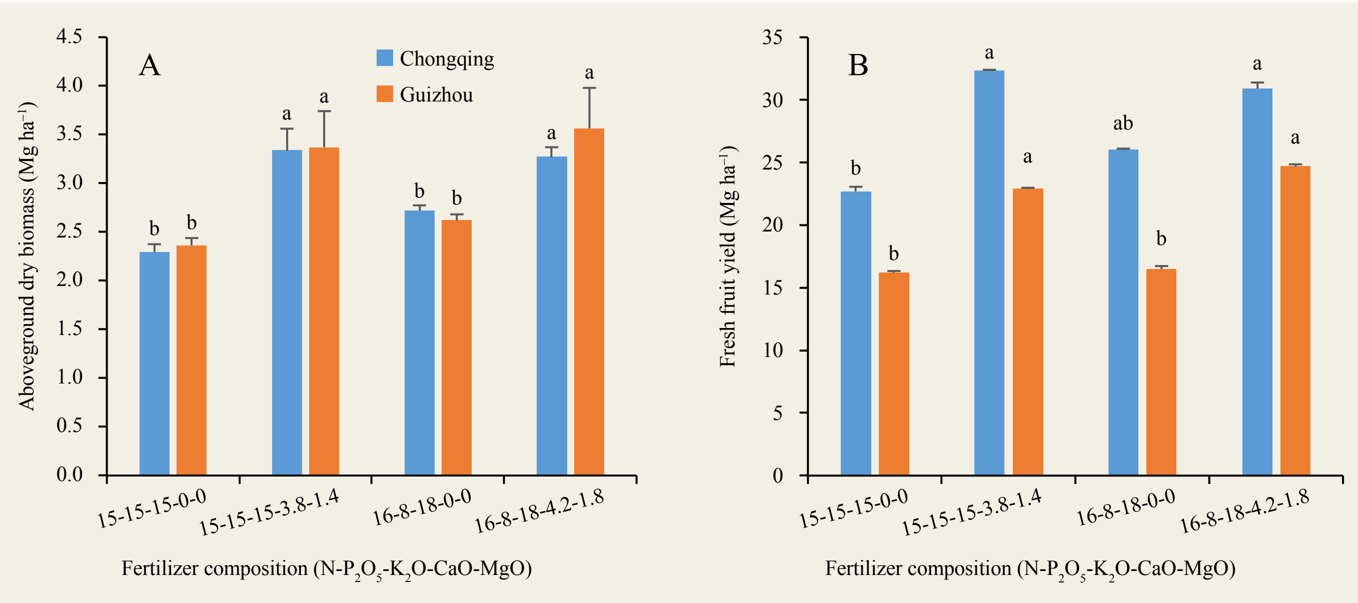

Fig. 1. Effects of fertilizer treatments on the aboveground dry biomass (A) and on the fresh fruit yield (B) of pepper crops grown at two experiment sites in southwest China on yellow soils. Similar letters indicate no significant differences within a site at $P<0.05$.

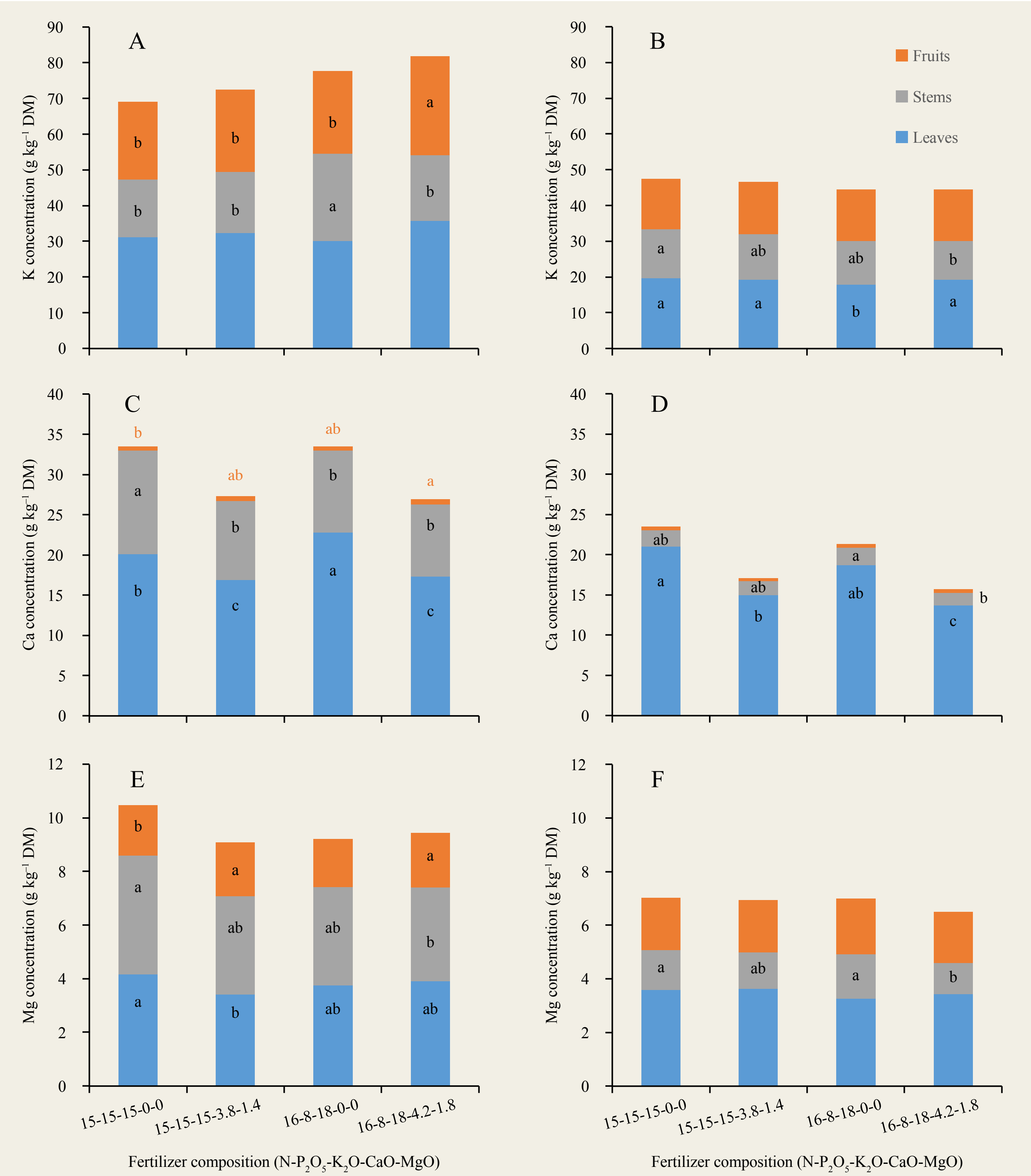

Fig. 2. Effects of fertilizer treatments on K (A and B), Ca (C and D), and Mg (E and F) concentration in pepper leaves, stems, and fruit, at two experiment sites, Chongqing (A,C,E) and Guizhou (B,D,F). Similar letters indicate no significant differences within a plant organ and site at $P<0.05$; no letters indicate no significant differences. For detailed description of the treatments T1-T4, refer to Table 2.

and to increase it in the fruit. Nevertheless, this tendency was not always clear.

The seasonal nutrient uptake was calculated from the organ biomass yield, multiplied by the nutrient concentration, at harvest. Therefore, both factors should be considered evaluating nutrient uptake. Polyhalite application increased leaf K uptake, reduced leaf Ca uptake at Chongqing but not at Guizhou, and increased leaf Mg uptake – only at Guizhou (Table 4). Stem K uptake was significantly increased by the pepper-NPK formula (16-8-18) at Chongqing, while polyhalite just tended to increase stem K uptake at both sites. While stem K uptake was greater somewhat at Guizhou, stem Ca uptake was about 3-fold greater there, compared to Chongqing (Table 4). However, polyhalite did not have any significant influence on stem Ca uptake at either site. Similarly, the fertilizer treatments did not affect stem Mg uptake. Fruit K uptake was twice as high at Chongqing and was significantly enhanced by the polyhalite+NPK fertilizer, with a slight advantage for the 16-8-18 NPK formula (Table 4). Similar patterns, though less pronounced, were observed for fruit Ca and Mg uptake. Overall, K uptake by the total aboveground crop biomass was substantially higher at Chongqing (Table 4). Both K and Mg uptake by the crop biomass were significantly promoted by the polyhalite+NPK fertilizers, whereas Mg uptake remained unaffected by the fertilizer treatments (Table 4).

The difference between nutrients input (application dose) and nutrients uptake by a crop may be expressed as surplus, or deficit in the case of a negative balance. At both sites, the pure NPK fertilizers (T1 and T3) promoted higher K surplus, and Ca and Mg deficit (Fig. 3). On the contrary, the mixed NPK+polyhalite fertilizers reduced K surplus, and furthermore, led to considerable Ca and Mg surplus (Fig. 3).

The fertilizer treatments also had significant effects on the agronomic efficiency of the macronutrients N and P. This parameter is expressed by the ratio between the produce (e.g., fruit) yield and the nutrient application rate (kg fruit kg^{-1} nutrient). While the agronomic N efficiency was unaffected by the NPK formula modification from 15-15-15 to 16-8-18, the added polyhalite gave rise to significant increases of this parameter at both sites (Fig. 4A).

The agronomic P efficiency underwent an even more dramatic influence (Fig. 4B); the substantial reduction in P input in the modified NPK formula (T3) gave rise to a significant increase in this parameter, from 92 and 66 (T1), to 160 and 102 kg kg^{-1}, at Chongqing and Guizhou, respectively. Nevertheless, the added polyhalite, and particularly with the advanced NPK formula (T4), brought the agronomic P efficiency to 189 and 151 kg kg^{-1}, at Chongqing and Guizhou, respectively (Fig. 4B).

Table 4. Effects of the fertilizer treatments on the seasonal K, Ca, and Mg uptake by leaves, stems, fruit, and total aboveground crop biomass at harvest at Chongqing and Guizhou experiment sites.

Parts	Treatment	K		Ca		Mg	
		Chongqing	Guizhou	Chongqing	Guizhou	Chongqing	Guizhou
		kg ha^{-1}					
Leaves	T1, 15-15-15-0-0	11.4 ± 0.73b	7.62 ± 0.16b	7.30 ± 0.12b	8.16 ± 0.90a	1.51 ± 0.03a	1.39 ± 0.12b
	T2, 15-15-15-3.8-1.4	12.8 ± 0.54ab	11.1 ± 0.92a	6.72 ± 0.20b	8.75 ± 1.26a	1.36 ± 0.04a	2.08 ± 0.15a
	T3, 16-8-18-0-0	11.7 ± 0.44ab	8.72 ± 0.66b	8.92 ± 0.20a	9.10 ± 0.57a	1.48 ± 0.16a	1.58 ± 0.09b
	T4, 16-8-18-4.2-1.8	14.9 ± 1.69a	11.5 ± 0.52a	7.19 ± 0.23b	8.14 ± 0.72a	1.62 ± 0.09a	2.05 ± 0.17a
Stems	T1, 15-15-15-0-0	4.04 ± 0.77b	7.30 ± 0.66a	3.25 ± 0.47a	1.09 ± 0.12a	1.11 ± 0.14a	0.79 ± 0.07a
	T2, 15-15-15-3.8-1.4	6.84 ± 0.54ab	9.49 ± 0.63a	3.91 ± 0.35a	1.27 ± 0.14a	1.45 ± 0.09a	1.02 ± 0.02a
	T3, 16-8-18-0-0	7.86 ± 1.63a	7.42 ± 0.97a	3.18 ± 0.45a	1.32 ± 0.18a	1.12 ± 0.10a	1.00 ± 0.14a
	T4, 16-8-18-4.2-1.8	6.77 ± 1.12ab	8.74 ± 0.33a	3.26 ± 0.36a	1.29 ± 0.08a	1.27 ± 0.14a	0.96 ± 0.07a
Fruits	T1, 15-15-15-0-0	36.6 ± 3.56c	20.3 ± 1.08b	0.88 ± 0.15b	0.61 ± 0.04b	3.17 ± 0.30b	2.82 ± 0.06b
	T2, 15-15-15-3.8-1.4	58.3 ± 1.47ab	29.7 ± 1.28a	1.45 ± 0.10a	0.67 ± 0.01ab	5.10 ± 0.10a	3.95 ± 0.08a
	T3, 16-8-18-0-0	46.6 ± 2.29bc	22.1 ± 0.80b	1.05 ± 0.01b	0.62 ± 0.04b	3.59 ± 0.19b	3.19 ± 0.32b
	T4, 16-8-18-4.2-1.8	69.1 ± 7.78a	31.1 ± 0.63a	1.50 ± 0.14a	0.84 ± 0.12a	5.06 ± 0.48a	4.09 ± 0.09a
Total above ground biomass	T1, 15-15-15-0-0	52.0 ± 4.76c	35.2 ± 1.53b	11.4 ± 0.70a	9.85 ± 0.87a	5.79 ± 0.44b	5.00 ± 0.11b
	T2, 15-15-15-3.8-1.4	78.0 ± 0.41ab	50.3 ± 2.36a	12.1 ± 0.48a	10.7 ± 1.15a	7.91 ± 0.13a	7.05 ± 0.17a
	T3, 16-8-18-0-0	66.2 ± 3.87bc	38.2 ± 2.23b	13.2 ± 0.55a	11.0 ± 0.58a	6.18 ± 0.41b	5.77 ± 0.55b
	T4, 16-8-18-4.2-1.8	90.8 ± 8.86a	51.3 ± 0.06a	12.0 ± 0.51a	10.3 ± 0.71a	7.94 ± 0.44a	7.10 ± 0.17a

Similar letters indicate no significant differences between treatments within an organ and site ($P<0.05$).
Detailed description of the fertilizer treatments is given in Table 2.

Vitamin C content

Pepper fruit are known to contain relatively high levels of vitamin C. Therefore, the concentration of this vitamin in pepper fruit is considered a quality parameter. As a rule, vitamin C contents at Guizhou were substantially higher than at Chongqing (Fig. 5). At Chongqing, all three modified fertilizer formulae brought about significant increases in vitamin C, compared to the common NPK control. At Guizhou, vitamin C tended to increase in response to the fertilizer modifications, but only T4, NPK 16-8-18 + polyhalite obtained a significantly higher concentration of vitamin C (Fig. 5).

Economic analyses

The purchase prices of inputs (e.g., fertilizers) and of the produce (pepper fruit) in China are dynamic and might significantly differ from one region to another, as well as over time. Therefore, any economic analysis should be considered real at location and time of execution. Converting the NPK formula from 15-15-15 to 16-8-18 reduced the fertilizer cost to the farmer, but the benefit was insignificant, 16 and 2% at Chongqing and Guizhou, respectively (Table 5). In contrast, adding polyhalite to the NPK formulas increased the farmer's benefit by 44 and 37% at Chongqing, and by 44 and 56% at Guizhou (T2 and T4, respectively). Consequently, the added values of the polyhalite treatments were substantially higher than that of the converted NPK (16-8-18) alone (Table 5). The ratio between the benefit and fertilizer cost increased at both sites as a result of the improved fertilizer treatment, but it was much lower at Guizhou due to the lower fruit yields there. The return on investment (ROI) in polyhalite was striking. Adding polyhalite to the formula raised the fertilizer cost by 1,010 and 1,168 CNY ha^{-1}, at T2 and T4, respectively; every invested CNY in polyhalite resulted in very positive ROI of 27.5 or 20 CNY at Chongqing, and 15.4 or 17.2 CNY at Guizhou, at T2 or T4, respectively (Table 5).

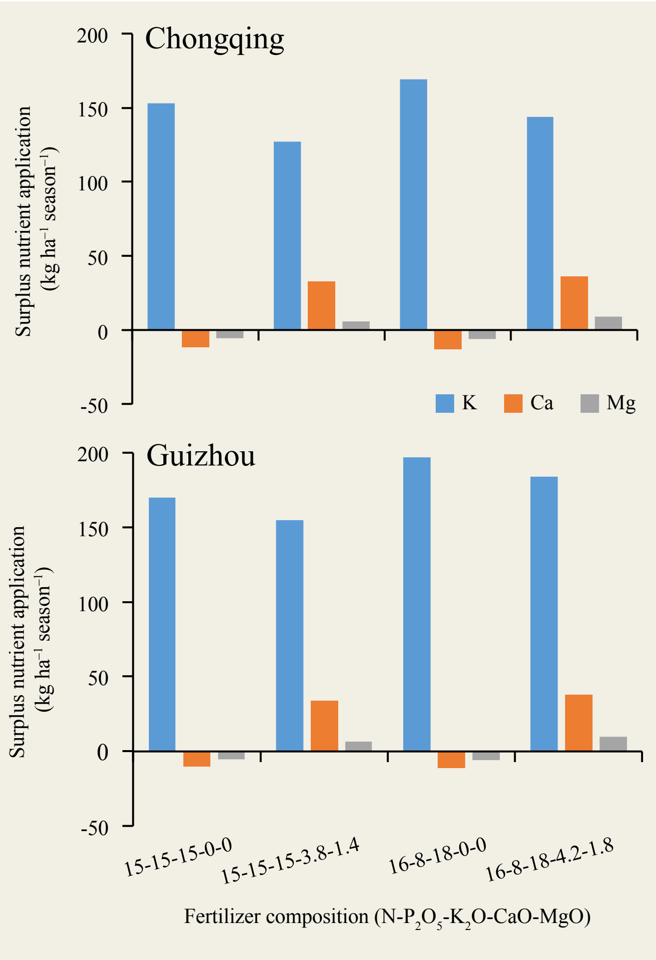

Fig. 3. Effects of fertilizer treatments on the seasonal balance between nutrient (K, Ca, and Mg) input and uptake by pepper crops at Chongqing and Guizhou experiment sites. Detailed description of the fertilizer treatments is given in Table 2.

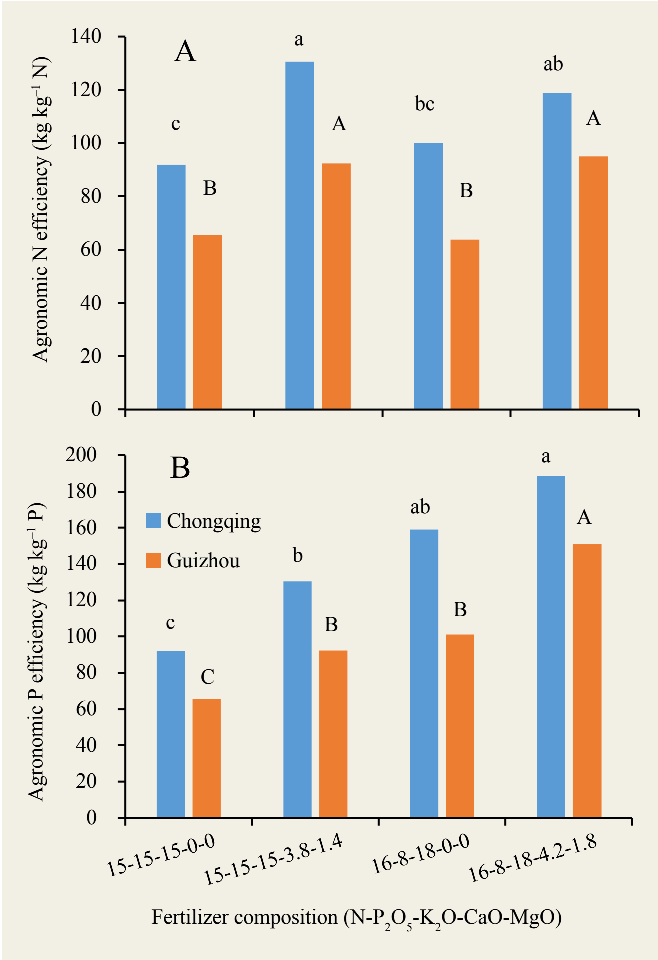

Fig. 4. Effects of fertilizer treatments on the agronomic efficiencies of N (A) and P (B) in pepper crops at Chongqing and Guizhou experiment sites. Similar letters indicate no significant differences between treatments (P<0.05) at Chongqing (small letters) and at Guizhou (capital letters).

Table 5. Economic analysis of the cost and return on investment (ROI) of fertilizer treatments employed in pepper cultivation at Chongqing and Guizhou, southwest China.

Sites	Treatments	Revenue	Fertilizer cost	Benefit	Added value	Benefit/cost ratio	Polyhalite ROI
		----------CNY ha^{-1}----------					
Shizhu, Chongqing	T1, 15-15-15-0-0	68,172 b	4,950	63,222 b	–	12.8	–
	T2, 15-15-15-3.8-1.4	96,987 a	5,960	91,027 a	27,805	15.3	27.5
	T3, 16-8-18-0-0	77,990 ab	4,830	73,160 ab	9,938	15.1	–
	T4, 16-8-18-4.2-1.8	92,559 a	5,998	86,561 a	23,339	14.4	20.0
Jinping, Guizhou	T1, 15-15-15-0-0	40,572 b	4,950	35,622 b	–	7.2	–
	T2, 15-15-15-3.8-1.4	57,153 a	5,960	51,193 a	15,571	8.6	15.4
	T3, 16-8-18-0-0	41,304 b	4,830	36,474 b	852	7.6	–
	T4, 16-8-18-4.2-1.8	61,697 a	5,998	55,699 a	20,077	9.3	17.2

Similar letters indicate no significant differences between treatments within a site (P<0.05).
Detailed description of the fertilizer treatments is given in Table 2.

Discussion

In the current agricultural practices used to grow pepper on the yellow soils of southwest China, the application doses of N, P_2O_5, and K_2O are rigid and even (15-15-15), and targeted at the lower level of fertilizer cost rather than at the crop requirements. In addition, farmers ignore the input of secondary but essential nutrient elements, such as Ca and Mg. Calcium and Mg are both essential secondary elements for the normal growth and development of vegetables, and the Ca and Mg requirements of peppers both exceed P requirements (Ma *et al.*, 2010a). Due to the regional characteristics of highly intensive agriculture, high temperature and precipitation regimes, and a high degree of soil acidification (Table 1), the leaching problems of soil Ca and Mg nutrient are very serious in the region. Consequently, soil Ca and Mg deficiencies are very common. Thus, the current fertilization practices result in low fertilizer use efficiency and increase the environmental burden, while the crop potential of yield and quality remains unrealized (Lu *et al.*, 2011).

In the present study, two different steps were examined, alone and together, in order to improve the crop nutrient status, increase nutrient use efficiency, enhance pepper yield and quality, and raise the economic benefits to farmers. The first step was an adjustment of the compound NPK fertilizer composition ratio from 15-15-15 to 16-8-18, as formerly suggested by Ma *et al.*, 2010a, Lu *et al.*, 2011, and Liu *et al.*, 2017. The second step was adding polyhalite as a supplementary fertilizer contributing Ca, Mg, K, and S, to the NPK application doses.

Compared to the common NPK fertilizer treatment (T1), the new NPK fertilizer designed especially for pepper requirements (T3) increased N and K_2O inputs by 12 and 36 kg ha^{-1}, respectively; however, it lessened the total nutrient input, mainly through the considerably reduced P input (-84 kg ha^{-1}). Since the fruit yield was unaffected or even slightly increased (Fig. 1B), this step significantly increased the agronomic P use efficiency (Fig. 4B), while no influence was observed on N use efficiency (Fig. 4A). Nevertheless, the impacts of the second step – adding polyhalite to the NPK fertilizers – were much greater. It significantly increased pepper crop performance and yield (Fig. 1). These results are consistent with previous studies (Ma *et al.*, 2010a; Zhang *et al.*, 2015) and indicate that soil Ca and Mg deficiency have been two of the main limiting factors for pepper production in the yellow soils of this region. In addition, this study also showed that the application of Ca and Mg nutrients significantly increased the dry

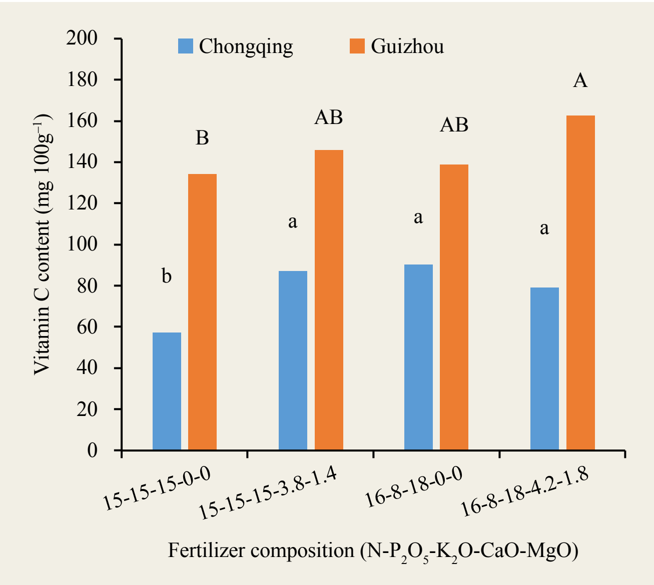

Fig. 5. Effects of fertilizer formulation on the concentration of vitamin C in pepper fruit at Chongqing and Guizhou experiment sites. Similar letters indicate no significant differences between treatments (P<0.05) at Chongqing (small letters) and at Guizhou (capital letters).

matter accumulation of all plant organs (Table 3), which is the basis for obtaining high yield (Ma *et al.*, 2010b). Furthermore, the added polyhalite significantly increased the nutrient use efficiency of both N and P (Fig. 4), suggesting positive interactive relationships between the four nutrients under the circumstances of the study. In areas with intense subtropical rainfall, Ca, Mg, and K are often substantially leached and lost (Oliveira *et al.*, 2002; Huang *et al.*, 2016; Li *et al.*, 2018). The inclusion of polyhalite in the fertilizer blend seemed to replenish the soil Ca and Mg reserves (Fig. 3) and simultaneously increase K and Mg crop uptake (Table 4). Nevertheless, more research is still needed to overcome the fertility problems of yellow soils. Polyhalite, which provides four essential nutrients over a prolonged period and in a slow-release manner (Yermiyahu *et al.*, 2017; 2019; Huang *et al.*, 2020), demonstrates the principles that should rule the required changes: balanced soil nutrition; adjustment to crop requirements; use of slow- or control-release fertilizers.

Previous studies have shown that the addition of Ca and Mg significantly increased the accumulation of mineral nutrients such as K, Ca and Mg in tomato, peppers, and Chinese cabbage (Xiao and Yang, 2000; Yao *et al.*, 2008). Recently, Mg was found to be particularly concentrated in pepper fruit and seeds (Ma *et al.*, 2019). In the present study, polyhalite application increased the accumulation of K and Mg in leaves and in fruit (Table 4), and in some cases, increased their concentrations in fruit (Fig. 2). Pepper has a high edible and medicinal value and tops the list of vegetables in terms of its vitamin C content (International Food Information Council, 2002). It has been found that in vegetable crops such as tomato, cucumber, and Chinese cabbage, the application of intermediate elements (Ca and Mg) effectively enhanced vitamin C content (Qin *et al.*, 2008; Luo *et al.*, 2015; Song *et al.*, 2015). In this experiment, added Ca and Mg (through polyhalite), and reduced P proportion (and dose) in the NPK fertilizer significantly increased vitamin C content in pepper fruit at the Chongqing experiment site. However, this approach failed to increase the Ca and Mg concentrations in the pepper fruit, possibly due to the dilution effect of the substantial increase in yield (7.3%-44.3% on average at the two test sites).

Photo 2. Pepper vines grown on the Chongqing experiment plot. Photo by the authors.

As one of the typical cash crops for the region, pepper is of great importance to the agricultural economy and development of southwest China. Compared with the common fertilization practices, the application of the enhanced fertilizer formula, and furthermore, the blend with polyhalite, demonstrated obvious advantages in all economic parameters (Table 5). Usually, a rise in the net income is considered significant when the output-input ratio (added-value/cost) is higher than 2.0 (Zou *et al.*, 2009). Applying polyhalite (treatments T2 and T4), the mean values of output-input ratio in the two test sites in this study were as high as 3.64, strongly indicating that using this fertilizer can significantly enhance the economic performance of pepper. Moreover, the calculated ROI for polyhalite application in the present study was very high, ranging from 15-27, clearly demonstrating the economic advantages of pepper production, and possibly of many other vegetable species, on the yellow soils of southwest China.

Acknowledgements

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The paper "Enrichment of Compound NPK Fertilizer with Polyhalite Enhances Pepper (*Capsicum annuum*) Yield and Quality on Poor Yellow Soils in Southwest China" also appears on the IPI website.

Research Findings

Photo 1. Beans growing in Guanajuato, Mexico. Photo by the authors.

Polyhalite Effects on Corn and Bean Performance in Guanajuato, Mexico

Baez-Perez, A.[(1)*], E.A. Olivares-Arreola[(2)], A. Salamanca-Jimenez[(3)], and F. Vale[(4)]

Abstract

Corn (*Zea mays*) and beans (*Phaseolus vulgaris*) are deeply rooted in ancient Mesoamerican cultures and are among the major staple foods in Mexico today. Irrigation, where available, brings about a significant increase in production and yield of both crop species; however, more balanced mineral nutrition is presumed to further improve grain yields and quality. So far, crop nutrition has focused on nitrogen (N), phosphorus (P), and potassium (K), ignoring secondary, though essential, nutrients such as calcium (Ca), magnesium (Mg), and sulfur (S). Polyhalite is a new natural fertilizer which contains 48% SO_3, 14% K_2O, 6% MgO, and 17% CaO, with significantly slower mineral release compared to other relevant commercial fertilizers.

The present study took place at INIFAP, Campo Agrícola Experimental Bajío, Celaya, Guanajuato State, Mexico, and was designed to evaluate the dose-response curve of corn to polyhalite at rates of 0, 34, 68, 136, and 272 kg ha^{-1} during two production years, as well as studying the residual effects of polyhalite on a subsequent

[(1)]Instituto Nacional de Investigaciones Forestales Agrícolas y Pecuarias (INIFAP), Mexico
[(2)]Instituto Tecnológico Nacional de México
[(3)]ICL Consultant in Latin America, ASJ Agroservices
[(4)]IPI Coordinator for Latin America, International Potash Institute, Zug, Switzerland
*Corresponding author. Email: baez.aurelio@inifap.gob.mx

bean crop. Principally, N, P, and K doses were kept equal (300, 100, and 50 kg ha^{-1} of N, P_2O_5, and K_2O, respectively) in all treatments, while S was supplied through polyhalite or ammonium sulfate at rates ranging from 0-52 kg ha^{-1}.

Despite significant restrictive weather conditions during the late corn season in 2018, polyhalite showed a remarkable positive influence on root development, and on grain N and protein contents. The 2019 bean crop, grown on the footprint of the former corn crop, displayed the impressive residual impact of polyhalite fertilizer application, with grain yields exceeding 3 Mg ha^{-1}, 20% higher than the control. The 2019 spring-autumn corn cycle exhibited significant responses to elevated polyhalite doses for all crop performance parameters measured, reaching a grain yield of 15.6 Mg ha^{-1}, at the top level of corn yields in the region. These results demonstrate the significant potential of polyhalite to serve as a first-choice multi-nutrient fertilizer, not only providing additional essential macronutrients, but also increasing the crops' nutrient use efficiency and hence, promoting more balanced crop nutrition.

Keywords: calcium; grain yield; magnesium; *Phaseolus vulgaris*; Polysulphate; potassium; *Zea mays*.

Introduction

Corn (*Zea mays*) and beans (*Phaseolus vulgaris*), together with winter squash (*Cucurbita pepo*), comprise the "Three Sisters", the three main agricultural crops cultivated by ancient indigenous peoples in Mesoamerica (Mt. Pleasant, 2016). These crop species are still deeply rooted in Mesoamerican culture today. Furthermore, in Mexico, corn and beans are the two main staple crops for food and industry.

More than 7.5 million ha of corn is planted annually in Mexico, with an average yield of 3.7 Mg ha^{-1} (SIAP, 2021). During the last decade, Guanajuato State was the fourth largest corn producing region in Mexico, with an average yield, under irrigation, ranging from 7.5-8.9 Mg ha^{-1}; however, maximum yield data often exceeds 18 Mg ha^{-1}, indicating the local potential productivity under irrigation (Baez-Perez and González-Torres, 2020; Peña-Ramos *et al.*, 2017). The area in Guanajuato State with irrigation availability may fluctuate from 120,000 to 170,000 hectares (SIAP, 2018).

Meanwhile, the annual bean production in Mexico covers more than 1.4 million ha with an average yield of 0.72 Mg ha^{-1} (SIAP, 2021). As with corn, irrigation of beans significantly enhances crop performance, giving rise to an average yield of 1.75 Mg ha^{-1}, from about 170,000 ha. Guanajuato State is also Mexico's fourth largest beans producer, with about 9,000 ha that produce an average yield of 2.22 Mg ha^{-1}; nevertheless, the yield potential may exceed 3.5 Mg ha^{-1} (Acosta-Gallegos *et al.*, 2014).

In the irrigated areas of Guanajuato, nitrogen (N) fertilizers are used excessively for cereal production, resulting in a significant increase in economic cost and substantial risk of environmental pollution (Baez-Perez *et al.*, 2012). A more rational use of fertilizers is required which would take into account crop requirements based on the yield potential, soil nutrient status, and crop nutrient use efficiency (Etchevers-Barra, 1999). Based on this, a corn yield

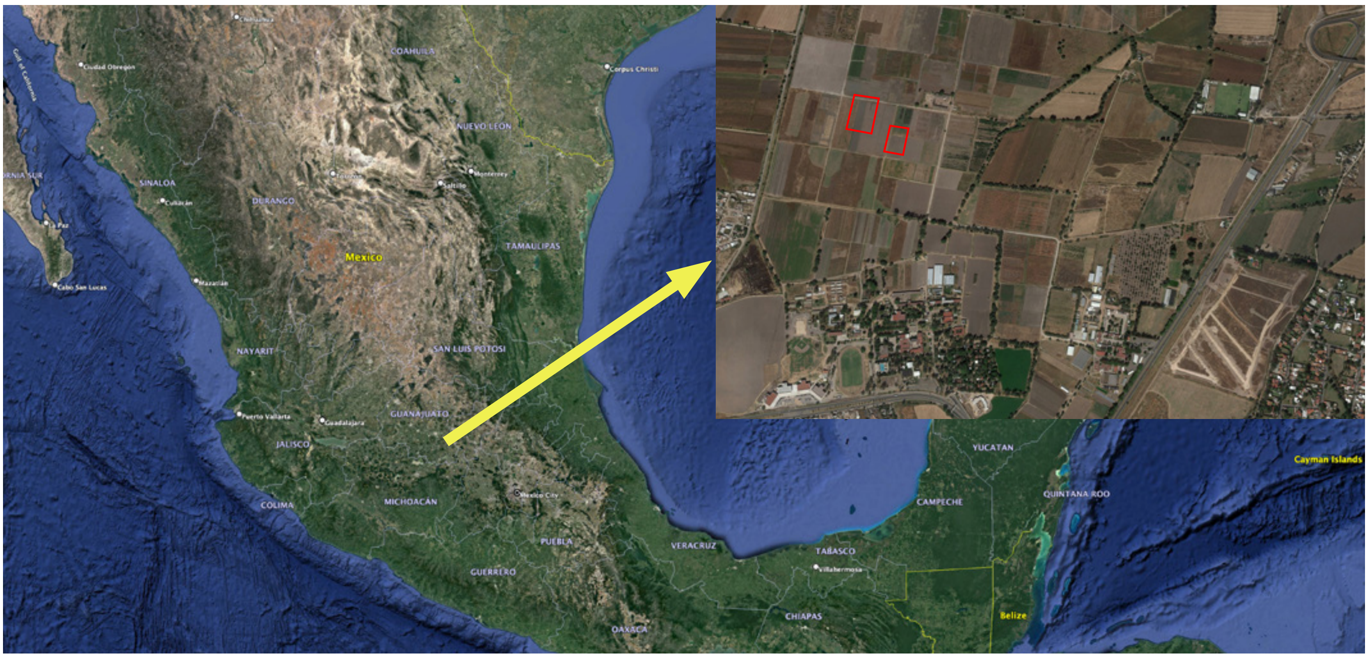

Fig. 1. Location of INIFAP's Bajío experiment field in Celaya, Guanajuato State, Mexico. Source: Google Earth.

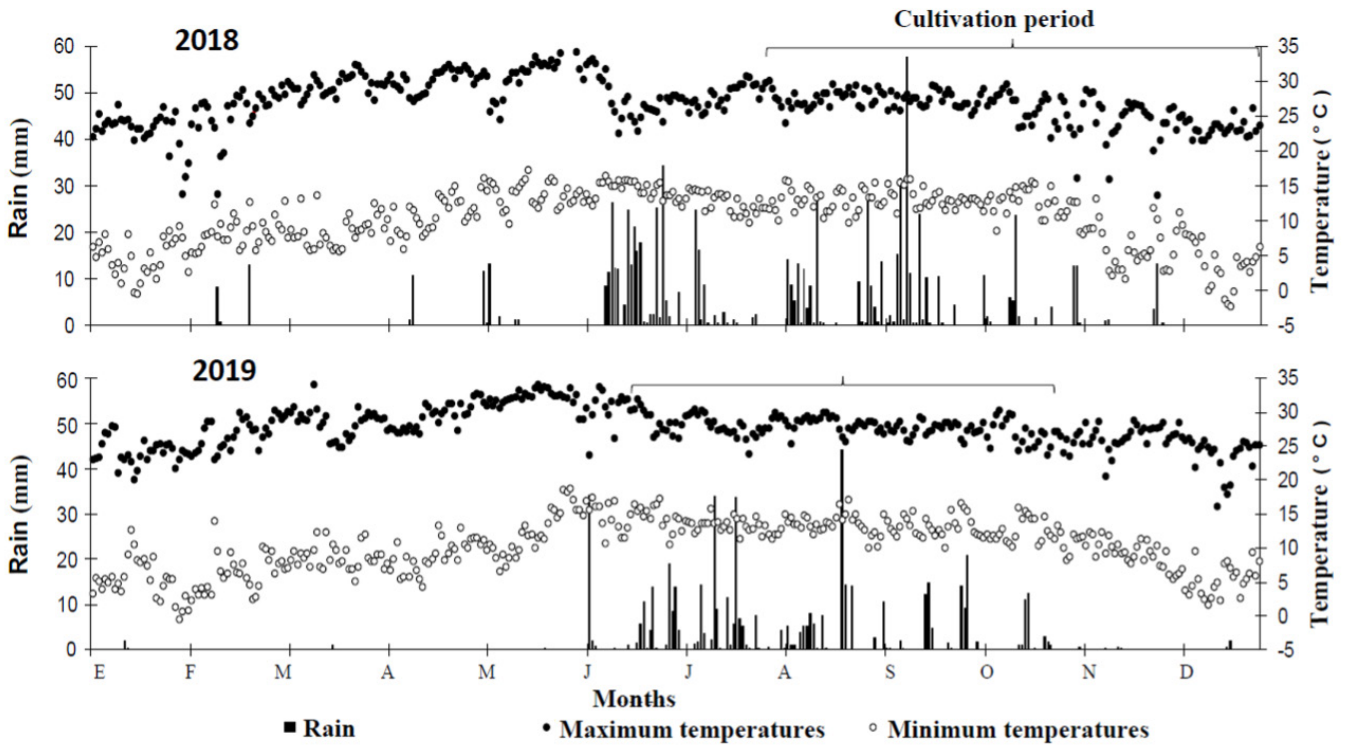

Fig. 2. Daily rain, and maximum and minimum temperatures at Bajío experiment field, Celaya, Guanajuato, Mexico, in 2018 and 2019.

exceeding 18 Mg ha^{-1} in Guanajuato, may require approximately 400, 100, 50, and 5-15 kg ha^{-1} of N, P_2O_5, K_2O, and MgO respectively (Medina-Rojas, 2015).

In terms of timing, N is usually split into 2 or 3 applications, while the other nutrients are usually applied 100% at planting. Urea, ammonium sulfate, di-ammonium phosphate (DAP), and potassium chloride (KCl) are commonly used as the main N, phosphorus (P), and potassium (K) fertilizers, and more recently polyhalite has been explored as a complementary K, calcium (Ca), magnesium (Mg), and sulfur (S) source (Yermiyahu *et al.*, 2017).

Polyhalite contains 48% SO_3, 14% K_2O, 6% MgO, and 17% CaO (Imas, 2016) and can be applied to all soil types. It is a certified organic product that releases its nutrients gradually over a prolonged period, reducing the risk of leaching (Huang *et al.*, 2020), reducing the limiting effects of chloride associated with the excessive application of KCl, and contributing to more balanced crop nutrition which results in higher yield, quality, and profitability for multiple crops. Little information could be found with respect to the effects of polyhalite on corn (Pavuluri *et al.*, 2017; Foxhoven, 2019; Lillywhite *et al.*, 2020), and even less on bean yield. The present study was aimed, therefore, at evaluating the dose-response curve of corn to polyhalite during two production years, as well as studying the residual effects of polyhalite on a subsequent bean crop. Principally, N, P, and K doses were kept equal in all treatments, while S was supplied through polyhalite or ammonium sulfate. This approach was designed to assess the role of polyhalite as a source of Mg and Ca and compare polyhalite with KCl as the K source.

Materials and methods

Location

The experiments were carried out at the National Institute of Agricultural and Livestock Forestry Research (INIFAP), Campo Agrícola Experimental Bajío, Mexico, located 6.5 km from the Celaya-San Miguel de Allende Highway S/N, Colonia Roque, Celaya, in Guanajuato State (Fig. 1). The field is located at 20º35’18.2”N and 100º49’34”W, at an altitude of 1,706 m above sea level.

Climate

According to Garcia (1984), the region exhibits a Hot Semi-Arid climate (BS_1hw(w)(e)) with an average annual temperature of 20.6°C and an average annual precipitation of 597 mm. During the experiment, maximum and minimum temperatures, and rainfall, were recorded daily by an automated station established near the experiment plots.

The maximum temperature during the 2018 corn cycle was more than 30°C during July and August, while minimum temperatures were -2°C in mid-December 2018 (Fig. 2). First frosts were recorded with an extreme minimum temperature of 2.2°C in mid-November. From 20 December 2018, temperatures below 0°C were recorded

Table 1. Soil physical properties at the experiment site.

Soil samples	Elementary particles			Textural class	Bulk density	Field capacity
	Sand	Silt	Clay			
	---------------------------- % ----------------------------				*g cm^{-3}*	*%*
1 (2018)	15.3	34.0	50.6	clayey	1.02	52.5
2 (2018)	19.3	34.0	46.6	clayey	1.05	48.0
3 (2019)	19.5	18.1	62.4	clayey	1.04	64.5

Table 2. Soil chemical properties at the experiment site.

Soil samples	pH	OM	Inorg. N	Extrac. P	K	Ca	Mg	Na	Fe	Zn	Mn	Cu
		%	-----------------------------*ppm*-----------------------------									
1	7.18	1.37	40.1	16.8	1,199	4,979	898	349	24.2	1.6	16.6	1.2
2	7.76	1.62	44.8	16.2	1,148	4,774	809	334	22.6	1.1	16.4	1.1
3	7.31	1.75	33.7	23.2	956	4,723	737	217	2.8	0.9	4.9	0.6

Table 3. Analysis of soil salinity in a saturated soil paste.

Soil samples	pH	EC	RAS	PSI	Cations				Anions			
					Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	CO_3^{2-}	HCO_3^{-}	Cl^{-}	SO_4^{2-}
		dS m^{-1}			--------------*meq L^{-1}*--------------				----------------*meq L^{-1}*----------------			
1	8.28	1.18		16.2	4.31		5.97	1.49	0.12	0.76	3.39	7.5
2	8.54	0.79		16.6	3.35		3.71	0.81	0.12	0.52	2.12	5.1
3	7.75	1.14	2.42	12.5	3.91	2.18	4.22	1.13	0.24	0.72	4.00	6.5

during four consecutive days, with an extreme minimum temperature of -2.3°C on 22 December 2018; by this time the crop had reached physiological maturity, and the grain contained more than 35% moisture. Annual rainfall during 2018 was 800 mm, an exceptionally wet year compared to the average annual rainfall of 600 mm. During the growth period the crop received 430 mm of rain, with large amounts of water between mid-August and mid-September, just after the first irrigation on 5 August. During 2019, the temperature pattern was similar to 2018, but no frosts were observed during the period of corn and bean cropping (Fig. 2). Annual rainfall was 518.8 mm distributed from June to October, which approximately corresponded to the growing period, therefore there was no need to irrigate the beans experiment.

Soil

According to the USDA classification, the soil of the experiment field corresponds to a Vertisol and is representative of the Bajío region. Soil texture is clayey, with about 50% clay, mainly of the Smectite type. A bulk density of 1.04 indicates that the soil did not present compaction problems, and the field capacity was about 50% (Table 1). Soil was slightly alkaline, contained a low level of organic matter, and a considerably high inorganic N reserve (130 kg ha^{-1}) in the upper 30 cm layer (Table 2). The high N content may be explained by the previous year's legume crop. The extractable P content was medium, while K, Ca, and Mg were extremely high (Table 2). Sodium (Na) content was high, but tolerable for cereal and vegetable production. At the micronutrient level, low iron (Fe), zinc (Zn), and copper (Cu) contents were observed. In saturated paste, soil showed alkaline pH and medium salinity (Table 3). No gypsum application was required for balancing pH.

Description of the experiments

Two experiments, A and B, were carried out in years 2018-2019. Experiment A examined polyhalite as an S source for late-season (summer-autumn 2018) corn crop, and its residual effects on beans planted in spring 2019. Experiment B evaluated the impact of polyhalite on a regular corn crop (spring-autumn 2019).

Experiment A included ten treatments consisting of four sulfur rates supplied from one of two S sources, polyhalite or ammonium sulfate [$(NH_4)_2SO_4$], and three controls, as described in Table 4. The treatments were designed to compare the corn and bean responses to

Table 4. Detailed description of the treatments for polyhalite evaluation in late (summer-autumn, 2018) corn crop and a subsequent bean crop (spring-summer, 2019) in Bajío experiment field (Experiment A).

Treatment	Fertilizer					Nutrients					
	Urea	DAP	KCl	Polyhalite	$(NH_4)_2SO_4$	N	P_2O_5	K_2O	S	CaO	MgO
	kg ha⁻¹ year⁻¹										
T1	567	217	0	0	0	300	100	0	0	0	0
T2	567	217	83	0	0	300	100	50	0	0	0
T3	567	217	75	34	0	300	100	50	6.5	6	2
T4	567	217	67	68	0	300	100	50	13	12	4
T5	567	217	52	136	0	300	100	50	26	23	8
T6	567	217	0	272	0	300	100	38	52	46	16
T7	542	217	83	0	55	300	100	50	13	0	0
T8	517	217	83	0	109	300	100	50	26	0	0
T9	468	217	83	0	218	300	100	50	52	0	0
T10	0	0	0	0	0	0	0	0	0	0	0

polyhalite as an alternative S source, and to evaluate the effects of K and S deficiencies on the background of the corresponding controls. Experiment units consisted of six 15-m rows separated by 0.8 m, for an individual plot area of 73 m^2 and a total area of 3,000 m^2. The experiment plan followed a Randomized Complete Block Design (RCBD), and data analyses were performed accordingly using Tukey's test for variable comparison.

All treatments in Experiment A produced low yields (compared to the common local commercial production). This was mainly associated with the late planting, the consequent reduced plant density, and the frost damage in 2018. For this reason, a new trial, Experiment B, was established in spring 2019 with a smaller number of similar treatments which preserved the nature and numbers of Experiment A treatments 1, 4, 5, 6, and 9, with three increasing polyhalite rates, one high S rate with ammonium sulfate, and one control without K (Table 5). Experiment B was also planned in a Randomized Complete Block Design with four replicates.

Agronomic management

Corn 2018

Intermediate cycle "Ocelot" corn hybrid was planted on 27 July 2018, on semi-dry soil. Potassium-phosphate (KP) fertilizers were manually applied a day before planting, and polyhalite (Polysulphate®, ICL, UK) was applied two weeks after germination, in a single application. Nitrogen supply (urea), however, was split into two applications. First irrigation was applied five days after planting; the second irrigation took place in September and was followed by a heavy rain. The final irrigation was applied in November to ameliorate cold weather effects. Chemical and manual pest and weed management were carried out according to crop requirements.

Beans 2019

Bean seedlings of the variety "Flor de Junio" were planted on 10 June 2019. Prior to planting, the stubble was crushed and left on the surface and no soil preparation was performed. After direct planting, furrows were lifted keeping the same plots as the previous corn harvest. An additional dose of 60 kg N ha^{-1} was applied during the season.

Table 5. Detailed description of the treatments for polyhalite evaluation in regular (spring-autumn, 2019) corn crop in Bajío experiment field (Experiment B).

Treatment	Fertilizer					Nutrients					
	Urea	DAP	KCl	Polyhalite	$(NH_4)_2SO_4$	N	P_2O_5	K_2O	S	CaO	MgO
	kg ha⁻¹ year⁻¹										
T1	567	217	0	0	0	300	100	0	0	0	0
T4	567	217	67	68	0	300	100	50	13	12	4
T5	567	217	52	136	0	300	100	50	26	23	8
T6	567	217	0	272	0	300	100	38	52	46	16
T9	468	217	83	0	218	300	100	50	52	0	0

Corn 2019

Soil was conventionally prepared at the beginning of May with the corresponding tillage and leveling practices. On 28 May 2019 (2 months earlier than in 2018), Cenzontle corn hybrid, with a high yield potential for the region, was planted in furrows 0.8 m wide. Excluding some technical adjustments, crop water requirements were fully satisfied by precipitation (Fig. 2).

Measurements

Corn 2018

Crop development was monitored, and the number of days from germination to male spike emergence were counted. Root volume and biomass were measured for one plant per plot. A cubic soil monolith of 30 cm per side (27 L) was extracted, and roots were washed and collected. Root volume was assessed by dipping all roots into a graduated 2,000 mL beaker and recording the volume of displaced water. Later, roots were oven dried at 70°C for 72 hours to obtain dry weight.

At the onset of flowering, the foliar nutrient status was determined. Flag leaves from 10 plants per plot were sampled, oven-dried at 70°C for 72 h, ground to a fine powder, and stored in a deep freeze until chemical examination.

Sampling plots comprised of two 0.8 m wide and 5 m long rows (8.0 m^2). Each plot was predefined in each experiment unit and served for the determination of crop performance determined from plant and cob counts, plant height from soil surface to the spike base, shoot biomass, and grain yield. To measure shoot biomass, all plant shoots from the sampling plot were collected and separated from the cobs, oven dried at 70°C for 72 h, and weighed. To determine the grain yield, grains were separated from the cobs, oven dried to 14% moisture content, and weighed. The cobs were also oven dried and were added to the shoot biomass. These results were converted to Mg ha^{-1}.

A grain sample from each experiment plot was finely ground and homogenized. Nitrogen, P, K, S, and protein contents in the grain, as well as in the foliar samples, were determined in the laboratory, according to the techniques and procedures used in the National Laboratory of Soil Fertility and Plant Nutrition of INIFAP, Bajío Experimental Field. Grain protein content was estimated using the Kjeldahl N analysis, which was multiplied by the conversion factor of 6.25 (Jackson, 1976).

Beans 2019

Bean plants were counted from each experiment unit in a sampling plot of two rows, 0.8 m wide and 5 m long (8 m^2). Grain yield was determined in the same sampling plots. Grains were harvested, dried to 14% moisture content, and weighed.

Corn 2019

Using the same methodologies described for the 2018 evaluations, the following variables were measured: plant and cob counts, plant height, shoot biomass, and grain yield. Harvest index was calculated from grain and shoot biomass data.

Results and discussion

Corn 2018

All treatments which included fertilizers displayed similar plant development rates, reaching 80-90% male flowering within 60-65

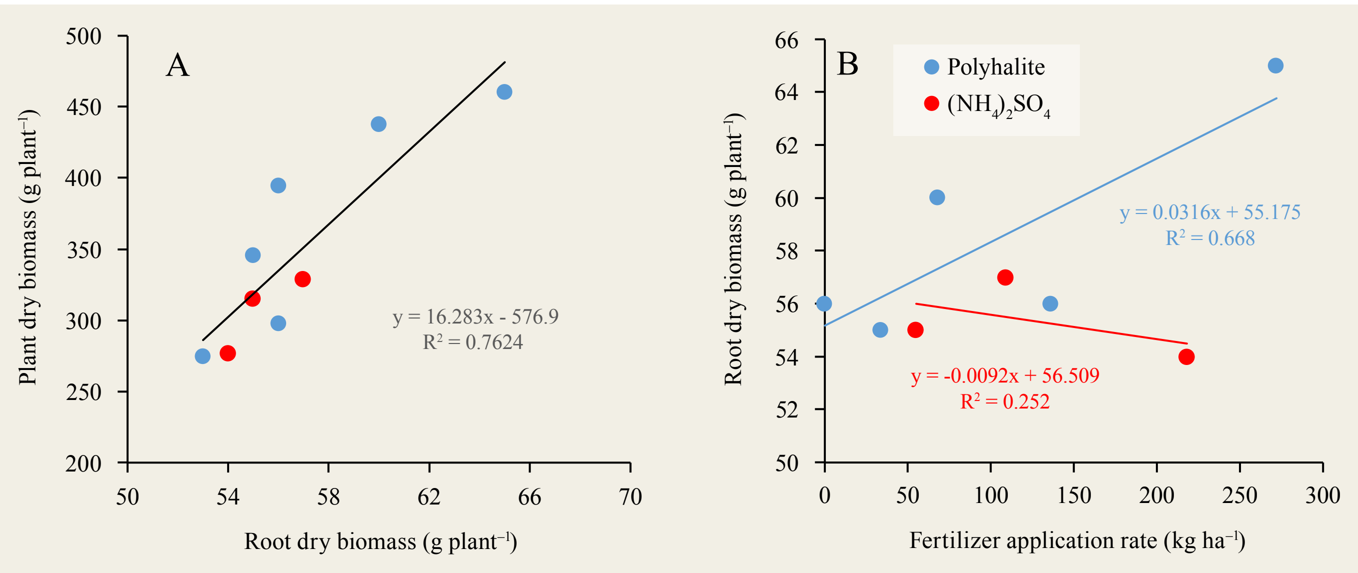

Fig. 3. The relationship between root biomass and plant biomass (A), and the effect of the fertilizer type and application rate on these parameters (B).

days. The very early flowering of the unfertilized control (10) might be associated with N deficiency stress. This stress was clearly manifested by a general chlorosis in leaves and stems, and shorter plant height compared to the N-applied treatments.

Close relationships were observed between root dry weight and root volume (data not shown), and between root dry weight and total plant weight; the greater the root biomass, the larger the plant biomass (Fig. 3A). Interestingly, root biomass increased with the rising polyhalite application rate (Fig. 3B), and the consequent effect on plant biomass was clear (Fig. 3A). Recent studies on the effects of polyhalite on crop performance in corn, as well as other crop species, show that this fertilizer effectively enhances yields (Pavuluri *et al.*, 2017; Bai-Yi *et al.*, 2018). However, very few studies demonstrated a connection between polyhalite application rate and root growth. While some studies partially attribute the advantages of polyhalite to enhanced root growth or capacity, direct evidence was observed only in lettuce on a soilless culture (Beer *et al.*, 2020). The correlation between polyhalite and root size, as indicated in the present study, requires further investigation to reveal the possible physiological mechanisms. As a K, Ca, and Mg donor the influence of polyhalite in this case is surprising, since the soil was rich with these nutrients (Table 3). Improved S availability could have provided an answer, but rising application rates of ammonium sulfate had a slightly negative effect on the root biomass (Fig. 3B).

Plant density at harvest ranged from 6.0-6.9 plants m^{-2} which was considerably less than the expected 7.5 plants m^{-2}. This was attributed to the heavy rains during the early stages of plant establishment (Fig. 2). The effect of the fertilizer treatment on plant density was inconsistent, although the ammonium sulfate treatments demonstrated a slight advantage (Table 6). Cob counts were generally unaffected by the fertilizer treatment, with the exception of the unfertilized control and the highest ammonium sulfate treatment that differed significantly from each other, with 5.8 and 7.0 cobs m^{-2}, respectively. All other treatments displayed intermediate values ranging from 6.2-6.8 cobs m^{-2} (Table 6).

Average plant height fluctuated from 2.0-2.9 m. The unfertilized plants were significantly smaller than those of all other treatments, which did not differ in height (Table 6). In the state of Guanajuato the "Ocelot" maize hybrid has an average height of about 1.7 m (Pons-Hernández *et al.*, 2013); the unusual plant height observed in this trial might be associated with high N availability and excessive rainfall during the crop cycle. Earlier studies that evaluated N fertilization in late-planted Ocelot corn hybrid in the Bajío Experiment Field also reported considerable growth in response to rising fertilizer doses (Carmona-Palma, 2018).

Grain yield and above-ground biomass of all treatments ranged from 8.0-9.4 and 16.4-19.2 Mg ha^{-1}, respectively, except for the unfertilized treatment which recorded significantly lower values (Table 6). This productivity level was considerably lower than the typical 15 Mg ha^{-1} grain yield for long-cycle corn varieties planted under irrigation at the end of April or beginning of May at the Bajío Experiment Field. Yields up to 10 Mg ha^{-1} were obtained in this region when planted late, in August, with plants exposed to frost in December, before physiological maturity. It appears that such a scenario occurred in the present study with frost and freezing night temperatures over prolonged periods in November and December 2018 (Fig. 2). Unfortunately, these restrictive conditions provided no room for other limiting factors, such as nutrient availability, and therefore no significant differences could be detected between the yields of the different fertilizer treatments (Table 6).

Table 6. Effects of the fertilizer treatment on corn crop performance in 2018 (Experiment A).

Treatment	Fertilizer					Number of		Plant height	Grain yield	Shoot biomass	Harvest index
	KCl	Polyhalite	$(NH_4)_2SO_4$	Urea	DAP	plants	cobs				
	kg ha⁻¹					*m²*		*m*	*Mg ha⁻¹*		
T1	0	0	0	567	217	6.2 ab	6.2 ab	2.7 a	8.0 a	16.4 a	0.49
T2	83	0	0	567	217	6.6 ab	6.5 ab	2.8 a	8.7 a	17.3 a	0.51
T3	75	34	0	567	217	6.0 b	6.3 ab	2.8 a	9.1 a	18.2 a	0.50
T4	67	68	0	567	217	6.0 b	6.2 ab	2.9 a	8.7 a	18.9 a	0.46
T5	52	136	0	567	217	6.3 ab	6.6 ab	2.8 a	8.9 a	18.5 a	0.48
T6	0	272	0	567	217	6.2 ab	6.3 ab	2.8 a	8.6 a	17.6 a	0.49
T7	83	0	55	542	217	6.6 ab	6.4 ab	2.8 a	9.0 a	18.4 a	0.49
T8	83	0	109	517	217	6.7 ab	6.8 ab	2.8 a	9.2 a	19.2 a	0.48
T9	83	0	218	468	217	6.9 a	7.0 a	2.8 a	9.4 a	19.0 a	0.50
T10	0	0	0	0	0	6.0 b	5.8 b	2.0 b	2.4 b	5.2 b	0.46

Note: Similar letters indicate no statistical difference at $p<0.05$

An additional indication of the very limited effectiveness of the fertilizer treatments under a heavy precipitation regime was provided by the flag leaf nutrient status at the onset of the reproductive phase. Leaf N varied from 1.9-2.29%, leaf P from 0.23-0.26%, leaf K from 1.94-2.11%, and leaf S was 0.01%. Neither consistency nor a significant difference were observed in the leaf N, P, K, or S concentrations, despite the large differences in polyhalite rates.

Corn grain protein content in Mexico usually varies from 9-14% (Zepeda-Bautistas *et al.*, 2009; Arellano-Vázquez *et al.*, 2017); in Experiment A the values obtained were very low, ranging from 8-10%. The relatively poor results may also be attributed to the late season and the frost damage in the autumn. Despite this, fertilizer type and dose did influence grain quality parameters in this case; grain N content, and consequently grain protein content, significantly increased with the increasing polyhalite application rate, peaking at a rate of about 180 kg polyhalite ha^{-1}, although saturation actually occurred at about 100 kg ha^{-1} (Fig. 4). No significant differences between treatments were found in grain K or S contents, two of the nutrients supplied by polyhalite. Moreover, ammonium sulfate, a fertilizer contributing N and S, exhibited a negative influence on grain N and protein contents (Fig. 4). These results suggest that polyhalite enhances plant nutrition status through complex mechanisms and interactions between various nutrients, all of which deserve further research.

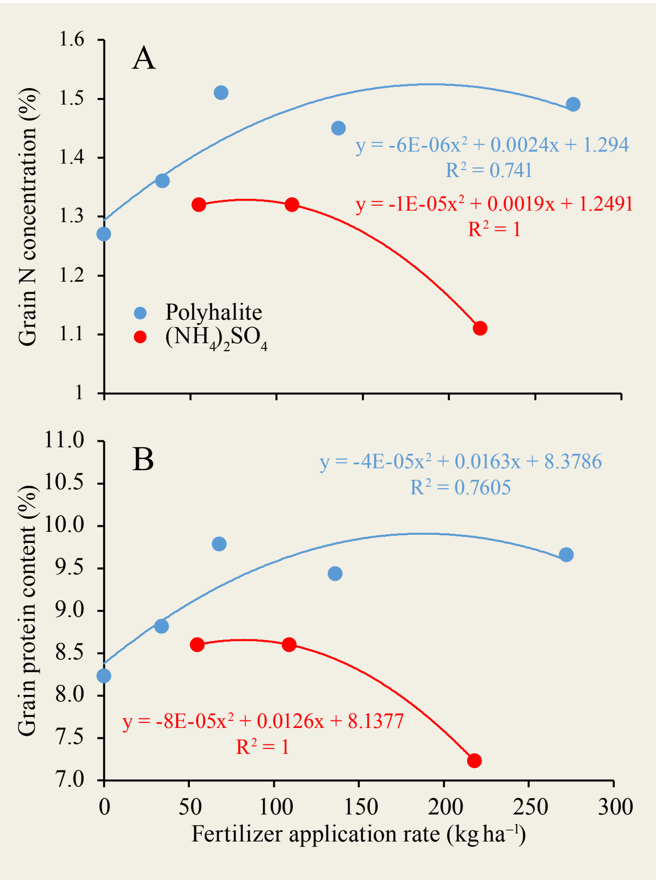

Fig. 4. Effects of fertilizer treatments on the grain N (A) and protein (B) contents in the 2018 corn crop season (Experiment A).

Beans 2019

Bean density fluctuated from 6.0-6.4 plants m^{-2}, with no significant differences among treatments ($p<0.05$) indicating a high degree of homogeneity in the crop density in all treatments, thus avoiding interferences in measuring effects on yield parameters.

Grain yield of beans ranged from 2.44-3.36 Mg ha^{-1}, considerably higher than the average yield in Guanajuato State under irrigation (2.22 Mg ha^{-1}). Polyhalite exhibited a much better residual impact on the bean yield, compared to ammonium sulfate (Fig. 5). Bean grain yield increased progressively in response to the previous year's rising polyhalite rates, while ammonium sulfate had null or negative influence under similar conditions. It should be noted that after the corn harvest in 2018, soil remained dry for approximately six months during winter and spring, thus the residual effect of the fertilizers was uninterrupted between the two crops. In contrast, the earlier corn cycle could not fully exploit the fertilizers applied. Nevertheless, in agreement with previous studies (Yermiyahu *et al.*, 2017; Yermiyahu *et al.*, 2019; Huang *et al.*, 2020) the capacity of polyhalite as a long-term soil fertilizer was clearly demonstrated.

Corn 2019

While the plant density of the corn cycle in 2019 (Experiment B) ranged from 8.2-9.0 plants m^{-2} and did not display significant differences between treatments, plant height (Fig. 6A) and the above ground plant biomass (Fig. 6B) showed clear positive responses to

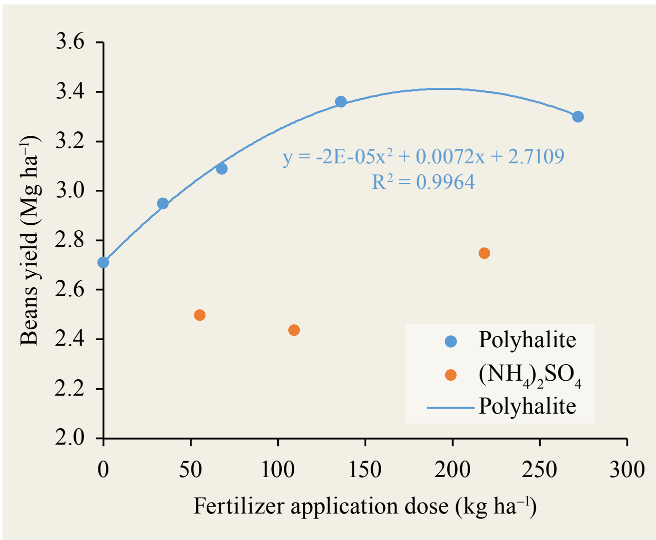

Fig. 5. Residual effect of the 2018 fertilizer application rate on bean yield in 2019.

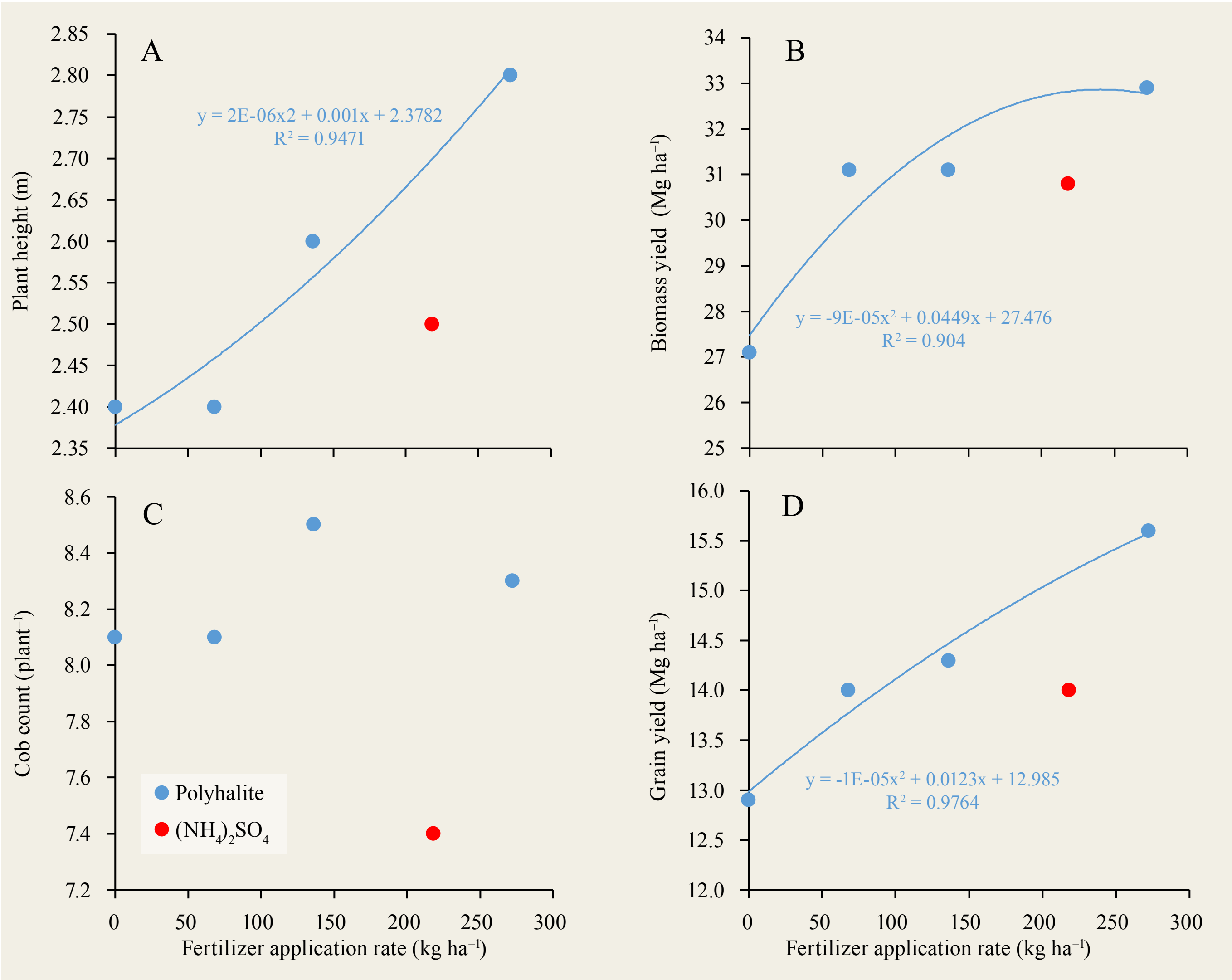

Fig. 6. Effects of fertilizer treatments on corn crop performance in 2019 (Experiment B)

the rising polyhalite application rates. It appears that plant height would increase further at polyhalite rates above 272 kg ha^{-1}, however plant biomass was probably saturated at that rate.

Cob counts tended to increase in response to the rising polyhalite dose, however, partially as a function of plant density, the differences were insignificant (Fig. 6C). Nevertheless, the grain yield increased consistently from 12.9 to 15.6 Mg ha^{-1} in response to increasing the polyhalite dose from zero to 272 kg ha^{-1}. Thus, polyhalite supported an additional grain production of 12.3 kg kg^{-1} (Fig. 6D). Ammonium sulfate application at 218 kg ha^{-1}, with a similar N and S contribution to the polyhalite treatment at 272 kg ha^{-1} (Table 5), failed to compete, obtaining much lower values for every crop performance parameter tested in Experiment B (Fig. 6). These results emphasize the possible significance of Ca and Mg, together or alone, that were provided by polyhalite beyond the standard, evenly supplied N, P, and K.

Magnesium is an essential nutrient for all crop species, including corn (Gransee and Führs, 2013; Ceylan *et al.*, 2016; Wang *et al.*, 2020). Various attempts have been made to overcome Mg deficiency in corn, including soil amendment using the Mg-rich mineral dunite (Crusciol *et al.*, 2019), foliar applications (Adnan *et al.*, 2020), or straw recycling (Zhang *et al.*, 2020). The importance of Ca to plant growth and function cannot be overestimated. Calcium is responsible for proper plant cell division and for strengthening cell walls, as well as functioning as an intra-cellular secondary messenger in numerous control and signaling mechanisms (Thor, 2019). Furthermore, Ca regulates phosphorylation systems that directly control uptake and balance of plant nutrients (Saito and Uozumi, 2020). Several recent papers recognize that balanced crop nutrition is equally important as sufficient supply of single limiting nutrients, particularly on poor soils (Njoroje *et al.*, 2018; Aliyu *et al.*, 2021). Polyhalite's contribution to the performance of the 2019 corn crop can be attributed to the more balanced plant nutrition delivered by the multi-nutrient nature of this fertilizer.

Conclusions

In spite of the significant restrictive weather conditions during the late corn crop cycle in 2018, polyhalite showed a remarkable positive influence on the root system development. Although crop biomass and grain yield were low and unaffected by the fertilizer treatments, N and protein contents significantly increased under the rising polyhalite application rates. The 2019 bean crop, grown on the footprint of the former corn crop, displayed the impressive residual impact of polyhalite application, with grain yields exceeding 3 Mg ha^{-1}, 20% higher than the control and substantially higher than the average bean yield in the region. The 2019 spring-autumn corn cycle exhibited significant responses to an elevated polyhalite dose in all crop performance parameters tested, reaching a grain yield of 15.6 Mg ha^{-1}, at the top level of corn yields in the region. These results demonstrate the significant potential of polyhalite to serve as a first choice multi-nutrient fertilizer, not only providing additional essential macronutrients, but also increasing the crops' nutrient use efficiency and hence promoting more balanced crop nutrition.

Photo 2. Maize growing in Guanajuato, Mexico. Photo by the authors.

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The paper "Polyhalite Effects on Corn and Bean Performance in Guanajuato, Mexico" also appears on the IPI website.

IPI Events

International Virtual Conference: Efficient Potassium Utilization for Food and Nutritional Security

13 December 2021

The international virtual conference on “Efficient Potassium Utilization for Food and Nutritional Security” was organized by the International Potash Institute and the Annamalai University Faculty of Agriculture, Department of Soil Science and Agricultural Chemistry. It examined key aspects of efficient potassium utilization to improve nutritional security. The event featured four presentations from the International Potash Institute (IPI), Potash Research Institute of India (PRII), and ICL India, introduced by members of the faculty of the Annamalai University.

Presentations

Polyhalite: The New Organic Multinutrient Fertilizer
Dr. P. Imas, IPI Scientific and Communications Coordinator

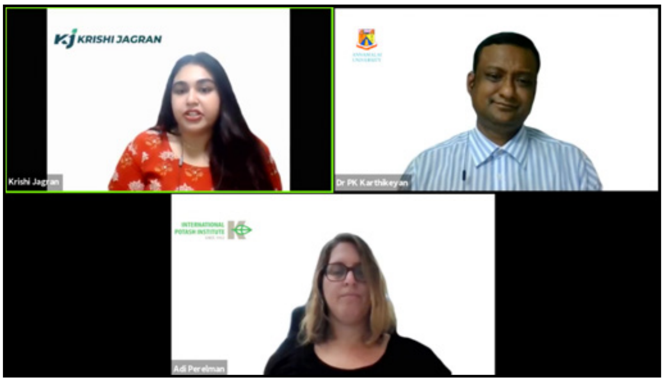
Potassium in Improving Nutrient Use Efficiency
Dr. A. Perelman, IPI Coordinator for India

Climate Change and the Role of Potassium in Mitigating Abiotic Stresses
Dr. S.K. Bansal, Director, Potash Research Institute of India

Insights into Research by the Fertilizer Industry and Research Organizations - the Way Forward
Dr. S. Naithani, Chief Agronomist, ICL India

The event also saw the launch of the latest brochure from the IPI, “Fertilizing Turmeric with Polyhalite for High Yield and Quality”.

Watch the conference at https://youtu.be/UWb50lrxnE0



Enhancing Yield and Quality of Turmeric Crop with Polyhalite Fertilizer

8 July 2021

Turmeric, *Curcuma longa*, part of the ginger family, is used as a dye, spice, medicine, and for cosmetics. India is the world’s leading producer and exporter of turmeric.

Turmeric has a high potassium demand and the yield generally depends on the variety selected, the soil, and prevailing weather conditions during the crop growth.

In this IPI event, Dr. A. Perelman, IPI Coordinator for India, and Dr. P.K. Karthikeyan from Annamalai University, review the findings of a recent IPI study carried out in collaboration with Annamalai University in Tamil Nadu to test the effects of potash and polyhalite on the yield of turmeric.

Watch at www.facebook.com/watch/live/?v=546841659694981.

Recent Advances in Cassava Crop Nutrition with Polyhalite for Kerala Soils

15 July 2021

This detailed discussion covered basic details about the cassava crop, its nutrient management, nutrient depletion under continuous cultivation of cassava, the nutrient status of soils of Kerala in cassava growing regions, and the suitability of polyhalite for Kerala soil.

Dr. S. John, Principal Scientist at ICAR – Central Tuber Crop Research Institute (CTCRI) joined Dr. A. Perelman, IPI Coordinator for India, to review the methodology and findings of the recent IPI/CTCRI research exploring the possible role of polyhalite fertilizer for cassava production.

Join Dr. John, and Dr. Perelman as they explain how potassium, magnesium, and calcium are all important for cassava, and how polyhalite fertilizer can improve the yield, and quality of cassava in Kerala: www.facebook.com/watch/live/?v=1989556901204605.

Polyhalite - a Multinutrient Carrier for Enhancing Growth, Yield and Quality of Vegetables in Low Base Status Soils

5 August 2021

Increasingly, potassium is becoming a limiting nutrient in Indian agriculture. In this online presentation, Dr. A. Perelman, IPI Coordinator for India, and Dr. P.P. Mahendran, Soil Scientist, Crop Management Agriculture College and Research Institute of Tamil Nadu summarize the importance of potassium for vegetable production. One possible source of potassium is the multinutrient mineral fertilizer, polyhalite.

Tamil Nadu Agriculture University recently conducted a study in collaboration with the International Potash Institute on the effects of polyhalite, a multinutrient fertilizer, for enhancing growth, yield and quality of vegetables in low base status soils.

Join Dr. Perelman, and Dr. Mahendran as they explain the trials which demonstrate how polyhalite fertilizer application supplies potassium and secondary nutrients and has a remarkable impact on the growth, yield attributes, yield, and quality of onion, tomato, and cluster beans.

Watch at www.facebook.com/watch/live/?v=140069488196911.

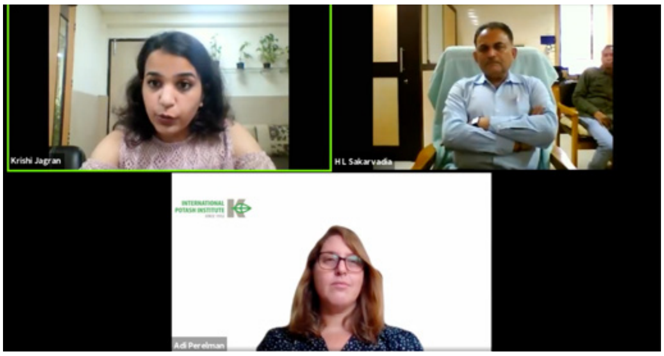
Management of Potassium for Maximization of Yield and Quality of Bt. Cotton in Saurashtra Region (India)

14 September 2021

Cotton is one of the most important fibre crops in India, the second largest producer of cotton in the world. Up to 10.85 million hectares of India's farmland is used for the production of cotton.

Yet the maximum yield potential for cotton is low for various reasons, including monocropping practices, declining soil fertility, delayed sowing, and imbalanced nutrition.

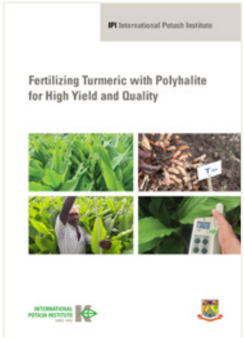
The role of potassium in cotton production was the theme of a recent live event conducted by the IPI. Watch Dr. H.L. Sakarvadia, Assistant Professor, Department of Agricultural Chemistry and Soil Science at the Junagadh Agricultural University, joined by Dr. A. Perelman, IPI Coordinator for India in this online event at facebook.com/krishijagran/videos/2256537431149573/.



Publications

Fertilizing Turmeric with Polyhalite for High Yield and Quality

By P.K. Karthikeyan, P. Imas, A. Perelman, and M.V. Sriramachandrasekharan. 2021. 6p.



Turmeric is a flowering plant, *Curcuma longa* of the ginger family, Zingiberaceae, which is used in cooking and Ayurvedic medicine.

The bright turmeric powder is a unique and versatile natural plant product combining the properties of a spice or flavourant, a colourant of brilliant yellow dye, a cosmetic, and a drug. Indian turmeric is considered the best in the world.

Turmeric has specific climate, soil and fertilizer requirements, which mean that cultivation is confined to Southeast Asian countries.

This IPI brochure examines the crop, the important quality attributes of turmeric, key varieties for the markets, the nutrient requirements, and required general growing conditions, before concluding with the recommended fertilizer treatments for optimum Turmeric production.

To download the publication go to the IPI website at https://www.ipipotash.org/publications/fertilizing-turmeric-with-polyhalite-for-high-yield-and-quality. For hardcopies, please contact ipi@ipipotash.org.

Publications by the PDA

Potassium and Nitrogen Interactions in Crops

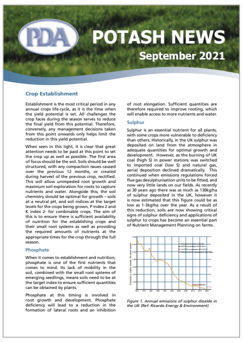
POTASH News, December 2021

Nitrogen has hit the headlines in the last few months, not just within agriculture, but across the mainstream media on the back of factory closures. Within agriculture the focus has clearly been on the steep price rises and the resulting impact on the economic optimum rates. These calculations are wholly justified, but as is often the case, are very singular focussed. Read more on the PDA website.

The Release of Nutrient Reserves in Soil
PDA Blog October 2021

Maintaining the fertility of agricultural soils is of paramount importance, not only for the present but also for the future. Soil analysis, and its interpretation, is an important management tool in assessing the need to apply nutrients to maintain soil fertility. Read more on the PDA website.

Crop Establishment
POTASH News, September 2021



Establishment is the most critical period in any annual crops life-cycle, as it is the time when the yield potential is set. All challenges the crop faces during the season serves to reduce the final yield from this potential. Therefore, conversely, any management decisions taken from this point onwards only helps limit the reduction in this yield potential. Read more on the PDA website.

Farming Rules for Water
PDA Blog September 2021

More than three years after their introduction, the Farming Rules for Water hit the spotlight due to increasing concerns surrounding the interpretation of the rules by the Environment Agency. Although manures are a good source of nutrients for crops, there is increasing scrutiny on their usage as farmers are encouraged to fully account for the nutrients they supply and closer match the timing of application to the soil or crop need. Read more on the PDA website.

Potash for Oilseed Rape
PDA Blog August 2021

With oilseed rape prices reaching well over £500/t before bonuses, the market appears to be telling growers to plant more of the crop. But with OSR's very high demand for potash, especially in the spring, serious consideration should be given to the major inputs for this crop. Read more on the PDA website.

Potash Development Association (PDA) is an independent organisation formed in 1984 to provide technical information and advice in the UK on soil fertility, plant nutrition and fertilizer use with particular emphasis on potash. See also www.pda.org.uk.

IPI Funded Research

Polyhalite Positively Influences the Growth, Yield and Quality of Sugarcane (*Saccharum officinarum* L.) in Potassium and Calcium-Deficient Soils in the Semi-Arid Tropics

Bhatt, R., P. Singh, O.M. Ali, A.A.H. Abdel Latef, A.M. Laing, and A. Hossain. 2021. Sustainability 13:10689. DOI: 10.3390/su131910689.

Abstract: In semi-arid tropics, sugarcane yield and quality are affected by deficiencies in soil nutrients, including potassium and calcium. We examined the effects of two different potassium fertilizers, a traditional muriate of potash (MOP) and polyhalite (which contains potassium and calcium), on sugarcane growth, yield, and quality. Experimental treatments compared a control 0 kg K ha^{-1} (T1) to potassium applied as MOP only at 80 kg K ha^{-1} (T2) and at 120 kg K ha^{-1} (T3), and potassium applied as an equal split of MOP and polyhalite at 80 kg K ha^{-1} (T4) and at 120 kg K ha^{-1} (T5). Relative to the control the potassium-enhanced treatments had improved rates of key growth parameters, and of cane yields, which were 4.4, 6.2, 8.2, and 9.9% higher in T2, T3, T4,, and T5, respectively, than in T1. Regardless of fertilizer used, potassium applied at 80 kg K ha^{-1} achieved the highest sugar purity and commercial cane sugar content. All potassium fertilizer treatments had reduced (although non-significant) incidences of three key sugarcane insect pests. The economic benefits of polyhalite were reduced due to its higher cost relative to MOP. Combining MOP and polyhalite equally to achieve an application rate of 80 kg K ha^{-1} is recommended to enhance sugarcane growth and yield.

Scientific Abstracts
K in the Literature

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Seasonal Nutrient Partitioning and Uptake in Hybrid Carrot Seed Production

Moore, A.D., J.F. Spring, E.A. Jeliazkova, and T.L. Wilson. 2021. Agronomy Journal 113:1934-1944. DOI: 10.1002/agj2.20503.

Abstract: Central Oregon is an important production region for hybrid carrot (*Daucus carota* L.) seed. Hybrid carrots are favored by the fresh vegetable market, but often produce lower and less consistent seed yields than traditional open-pollinated varieties. Understanding how hybrid carrots use nutrients to support seed production for hybrid varieties can help growers manage soil fertility

for optimal seed yield. The objective of this research was to evaluate seasonal nutrient partitioning and uptake in a modern Nantes-type hybrid carrot grown for seed. Plants from four randomized replicated plots in two commercial fields were destructively sampled throughout the growing season, separated into roots, tops, and umbels; seed samples were collected at harvest. Plant samples were weighed and dried for biomass content and analyzed for N, P, K, S, Ca, Mg, Na, Zn, Fe, Mn, Cu, and B concentration. Mean whole plant nutrient uptake at crop maturity for N, P_2O_5, K_2O, S, Ca, Mg, and Na was 137, 35, 229, 16, 105, 38, and 25 kg ha^{-1}, respectively; Zn, Fe, Mn, Cu, and B uptake was 156, 1,984, 414, 35, and 305 g ha^{-1}, respectively. Our findings highlighted the critical need for Cu in initial crop establishment, for N, K, Zn, and Fe in crown development, and for P and Zn in seed development, based on nutrient uptake proportion relative to the other nutrients taken up during that period. This information is available as a resource to agronomists, crop advisors, and growers who are interested in optimizing nutrient management practices for hybrid carrot seed production.

Estimating Nitrogen, Phosphorus, Potassium, and Sulfur Uptake and Requirement in Soybean

Salvagiotti, F., L. Magnano, O. Ortez, J. Enrico, M. Barraco, P. Barbagelata, A. Condori, G.D. Mauro, A. Manlla, J. Rotundo, F.O. Garcia, M. Ferrari, V. Gudelj, and I. Ciampitti. 2021. European Journal of Agronomy 127:126289. DOI: 10.1016/j.eja.2021.126289.

Abstract: Estimation of crop nutrient demand, seed nutrient removal, and nutrient use efficiency (yield to nutrient uptake ratio) are crucial for pursuing both balanced nutrition and more sustainable farming systems. However, the estimation of the nutrient requirements as the nutrient uptake per unit of seed yields is impaired in many situations due to the narrow variation of the dataset used to obtain these values or by the overgeneralization of considering a constant value for the nutrient demand at varying yield levels. Past studies focused on other crops and using linear models for estimation of the nutrient requirements, but not yet for soybeans (*Glycine max* L.). The aims of this research study were to: (i) quantify nitrogen (N), phosphorus (P), potassium (K), and sulfur (S) requirements in soybean and (ii) compare linear and non-linear (spherical) models in their relationship between plant and seed nutrient content all relative to seed yield at varying probabilities utilizing quantile regression. A large dataset from different studies conducted between 2009-2018 period, including data of seed yield, total biomass at physiological maturity, and N, P, K, and S uptake. Soybean seed yield ranged from 955 to 6,525 kg ha^{-1}, aboveground biomass from 1,990 to 15,814 kg ha^{-1}, and harvest index from 0.16 to 0.57. On average, nutrient uptake was 261 kg N ha^{-1}, 25 kg P ha^{-1}, 133 kg K ha^{-1}, and 16 kg S ha^{-1} (N:P:K:S ratio = 17:1.6:8.5:1), while nutrient content in seeds averaged 191 kg N ha^{-1}, 17 kg P ha^{-1}, 54 kg K ha^{-1}, and 9 kg S ha^{-1} (N:P:K:S ratio = 21:1.8:5.8:1). The spherical model described better than the linear model the relationship between plant nutrient uptake or nutrient content in seeds with seed yield in soybean, and thus, nutrient requirements per unit of yield decreased as seed yield increased. A relationship between nutrient internal efficiency and seed yield for the different percentiles as determined by the non-linear quantile regression offered probabilistic values for estimating nutrient uptake in soybean, providing useful information for obtaining more reliable estimates of nutrient balances at the system-level.

The Molecular–Physiological Functions of Mineral Macronutrients and their Consequences for Deficiency Symptoms in Plants

de Bang, T.C., S. Husted, K.H. Laursen, D.P. Persson, and J.K. Schjoerring. 2021. New Phytol 229:2446-2469. DOI: 10.1111/nph.17074.

Abstract: The visual deficiency symptoms developing on plants constitute the ultimate manifestation of suboptimal nutrient supply. In classical plant nutrition, these symptoms have been extensively used as a tool to characterise the nutritional status of plants and to optimise fertilisation. Here we expand this concept by bridging the typical deficiency symptoms for each of the six essential macronutrients to their molecular and physiological functionalities in higher plants. We focus on the most recent insights obtained during the last decade, which now allow us to better understand the links between symptom and function for each element. A deep understanding of the mechanisms underlying the visual deficiency symptoms enables us to thoroughly understand how plants react to nutrient limitations and how these disturbances may affect the productivity and biodiversity of terrestrial ecosystems. A proper interpretation of visual deficiency symptoms will support the potential for sustainable crop intensification through the development of new technologies that facilitate automatised management practices based on imaging technologies, remote sensing and in-field sensors, thereby providing the basis for timely application of nutrients via smart and more efficient fertilisation.

Groundwater Depths Affect Phosphorus and Potassium Resorption but not their Utilization in a Desert Phreatophyte in its Hyper-Arid Environment

Zhang B., G. Tang, H. Yin, S. Zhao, M. Shareef, B. Liu, X. Gao, and F. Zeng. 2021. Front. Plant Sci. 12:665168. DOI: 10.3389/fpls.2021.665168.

Abstract: Nutrients are vital for plant subsistence and growth in nutrient-poor and arid ecosystems. The deep roots of phreatophytic plants are necessary to access groundwater, which is the major source of nutrients for phreatophytes in an arid desert ecosystem. However, the mechanisms through which changes in groundwater depth affect nutrient cycles of phreatophytic plants are still poorly understood. This study was performed to reveal the adaptive strategies involving the nutrient use efficiency (NUE) and nutrient resorption efficiency

(NRE) of desert phreatophytes as affected by different groundwater depths. This work investigated the nitrogen (N), phosphorus (P), and potassium (K) concentrations in leaf, stem, and assimilating branch, as well as the NUE and NRE of the phreatophytic *Alhagi sparsifolia*. The plant was grown at groundwater depths of 2.5, 4.5, and 11.0 m during 2015 and 2016 in a desert-oasis transition ecotone at the southern rim of the Taklimakan Desert in northwestern China. Results show that the leaf, stem, and assimilating branch P concentrations of *A. sparsifolia* at 4.5 m groundwater depth were significantly lower than those at 2.5 and 11.0 m groundwater depths. The K concentrations in different tissues of *A. sparsifolia* at 4.5 m groundwater depth were significantly higher than those at 2.5 and 11.0 m groundwater depths. Conversely, the NRE of P in *A. sparsifolia* was the highest among the three groundwater depths, while that of K in *A. sparsifolia* was the lowest among the three groundwater depths in 2015 and 2016. The N concentration and NUE of N, P, and K in *A. sparsifolia*, however, were not influenced by groundwater depth. Further analyses using structural equation models showed that groundwater depth had significant effects on the P and K resorption of *A. sparsifolia* by changing soil P and senescent leaf K concentrations. Overall, our results suggest groundwater depths affect P and K concentrations and resorption but not their utilization in a desert phreatophyte in its hyper-arid environment. This study provides a new insight into the phreatophytic plant nutrient cycle strategy under a changing external environment in a hyper-arid ecosystem.

Partial Substitution of K by Na Alleviates Drought Stress and Increases Water Use Efficiency in *Eucalyptus* Species Seedlings

Mateus, N.S., A.L. Florentino, E.F. Santos, A.V. Ferraz, J.L.M. Goncalves, and J. Lavres. 2021. Front. Plant Sci. 12:632342. DOI: 10.3389/fpls.2021.632342.

Abstract: *Eucalyptus*, the most widely planted tree genus worldwide, is frequently cultivated in soils with low water and nutrient availability. Sodium (Na) can substitute some physiological functions of potassium (K), directly influencing plants' water status. However, the extent to which K can be replaced by Na in drought conditions remains poorly understood. A greenhouse experiment was conducted with three *Eucalyptus* genotypes under two water conditions (well-watered and water-stressed) and five combination rates of K and Na, representing substitutions of 0/100, 25/75, 50/50, 75/25, and 100/0 (percentage of Na/percentage of K), to investigate growth and photosynthesis-related parameters. This study focused on the positive effects of Na supply since, depending on the levels applied, the Na supply may induce plants to salinity stress (>100 mM of NaCl). Plants supplied with low to intermediate K replacement by Na reduced the critical level of K without showing symptoms of K deficiency and provided higher total dry matter (TDM) than those *Eucalyptus* seedlings supplied only with K in both water conditions. Those plants supplied with low to intermediate K replacement by Na had improved CO_2 assimilation (A), stomatal density (Std), K use efficiency (UE_K), and water use efficiency (WUE), in addition to reduced leaf water potential (Ψw) and maintenance of leaf turgidity, with the stomata partially closed, indicated by the higher values of leaf carbon isotope composition ($\delta^{13}C‰$). Meanwhile, combination rates higher than 50% of K replacement by Na led to K-deficient plants, characterized by the lower values of TDM, $\delta^{13}C‰$, WUE, and leaf K concentration and higher leaf Na concentration. There was positive evidence of partial replacement of K by Na in *Eucalyptus* seedlings; meanwhile, the ideal percentage of substitution increased according to the drought tolerance of the species (*Eucalyptus saligna* < *Eucalyptus urophylla* < *Eucalyptus camaldulensis*).

Response of Root Growth and Development to Nitrogen and Potassium Deficiency as well as microRNA-Mediated Mechanism in Peanut (*Arachis hypogaea* L.)

Li L., Q. Li, K.E. Davis, C. Patterson, S. Oo, W. Liu, J. Liu, G. Wang, J.E. Fontana, T.E. Thornburg, I.S. Pratt, F. Li, Z. Zhang, Y. Zhou, X. Pan, and B. Zhang. 2021. Front. Plant Sci. 12:695234. DOI: 10.3389/fpls.2021.695234.

Abstract: The mechanism of miRNA-mediated root growth and development in response to nutrient deficiency in peanut (*Arachis hypogaea* L.) is still unclear. In the present study, we found that both nitrogen (N) and potassium (K) deficiency resulted in a significant reduction in plant growth, as indicated by the significantly decreased dry weight of both shoot and root tissues under N or K deficiency. Both N and K deficiency significantly reduced the root length, root surface area, root volume, root vitality, and weakened root respiration, as indicated by the reduced O_2 consuming rate. N deficiency significantly decreased primary root length and lateral root number, which might be associated with the upregulation of miR160, miR167, miR393, and miR396, and the downregulation of AFB3 and GRF. The primary and lateral root responses to K deficiency were opposite to that of the N deficiency condition. The upregulated miR156, miR390, NAC4, ARF2, and AFB3, and the downregulated miR160, miR164, miR393, and SPL10 may have contributed to the growth of primary roots and lateral roots under K deficiency. Overall, roots responded differently to the N or K deficiency stresses in peanuts, potentially due to the miRNA-mediated pathway and mechanism.

Potential Networks of Nitrogen-Phosphorus-Potassium Channels and Transporters in Arabidopsis Roots at a Single Cell Resolution

Lhamo D., and S. Luan. 2021. Front. Plant Sci. 12:689545. DOI: 10.3389/fpls.2021.689545.

Abstract: Nitrogen (N), phosphorus (P), and potassium (K) are three major macronutrients essential for plant life. These nutrients are acquired and transported by several large families of transporters expressed in plant roots. However, it remains largely unknown how these transporters are distributed in different cell-types that work

together to transfer the nutrients from the soil to different layers of root cells and eventually reach vasculature for massive flow. Using the single cell transcriptomics data from Arabidopsis roots, we profiled the transcriptional patterns of putative nutrient transporters in different root cell-types. Such analyses identified a number of uncharacterized NPK transporters expressed in the root epidermis to mediate NPK uptake and distribution to the adjacent cells. Some transport genes showed cortex- and endodermis-specific expression to direct the nutrient flow toward the vasculature. For long-distance transport, a variety of transporters were shown to express and potentially function in the xylem and phloem. In the context of subcellular distribution of mineral nutrients, the NPK transporters at subcellular compartments were often found to show ubiquitous expression patterns, which suggests function in house-keeping processes. Overall, these single cell transcriptomic analyses provide working models of nutrient transport from the epidermis across the cortex to the vasculature, which can be further tested experimentally in the future.

The Associated with Carbon Conversion Rate and Source–Sink Enzyme Activity in Tomato Fruit Subjected to Water Stress and Potassium Application

Luo A., C. Zhou, and J. Chen. 2021. Front. Plant Sci. 12:681145. DOI: 10.3389/fpls.2021.681145.

Carbon metabolism in higher plants is a basic physiological metabolism, and carbon allocation and conversion require the activity of various enzymes in metabolic processes that alter the content and overall composition of sugars in the sink organ. However, it is not known how various enzymes affect carbon metabolism when tomato plants are subjected to water stress or treated with potassium. Although the process of carbon metabolism is very complex, we used the carbon conversion rate to compare and analyze the enzyme activities related to sugar metabolism and find out which carbon conversion rate are the most important. Results showed that water stress and potassium increased carbon import flux in the fruit, which was beneficial to carbon accumulation. Water deficit increased the activity of sucrose synthase (SuSy) and starch phosphorylase (SP) and decreased the activity of sucrose phosphate synthase (SPS) and adenosine diphosphate glucose pyrophosphorylase (AGPase) in the source. Water stress increased the activity of acid invertase (AI), SuSy and SP but decreased the activity of AGPase in the sink. Potassium modified the balance of enzymes active in sugar and starch metabolism by increasing the activity of AI, SuSy, SPS and SP and significantly decreasing the activity of AGPase, resulting in increase of hexose. Canonical correlational analysis revealed that the carbon conversion rate was mainly affected by the relative rate of conversion of sucrose to fructose and glucose [$p_1(t)$] and glucose to starch [$p_{5m}(t)$]. SuSy and AGPase had the greatest effect on enzyme activity in the fruit; respectively regulated $p_1(t)$ and $p_{5m}(t)$.

Relationships Between Leaf Carbon and Macronutrients Across Woody Species and Forest Ecosystems Highlight How Carbon is Allocated to Leaf Structural Function

Xing K., M. Zhao, Ü. Niinemets, S. Niu, J. Tian, Y. Jiang, H.Y.H. Chen, P.J. White, D. Guo, and Z. Ma. 2021. Front. Plant Sci. 12:674932. DOI: 10.3389/fpls.2021.674932.

Abstract: Stoichiometry of leaf macronutrients can provide insight into the tradeoffs between leaf structural and metabolic investments. Structural carbon (C) in cell walls is contained in lignin and polysaccharides (cellulose, hemicellulose, and pectins). Much of leaf calcium (Ca) and a fraction of magnesium (Mg) were further bounded with cell wall pectins. The macronutrients phosphorus (P), potassium (K), and nitrogen (N) are primarily involved in cell metabolic functions. There is limited information on the functional interrelations among leaf C and macronutrients, and the functional dimensions characterizing the leaf structural and metabolic tradeoffs are not widely appreciated. We investigated the relationships between leaf C and macronutrient (N, P, K, Ca, Mg) concentrations in two widespread broad-leaved deciduous woody species *Quercus wutaishanica* (90 individuals) and *Betula platyphylla* (47 individuals), and further tested the generality of the observed relationships in 222 woody eudicots from 15 forest ecosystems. In a subsample of 20 broad-leaved species, we also analyzed the relationships among C, Ca, lignin, and pectin concentrations in leaf cell walls. We found a significant leaf C–Ca tradeoff operating within and across species and across ecosystems. This basic relationship was explained by variations in the share of cell wall lignin and pectin investments at the cell scale. The C–Ca tradeoffs were mainly driven by soil pH and mean annual temperature and precipitation, suggesting that leaves were more economically built with less C and more Ca as soil pH increased and at lower temperature and lower precipitation. However, we did not detect consistent patterns among C–N, and C–Mg at different levels of biological organization, suggesting substantial plasticity in N and Mg distribution among cell organelles and cell protoplast and cell wall. We observed two major axes of macronutrient differentiation: the cell-wall structural axis consisting of protein-free C and Ca and the protoplasm metabolic axis consisting of P and K, underscoring the decoupling of structural and metabolic elements inherently linked with cell wall from protoplasm investment strategies. We conclude that the tradeoffs between leaf C and Ca highlight how carbon is allocated to leaf structural function and suggest that this might indicate biogeochemical niche differentiation of species.

Nutrient Removal by Grain in Modern Soybean Varieties

Esper Neto, M., L.M. Lara, S. Maciel de Oliveira, R.Fd. Santos, A.L. Braccini, T.T. Inoue, and M.A. Batista. 2021. Front. Plant Sci. 12:615019. DOI: 10.3389/fpls.2021.615019.

Abstract: Knowing the nutrient removal by soybean grain harvest in different varieties, locations, and over time is essential to correctly

adjust agronomic recommendations, update farmers' practices, and increase nutrient use efficiency. A field-based research trial was carried out to assess macronutrients [nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), and sulfur (S)] removed in grain by modern soybean varieties from southern Brazil introduced between 2007 and 2016. We examined changes between our set of modern varieties and a dataset of historical values encompassing a wide range of varieties introduced before 2007. Moreover, we undertook a synthesis analysis using scientific literature published after 2007 to investigate nutrient removal by grain among modern Brazilian soybeans and a dataset that included field trials from Argentina, United States, and India. There were no yield gains across the years for modern soybean varieties introduced among 2007 and 2016 in Brazil, although the grain N and Mg concentrations decreased. Modern Brazilian soybeans increased nutrient removal compared with that by soybeans historically planted in Brazil, with 11.1, 26.9, 45.0, and 31.6% more N, P, K, and Mg removed, respectively. Our results indicated that soybean growing in Brazil removed 4.3% less N relative to the values reported in the literature dataset, whereas K removal was 21.4% greater. A significant difference was also recorded for high-yield soybean varieties, and Brazilian varieties removed 11.8% less N and 8.6% more K than varieties in the literature dataset. No differences were found among locations for P removal, averaging 4.9 kg Mg^{-1} grain. In conclusion, this study indicates that the amounts of nutrients removed by modern soybean varieties were greater relative to the historical values recorded in Brazil, excluding Ca and S. Nonetheless, in the middle to long term (10 years), a significant impact of plant breeding on grain nutrient concentration was recorded only for N and Mg. The difference in nutrient removal patterns between Brazil and other countries indicates an integrated effect of management, genotype, and environment on nutrient removal. These findings provide guidance for optimal nutrient management and specific information for plant breeding programs to understand nutrient variability.

Nutrient Use Efficiency Indices of N, P, and K Under Rice-Wheat Cropping System in LTFE after 34th Crop Cycle

Bipin Bihari, Yanendra Kumar Singh, Shweta Shambhavi, Jajati Mandal, Sanjay Kumar, and Rakesh Kumar. 2021. Journal of Plant Nutrition 45(1):123-140. DOI: 10.1080/01904167.2021.1943674.

Abstract: Nutrient efficiency concept is used to increase the overall performance of cropping system by providing economically optimum nutrition to the crop and at same time minimizing nutrient losses from the crop yield. The study was undertaken on the AICRP-IFS experiment located at BAU, Sabour having twelve treatments replicated four times in randomized block design. The data were taken after 34th cropping cycle. In this study, a modest initiative has been undertaken to assess the various nutrient use efficiencies for N, P, and K in rice-wheat under different integrated nutrient management (INM) treatments involving substitution of N by farm yard manure, wheat straw, and green manure along with levels of recommended doses of fertilizers and farmers' practice. The results revealed that the overall AE, PE, APE, PFP, IUE, ARE, and partial nutrient balance (PNB) of N, P, and K for wheat crop was comparatively lower than that of rice crop which reflects that the residual effect of applied organic manures and fertilizers was more than the direct effect. PNB of crops for both the crops was near to 1 in INM plots which indicates that the yields and fertility status of soil is being sustained with respect N and P. However, K mining is being indicated through higher values of PNB for K. Overall, the results indicated that the integrated use of organic manures and inorganic fertilizers for last 34 years likely improved soil fertility, increased sustainable crop yield and uptake thereby led to increased nutrient use efficiency of applied nutrients and crops.

Imbalance Between Nitrogen and Potassium Fertilization Influences Potassium Deficiency Symptoms in Winter Oilseed Rape (*Brassica napus* L.) Leaves

Jing Li, Wenshi Hu, Zhifeng Lu, Fanjin Meng, Rihuan Cong, Xiaokun Li, Tao Ren, and Jianwei Lu. 2021. The Crop Journal ISSN 2214-5141. DOI: 10.1016/j.cj.2021.06.001.

Abstract: Chlorosis at leaf margins is a typical symptom of potassium (K) deficiency, but inappropriate application of K with other nutrients often masks symptoms of K deficiency. A two-year field experiment was conducted to measure the interactive effects of N and K on leaf photosynthesis and dry matter accumulation and the resulting growth dilution effect on K concentration and leaf K deficiency symptoms. N application aggravated the imbalance of N and K nutrients and further exacerbated K deficiency symptoms under K limitation. Synergistic effects of N and K promoted plant growth, amplified the growth dilution effect, and reduced the critical K concentration in leaves. Using 90% of the maximum shoot biomass as a threshold, the critical K concentration was 0.72% at the recommended N (N_{180}) fertilization level. The critical K concentration increased by 62.5% owing to the reduced biomass under insufficient N (N_{90}) supply. In contrast, high N (N_{270}) reduced the critical K concentration (0.64%), accelerating chlorophyll decomposition and exacerbating K deficiency symptoms. The basis of changing the critical K concentration by magnifying growth dilution effect was the functional synergistic effect of N and K on photosynthetic characteristics. Under insufficient N, the low maximum carboxylation rate (V_{cmax}) limited the net photosynthetic rate (A_n) and necessitated more K to maintain high CO_2 transmission capacity, to improve the total conductance g_{tot}/V_{cmax} ratio. High N supply increased g_{tot} and V_{cmax}, possibly mitigating the effect of K reduction on photosynthesis. In conclusion, it is unwise to judge K status of plants only by K concentration without accounting for crop mass (or dilution effect), critical K concentration and deficiency symptoms are affected by N fertilization, and the synergistic effect of N and K on leaf photosynthesis is the foundation of maximal growth of plants under diverse critical K concentrations.

Potassium and Zinc Co-Fertilization Provide New Insights to Improve Maize (*Zea mays* L.) Physiology and Productivity

Raza, H.M.A, M.A. Bashir, A. Rehim, M. Jan, Q.A. Raza, and G.P. Berlyn. 2021. Pakistan Journal of Botany 53(6). DOI: 10.30848/PJB2021-6(28).

Abstract: Potassium (K) and Zinc (Zn) are essential nutrients, and play key role in many physiological processes. The current study aims to identify their interactive impacts (i) in soil and plant body, (ii) on maize physiology and (iii) on production. A field experiment was conducted to assess the potassium co-fertilization with zinc sources and doses. The treatments were (kg ha^{-1}) as: K0 + Zn0, K0 + Zn16, K0 + Zn24, K60 + Zn0, K60 + Zn16, K60 + Zn24, K100 + Zn0, K100 + Zn16 and K100 + Zn24. Murate of potash (MOP) for K, Chelated Zinc (Zn-EDTA; S1) and Zinc Sulphate ($ZnSO_4$; S2) were the sources of Zn fertilization. Results revealed that co-fertilization have significantly improved maize productivity, and physiological traits. Plant height was significantly increased (27%), cob length (50%), 1000-grain weight (25%), dry weight (203%), membrane stability (191%), relative water content (170%), photosynthesis rate (237%), transpiration rate (353%), stomatal conductance (254%), internal CO_2 (105%) and chlorophyll contents (185%) with MOP + Zn-EDTA fertilization at K60 + Zn16 treatment as compared to control. Moreover, straw K and grain K contents were also improved with combined K and Zn fertilization, while straw and grain Zn was higher with sole Zn application. It is concluded that co-fertilization of MOP + Zn-EDTA at K60 +≈Zn16 (kg ha^{-1}) is beneficial for productivity, and physiological traits of maize in calcareous soils.

Potassium Control of Plant Functions: Ecological and Agricultural Implications

Sardans, J., and J. Peñuelas. 2021. Plants 10(2):419. DOI: 10.3390/plants10020419.

Abstract: Potassium, mostly as a cation (K^+), together with calcium (Ca^{2+}) are the most abundant inorganic chemicals in plant cellular media, but they are rarely discussed. K^+ is not a component of molecular or macromolecular plant structures, thus it is more difficult to link it to concrete metabolic pathways than nitrogen or phosphorus. Over the last two decades, many studies have reported on the role of K^+ in several physiological functions, including controlling cellular growth and wood formation, xylem–phloem water content and movement, nutrient and metabolite transport, and stress responses. In this paper, we present an overview of contemporary findings associating K^+ with various plant functions, emphasizing plant-mediated responses to environmental abiotic and biotic shifts and stresses by controlling transmembrane potentials and water, nutrient, and metabolite transport. These essential roles of K^+ account for its high concentrations in the most active plant organs, such as leaves, and are consistent with the increasing number of ecological and agricultural studies that report K^+ as a key element in the function and structure of terrestrial ecosystems, crop production, and global food security. We synthesized these roles from an integrated perspective, considering the metabolic and physiological functions of individual plants and their complex roles in terrestrial ecosystem functions and food security within the current context of ongoing global change. Thus, we provide a bridge between studies of K^+ at the plant and ecological levels to ultimately claim that K^+ should be considered at least at a level similar to N and P in terrestrial ecological studies.

Resveratrol Alleviates the KCl Salinity Stress of *Malus hupehensis* Rehd

Li T., Y. Li, Z. Sun, X. Xi, G. Sha, C. Ma, Y. Tian, C. Wang, and X. Zheng. 2021. Frontiers in Plant Science 12:729. DOI: 10.3389/fpls.2021.650485.

Abstract: Applying large amounts of potash fertilizer in apple orchards for high apple quality and yield aggravates KCl stress. As a phytoalexin, resveratrol (Res) participates in plant resistance to biotic stress. However, its role in relation to KCl stress has never been reported. Herein we investigated the role of Res in KCl stress response of *Malus hupehensis* Rehd., a widely used apple rootstock in China which is sensitive to KCl stress. KCl-stressed apple seedlings showed significant wilting phenotype and decline in photosynthetic rate, and the application of 100 μmol Res alleviated KCl stress and maintained photosynthetic capacity. Exogenous Res can strengthen the activities of peroxidase and catalase, thus eliminating reactive oxygen species production induced by KCl stress. Moreover, exogenous Res can decrease the electrolyte leakage by accumulating proline for osmotic balance under KCl stress. Furthermore, exogenous Res application can affect K^+/Na^+ homeostasis in cytoplasm by enhancing K^+ efflux outside the cells, inhibiting Na^+ efflux and K^+ absorption, and compartmentalizing K^+ into vacuoles through regulating the expression of K^+ and Na^+ transporter genes. These findings provide a theoretical basis for the application of exogenous Res to relieve the KCl stress of apples.

Yield and Quality of Ratoon Sugarcane are Improved by Applying Potassium under Irrigation to Potassium Deficient Soils

Bhatt, R., P. Singh, O.M. Ali, A.A.H. Abdel Latef, A.M. Laing, and A. Hossain. 2021. Agronomy 11:1381. DOI: 10.3390/agronomy11071381.

Abstract: The current study was carried out at the experimental farm of Rana Sugars Ltd., Buttar Seviyan, Amritsar, Punjab, India, to identify methods to improve the yield and quality of ratoon sugarcane in potassium-deficient soils. The treatments comprised two levels of irrigation, resulting in plants which either received sufficient water (I_1) or were water-stressed (I_2), and four rates of potassium (K) application: 0 (K_1), 40 (K_2), 80 (K_3) and 120 (K_4) kg K_2O ha^{-1}.

The results showed that the irrigation levels did not influence crop parameters significantly, although all parameters presented higher values for I_1-treated plots. Compared to the K_1 (i.e., 0 kg ha^{-1} K fertiliser applied) treatment, the K_2, K_3 and K_4 treatments yielded 11.16, 37.9 and 40.7%, respectively, higher millable canes and 1.25, 5.62 and 13.13% more nodes per plant, respectively. At 280 days after harvest of the first (plant) crop, the I_1 treatment provided ratoons which were up to 15.58% higher than those obtained with the I_2 treatment, with cane girths up to 7.69% wider and yields up to 7.29% higher than those observed with the I_2 treatment. While the number of nodes per plant did not differ significantly between treatments, there were significant differences in other parameters. Quality parameters (with the exception of extraction percentage) were significantly enhanced by the K_3 treatment. The benefit-to-cost ratio (B/C) was higher for the I_1 treatment than for the I_2, due to a reduced productivity associated with the I_2 treatment. At both irrigation levels, the K_3 treatment resulted in the highest quality parameters. K_1-, K_2- and K_4-treated plots presented more instances of insect infestations than plots receiving the K_3 treatment. Relative to the K_3 plots, infestation by the early shoot borer (*Chilo infuscatellus*) was 18.2, 6.0 and 12.2% higher, respectively, in plots that underwent the K_1, K_2 and K_4 treatments, while infestation by the top borer (*Scirpophaga excerptalis*) was 21.2, 9.21 and 14.0% higher, and that by the stalk borer (*Chilo auricilius*) was 10.7, 0 and 8.10% higher. Not all infestation differences between treatments were significant. Our research demonstrates that growing sugarcane in potassium-deficient soils with applications of 80 kg K_2O ha^{-1} under irrigation should be recommended to increase yield and quality while minimising insect infestation and to implement sustainable ratoon sugarcane production.

Exogenous Application of Different Silicon Sources and Potassium Reduces Pink Stem Borer Damage and Improves Photosynthesis, Yield and Related Parameters in Wheat

Jeer, M., Y. Yele, K.C. Sharma, and N.B. Prakash. 2021. Silicon 13:901–910. DOI: 10.1007/s12633-020-00481-7.

Abstract: Silicon (Si) and potassium are known to impart tolerance against numerous biotic stresses in crop plants. A study was conducted to determine the effect of diatomaceous earth (DE), a soil-applied Si source and soluble silicic acid, a foliar applied Si source at two levels of potassium for their efficacy against pink stem borer (PSB) incidence and damage in wheat under field conditions for two seasons. The effect of these Si sources and potassium levels on photosynthesis, yield, and related parameters were also studied. Soil application of DE @ 300 kg ha^{-1} significantly decreased the PSB incidence with the lowest percent white ear damage and recorded the highest grain yield of 3.31 t ha^{-1}. Both soil and foliar applied Si sources along with potassium @ 36 kg ha^{-1} significantly enhanced the net photosynthesis rate, stomatal conductance, water use efficiency, intercellular CO_2 concentration, spike length, spike weight, number of grains per spike, 1000 grains weight and significantly decreased the transpiration rate in contrast to untreated control (no Si application) and insecticidal check. Soil applied Si sources significantly enhanced plant-available Si content in soil solution and thereby Si content in stem tissues of wheat plants in contrast to foliar-applied Si sources. Maximum Benefit:Cost ratio (2.03) was recorded with soil application of DE @ 150 kg ha^{-1} which was more than recommended insecticidal check (1.74). Both Si sources proved significantly superior to insecticidal check in managing PSB in wheat under field conditions and improved photosynthesis, yield and related parameters, which can be integrated with other practices for sustainable, eco-friendly management of PSB in wheat.

Effect of the Application Date of Fertilizer Containing Silicon and Potassium on the Yield and Technological Quality of Sugar Beet Roots

Artyszak A, D. Gozdowski, and A. Siuda. 2021. Plants 10(2):370. DOI: 10.3390/plants10020370.

Abstract: Water shortage and drought are a growing problem in Europe. Therefore, effective methods for limiting its effects are necessary. At the same time, the “field to fork” strategy adopted by the European Commission aims to achieve a significant reduction in the use of plant protection products and fertilizers in the European Union. In an experiment conducted in 2018–2020, the effect of the method of foliar fertilization containing silicon and potassium on the yield and technological quality of sugar beet roots was assessed. The fertilizer was used in seven combinations, differing in the number and time of application. The best results were obtained by treating plants during drought stress. The better soil moisture for the plants, the smaller the pure sugar yield increase was observed. It is difficult to clearly state which combination of silicon and potassium foliar application is optimal, as their effects do not differ greatly.

The Ca^{2+}-CaM Signaling Pathway Mediates Potassium Uptake by Regulating Reactive Oxygen Species Homeostasis in Tobacco Roots Under Low-K^+ Stress

Yingfeng, W., X. Dai, G. Xu, Z. Dai, P. Chen, T. Zhang, and H. Zhang. 2021. Frontiers in Plant Science 12:859. DOI: 10.3389/fpls.2021.658609.

Potassium (K^+) deficiency severely threatens crop growth and productivity. Calcium (Ca^{2+}) signaling and its sensors play a central role in the response to low-K^+ stress. Calmodulin (CaM) is an important Ca^{2+} sensor. However, the mechanism by which Ca^{2+} signaling and CaM mediate the response of roots to low-K^+ stress remains unclear. In this study, we found that the K^+ concentration significantly decreased in both shoots and roots treated with Ca^{2+} channel blockers, a Ca^{2+} chelator, and CaM antagonists. Under low-K^+ stress, reactive oxygen species (ROS) accumulated, and the activity of antioxidant enzymes, NAD kinase (NADK), and NADP phosphatase (NADPase) decreased. This indicates that antioxidant enzymes, NADK, and NADPase might be downstream target proteins in the Ca^{2+}-CaM signaling pathway, which facilitates K^+ uptake in plant roots by mediating ROS homeostasis under low-K^+ stress. Moreover, the expression of *NtCNGC3*, *NtCNGC10*, K^+ channel genes, and transporter genes was significantly downregulated in blocker-treated, chelator-treated, and antagonist-treated plant roots in the low K^+ treatment, suggesting that the Ca^{2+}-CaM signaling pathway may mediate K^+ uptake by regulating the expression of these genes. Overall, this study shows that the Ca^{2+}-CaM signaling pathway promotes K^+ absorption by regulating ROS homeostasis and the expression of K^+ uptake-related genes in plant roots under low-K^+ stress.

Variation in Soil-Test-Based Phosphorus and Potassium Rate Recommendations across the Southern USA

Zhang, H., J. Antonangelo, J. Grove, D. Osmond, N.A. Slaton, S. Alford, R. Florence, G. Huluka, D.H. Hardy, J. Lessl, R. Maguire, R. Mylavarapu, J.L. Oldham, E.M. Pena-Yewtukhiw, T. Provin, L. Sonon, D. Sotomayor, J. Wang. 2021. Soil Sci Soc Am J. 85:975–988. DOI: 10.1002/saj2.20280.

Abstract: Thirteen states associated with the Southern Extension and Research Activities Information Exchange Group-6 (SERA-IEG-6) agreed to share their soil test based P and K rate recommendations for nine major crops. The objectives were to compare fertilizer P and K rate recommendations, to look for opportunities to rationalize similar recommendations across state lines, and to examine challenges to the development of a cooperative regional approach to P and K recommendations. Mehlich-3 (eight states), Mehlich-1 (five states), or Lancaster (one state) extractions were the basis of plant available soil P (STP) and K (STK) assessment. Fertilizer recommendation philosophies (sufficiency, build and maintain, and/or hybrid) variation among the states might be the main reason behind such discrepancies. Although a few similarities in P and K rate recommendations were found, the different philosophies, numerical presentations, and extraction procedures drove important recommendation differences. Widespread adoption of the Mehlich-3 extraction procedure has not reduced variation in fertilizer P and K rate recommendations among the states. Instead, for states using Mehlich 3, soil test critical concentrations ranged from 30 to 75 mg P kg^{-1} and 60 to 175 mg K kg^{-1} for corn (*Zea mays* L.) grain and warm-season grass hay production. The adoption of uniform soil testing terminology, sample collection guidelines, extraction methods, and interpretations across common physiographic regions, soils, and state lines remains a challenge. Differences arise because of the different soil orders and properties, climate conditions, and resulting crop responses to added P and K fertilizers. Such differences in soil-test-based fertilizer P and K recommendations are state specific and highlight needs to examine the soil testing and recommendation process, make soil test results end-user friendly, and, when appropriate, standardize fundamental information used in the soil testing guidelines.

Effects of Reduced Nitrogen Application Rate on Drip-Irrigated Cotton Dry Matter Accumulation and Yield Under Different Phosphorus and Potassium Managements

Liu, Y., M. Wen, M. Li, W. Zhao, P. Li, J. Cui, and F. Ma. 2021. Agronomy Journal 113:2524–2533. DOI: 10.1002/agj2.20625.

Abstract: To elucidate effects of reduced N application rate on dry matter accumulation and yield of drip-irrigated cotton (*Gossypium hirsutum* L.) under different phosphorus and potassium managements (PK-Ms), field studies with four reduced N application rates and four PK-Ms were conducted in 2018 and 2019. Results show that after early peak boll-forming (PB) stage, the leaf area (LA) in N3PK-M3 was the highest among all treatments. The net assimilation rate (NAR), crop growth rate (CGR), boll dry weight (BDW), and boll growth rate (BGR) were highest in N2, followed by N3 with insignificant differences, and those parameters in PK-M3 were the highest. The reproductive/vegetative biomass ratio (RVR) for N3PK-M3 was the highest. The CGR, BDW, BGR, and NAR for N3PK-M3 were insignificantly lower than those for N2PK-M3, which increased yield in N2PK-M3 and N3PK-M3 treatments. Correlation analysis showed that BGR was positively related with CGR and NAR from peak flowering (PF) stage to boll opening (BO) stage, and CGR was significantly correlated with NAR and LA from PF to BO stage, and BO stage, respectively. Moreover, the yield was positively correlated with boll weight (BW) and boll number (BN), and BGR was significantly correlated with BN and BW from peak squaring stage to late PB stage. Therefore, high yield in N3PK-M3 due to higher value in LA after boll-forming stage, with higher NAR, CGR, RVR, and BGR, suggesting that early boll formation and successive partitioning of dry matter in boll growth were important factors for yield formation.

Legumes and Nutrient Management Improve Phosphorus and Potassium Balances in Long-Term Crop Rotations

White, K.E., M.A. Cavigelli, G.Bagley. 2021. Agronomy Journal 113:2681–2697. DOI: 10.1002/agj2.20651.

Abstract: Balancing P and K inputs with crop needs is challenging in cropping systems applying poultry litter (PL) for N. We compared P and K balances of PL-amended organic and mineral-fertilized conventional systems over 13 yr. In organic systems, lower legume cover crop biomass (3,462 ± 421 vs. 4,691 ± 436 kg ha^{-1}) and N contributions in a corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.] rotation (Org2) led to 58% greater PL applications to corn than in a corn–soybean–wheat (*Triticum aestivum* L.) rotation (Org3); as did alfalfa (*Medicago sativa* L.) in a corn–soybean–wheat–alfalfa rotation (Org6). Greater Org2 and Org3 P inputs reduced harvest

exports by 106 and 102 kg ha^{-1}, respectively, increased mean P balances by 209 kg ha^{-1}, and mean Mehlich 3 P concentrations by 9.6 mg kg^{-1} compared to Org6. Alfalfa exported 62% of P and 56% of K applied throughout the Org6 rotation. Due to alfalfa export, the annual P surplus was small (9 kg ha^{-1}) and soil P was "optimum" in Org6. Soil test-based fertilizer application in tilled and no-till conventional systems with initially high soil P led to a –124 kg ha^{-1} P balance and optimum soil P. Fertilizer and PL K applications exceeding crop uptake led to positive K balances in all systems but greater retention of PL than fertilizer K. Legume cover crops or forages and increasing crop rotation length/complexity improved organic system P and K balances. Soil test-based fertilizer application in conventional systems reduced high soil test P while maintaining yields.

Soil Potassium Regulation by Changes in Potassium Balance and Iron and Aluminum Oxides in Paddy Soils Subjected to Long-Term Fertilization Regimes

Han, T., J. Huang, K. Liu, H. Fan, X. Shi, J. Chen, X. Jiang, G. Liu, S. Liu, L. Zhang, Y. Xu, G. Feng, and Z. Huimin. 2021. Soil and Tillage Research 214:105168. DOI: 10.1016/j.still.2021.105168.

Abstract: Southern China's paddy soils are poor in potassium (K) and rich in iron (Fe) and aluminum (Al) oxides, both of which are affected by fertilizer application. However, the response of soil K budget to long-term K fertilization and Fe and Al oxides remains unclear, especially in the subsurface horizons in different soil types. Here, four long-term fertilization treatments (no fertilizer, CK; inorganic nitrogen and phosphorus fertilizers, NP; NPK; and the combined NPK and manure, NPKM) were selected to determine the effects of K input and different forms of Fe and Al oxides on soil K status at two soil layers (0–20, surface; and 20–40 cm, subsurface) in red (Ferralsols) and purple (Cambisols) paddy soils across China. Overall, treatments where K fertilizer application was withheld had lower surface soil exchangeable K (EK), non-exchangeable K (NEK), and total K contents than treatments applied with K fertilizer. In contrast, the treatment including K with manure fertilizer increased EK and NEK contents. Regardless of fertilization regimes, the contents of EK and NEK in both soil depths of purple soil were significantly higher than those in their corresponding depths of red soil. Moreover, there were significantly lower EK and NEK contents in the subsurface layer than those in the surface layer of red soil, while no significant differences were observed in purple soil. A positive correlation was obtained between K balances and soil EK contents ($P<0.05$) and the slopes of linear regressions in red soil was higher than that in purple soil. A three-way ANOVA showed that the lone and interactive effects of experimental site, fertilization regime, and soil depth significantly influenced the contents of Fe and Al oxides in both soils. The application of NPKM can inhibit the decrease of free Fe and Al oxides in the surface layer of soil and increase the amorphous and chelated Fe and Al oxides, especially in red soil. Redundancy analysis showed that the amorphous Fe and Al oxides were the most important factors for regulating surface soil EK content. The free and chelated oxides were the most important factors for regulating NEK contents in red and purple soils, respectively, particularly in subsurface soil. Our results imply that the combined application of inorganic fertilizer and manure is a viable strategy for improving soil K availability by increasing K balance and regulating the contents and forms of Fe and Al oxides in different depths of paddy soil.

Wheat Nitrogen, Phosphorus, Potassium, and Sulfur Uptake Dynamics Under Different Management Practices

De Oliveira Silva, A., B.R. Jaenisch, I.A. Ciampitti, and R.P. Lollato. 2021. Agronomy Journal 113:2752–2769. DOI: 10.1002/agj2.20637.

Abstract: Information is limited on the effect of intensified management on winter wheat (*Triticum aestivum* L.) nutrient uptake dynamics. Our goal was to evaluate the effect of agronomic practices on wheat yield and uptake of N, P, K, and S by evaluating the (a) nutrient utilization and uptake at varying yield levels, (b) variation in nutrient concentration as function of biomass, and (c) plant nutritional status. The genotype 'Everest' was grown under standard (SM) and intensive (IM) management. Treatments (i.e., N, Cl, and S fertilizers, fungicide, plant density, and growth regulator) were individually added to the SM or removed from the IM controls. The IM control increased yield by as much as 0.9 Mg ha^{-1} and uptake of N, K, and S by 37, 30, and 60%, respectively, relative to the SM control, with no changes in P uptake. Fungicide was the main treatment limiting yield and nutrient uptake, and its removal from the IM control reduced yield by 1 Mg ha^{-1} and nutrient uptake in high disease-pressure seasons. Across all treatments and nutrients, 20% of the uptake at maturity was accumulated by stem elongation, 50% at flag leaf, and 70% at heading. The IM control maintained higher shoot nutrient concentration relative to the SM control during the season, increasing nutrition indices for N and S, and indicating possible luxury uptake under IM. Intensification strategies may increase nutrient demand but it does not seem to affect the overall timing and rate of uptake during the season.

Rice Potassium Transporter OsHAK8 Mediates K^+ Uptake and Translocation in Response to Low K^+ Stress

Wang, X., J. Li, F. Li, Y. Pan, D. Cai, D. Mao, L. Chen, S. Luan. 2021. Frontiers in Plant Science 12:1632. DOI: 10.3389/fpls.2021.730002.

Abstract: Potassium (K^+) levels in the soil often limit plant growth and development. As a result, crop production largely relies on the heavy use of chemical fertilizers, presenting a challenging problem in sustainable agriculture. To breed crops with higher K^+-use efficiency (KUE), we must learn how K^+ is acquired from the soil

by the root system and transported to the rest of the plant through K^+ transporters. In this study, we identified the function of the rice K^+ transporter *OsHAK8*, whose expression level is downregulated in response to low-K^+ stress. When *OsHAK8* was disrupted by CRISPR/Cas9-mediated mutagenesis, *Oshak8* mutant plants showed stunted growth, especially under low-K^+ conditions. Ion content analyses indicated that K^+ uptake and root-to-shoot K^+ transport were significantly impaired in *Oshak8* mutants under low-K^+ conditions. As the *OsHAK8* gene was broadly expressed in different cell types in the roots and its protein was targeted to the plasma membrane, we propose that OsHAK8 serves as a major transporter for both uptake and root-to-shoot translocation in rice plants.

Irrigated Grain Sorghum Response to Long-Term Nitrogen, Phosphorus, and Potassium Fertilization

Schlegel, A., and D. Bond. 2021. Kansas Agricultural Experiment Station Research Reports 7:7. DOI: 10.4148/2378-5977.8109.

Abstract: Long-term research shows that phosphorus (P) and nitrogen (N) fertilizer must be applied to optimize production of irrigated grain sorghum in western Kansas. In 2020, N applied alone increased yields 60 bu/a, whereas N and P applied together increased yields up to 83 bu/a. Averaged across the past 10 years, N and P fertilization increased sorghum yields up to 82 bu/a. The application of 160 lb/a N (with P) produced the maximum yield in 2020, which is slightly less than the 10-year average (2011–2020). The application of potassium (K) has had no effect on sorghum yield throughout the study period. The 10-year average grain N content reached a maximum of ~0.7 lb/bu while grain P content reached a maximum of 0.15 lb/bu (0.34 lb P_2O_5/bu) and grain K content reached a maximum of 0.19 lb/bu (0.23 lb K_2O/bu). At the highest N, P, and K rate, apparent fertilizer recovery in the grain was 33% for N, 69% for P, and 40% for K. Nitrogen fertilization increased soil organic matter and decreased soil pH. Phosphorus fertilization tended to maintain or increase soil test P levels.

Evaluation of Soil Potassium-Holding Capacity Based on Waterlogging-Simulation Experiments

Zhao, X., S. Gao, D. Lu, X. Chen, H. Wang, J. Zhou. 2021. Agronomy Journal 113:2863–2874. DOI: 10.1002/agj2.20697.

Abstract: Evaluating the capacity and loss risk of soil nutrients is helpful to make fertilization strategies. Herein, the term of soil potassium (K)-holding capacity (SKHC) was put forward to assess the capacity and loss risk of plant-available K of specific soils. In this study, SKHC was evaluated via soil waterlogging-simulation experiments using 14 different soils. The K concentrations in surface water were measured, and a critical K concentration was selected to indicate high soil K loss. Results showed that the surface water K concentration (K_{sw}) was significantly affected by waterlogging time, temperature, and soil thickness. The average K_{sw} of 5-cm soil columns waterlogged for 24 h for the 14 soils was 5 mg L^{-1} (1.57–8.57 mg L^{-1}); this was subsequently used as the critical K concentration. By repeating the waterlogging simulation experiment with soils treated with different rates of K fertilizer, a quadratic relationship between the K rate and K_{sw} was found and used to determine the K rate required making the K_{sw} reach the critical K concentration. For the 14 soils, SKHC ranged from 133 to 2,054 mg kg^{-1} and can be classified into four levels: low, <500 mg kg^{-1}; moderate, 500–1,000 mg kg^{-1}; high, 1,000–1,500 mg kg^{-1}; and extremely high, >1,500 mg kg^{-1}. These results allowed the preliminary establishment of an SKHC evaluation method and grading system. Future studies should verify the SKHC under field conditions and optimize the assessment method proposed in this study.

Rising Trend of Hypokalemia Prevalence in the US Population and Possible Food Causes

Sun H., and C.M. Weaver. 2021. Journal of the American College of Nutrition, 40(3):273-279. DOI: 10.1080/07315724.2020.1765893.

Background: Potassium intake deficiency is a chronic issue in the US and many other countries. Possible causes of the deficiency are understudied.

Objective: This study examined potassium deficiency in the US population and possible causes for the new trend.

Methods: Serum potassium data of 28,379 men and 29,617 women between ages 12 and 80 years old who participated in the US National Health and Nutrition Examination Survey (NHANES) between 1999 and 2016 were examined. Blood samples were collected by NHANES and blood biochemistry data were measured in designed laboratories. The data were released bi-annually. Possible causes of low potassium intakes were explored.

Results: There was an apparent decline of serum potassium in the US population between ages 12 and 80 years from 1999 to 2016. Annual average serum potassium concentrations changed from 4.14±0.01 to 3.97±0.01 mmol/l during this period. Hypokalemia prevalence in the US rose from 3.78%±0.68% to 11.06%±1.08% during this period with a higher hypokalemia prevalence in non-Hispanic black than in non-Hispanic white persons. It is possible that declining potassium concentration in food sources in the US contributed to lower potassium intake and increasing potassium deficiency.

Conclusion: The rising trend of hypokalemia prevalence in the US population between 1999 and 2016 is alarming. Renewed efforts to reduce potassium intake deficiency in the US at population level are needed. The impact of possible decreasing crop available potassium levels and increasing consumption of processed food on the potassium deficit trend in the US are possible explanations for the rise in hypokalemia prevalence and require further study.

Insufficient Potassium and Sulfur Supply Threaten the Productivity of Perennial Forage Grasses in Smallholder Farms on Tropical Sandy Soils

Philp, J.N.M., P.S. Cornish, K.S.H. Te, R.W. Bell, W.Vance, V. Lim, X. Li, S. Kamphayae, and M.D. Denton. 2021. Plant Soil 461:617–630. DOI: 10.1007/s11104-021-04852-w.

Aims: Perennial forage grass production has the potential to improve smallholder livelihoods in the tropics. However, nutrient management is often challenging, especially on infertile sandy soils. This study tested whether typical nutrient management limits the productivity and sustainability of perennial forage grass systems on sandy soils.

Methods: Nutrient balances were estimated for four fields of either *Megathyrsus maximus* cv. Tanzania or *Urochloa* hybrid Mulato II. Nutrient limitations were then evaluated in a nutrient omission experiment.

Results: All soils were sandy (< 10% clay), neutral to acidic (pH ($CaCl_2$) 4.6 to 6.7) and had plant-limiting concentrations of total nitrogen, extractable potassium and extractable sulfur. Nitrogen inputs were typically higher than outputs, with balances ranging from −16 kg ha^{-1} yr^{-1} to 293 kg ha^{-1} yr^{-1}, yet concentrations in forage shoots were low at all sites. Phosphorus balances ranged from −5 kg ha^{-1} yr^{-1} to 77 kg ha^{-1} yr^{-1} and concentrations in forage shoots were adequate. Potassium inputs were low, resulting in balances from −79 kg ha^{-1} yr^{-1} to −138 kg ha^{-1} yr^{-1} at locations that did not apply inorganic potassium fertilizer. Potassium concentrations in forage shoots were low and omission of potassium resulted in severely depressed biomass production. Inorganic sulfur fertilizers were not applied to forages and the sulfur balance varied from −1 kg ha^{-1} yr^{-1} to −24 kg ha^{-1} yr^{-1}. Sulfur concentrations in shoots were correspondingly low and production was depressed when sulfur was omitted in the experiment.

Conclusion: Balanced nutrition was not achieved, despite substantial fertilizer inputs, resulting in deficiencies of potassium and sulfur, inefficient use of nitrogen and excesses of phosphorus. If current practices continue, potassium and sulfur depletion, phosphorus accumulation and soil acidification can be expected. Recommendations for balanced nutrient management that accounts for high rates of removal in biomass, variable concentrations in organic fertilizers, and leaching potential, are needed to sustain the productivity of perennial forages on tropical sandy soils.

Detection of Potassium Deficiency and Momentary Transpiration Rate Estimation at Early Growth Stages Using Proximal Hyperspectral Imaging and Extreme Gradient Boosting

Weksler, S., O. Rozenstein, N. Haish, M. Moshelion, R. Wallach, E. Ben-Dor. 2021. Sensors 21(3):958. DOI: 10.3390/s21030958.

Abstract: Potassium is a macro element in plants that is typically supplied to crops in excess throughout the season to avoid a deficit leading to reduced crop yield. Transpiration rate is a momentary physiological attribute that is indicative of soil water content, the plant's water requirements, and abiotic stress factors. In this study, two systems were combined to create a hyperspectral–physiological plant database for classification of potassium treatments (low, medium, and high) and estimation of momentary transpiration rate from hyperspectral images. PlantArray 3.0 was used to control fertigation, log ambient conditions, and calculate transpiration rates. In addition, a semi-automated platform carrying a hyperspectral camera was triggered every hour to capture images of a large array of pepper plants. The combined attributes and spectral information on an hourly basis were used to classify plants into their given potassium treatments (average accuracy = 80%) and to estimate transpiration rate (RMSE = 0.025 g/min, R^2 = 0.75) using the advanced ensemble learning algorithm XGBoost (extreme gradient boosting algorithm). Although potassium has no direct spectral absorption features, the classification results demonstrated the ability to label plants according to potassium treatments based on a remotely measured hyperspectral signal. The ability to estimate transpiration rates for different potassium applications using spectral information can aid in irrigation management and crop yield optimization. These combined results are important for decision-making during the growing season, and particularly at the early stages when potassium levels can still be corrected to prevent yield loss.

Science-Based Maize Stover Removal can be Sustainable

Nunes, M.R., M. De, M.D. McDaniel, J.L. Kovar, S. Birrell, D.L. Karlen. 2021. Agronomy Journal 113:3178–3192. DOI: 10.1002/agj2.20724.

Abstract: Maize (*Zea mays* L.) stover can be harvested for multiple uses or left in the field to sustain soil organic carbon (SOC), cycle essential plant nutrients, and protect soil health. This 13-yr field study quantified effects of no (0 Mg ha^{-1} yr^{-1}), low (1.0–1.4 Mg ha^{-1} yr^{-1}), moderate (3.5–4.0 Mg ha^{-1} yr^{-1}), or high rates (4.7–5.4 Mg ha^{-1} yr^{-1}) of stover harvest from either continuous maize or maize–soybean [*Glycine max* (L.) Merr.] rotation on grain yield, plant nutrient concentrations, and multiple soil properties at two sites in Iowa. Stover harvest increased plant macro- and micro-nutrient removal, but did not affect average grain yields of either crops. Soil inorganic carbon (IC), SOC, bulk density, pH, and cation exchange capacity (CEC) showed no significant differences due to stover harvest. Plant tissue and soil-test nutrient concentration effects were also minor and site-specific. Stover harvest significantly ($p < .05$) decreased exchangeable K and Ca concentrations by 8.3–23.8% and 0.3–22.5% but overall soil health indicator effects were minimal. Overall, based on crop yields, plant nutrient and soil-test concentrations, soil health indicators, and carbon sequestration estimates, maize stover harvest can be sustainable provided: (a) grain yields consistently exceed 11 Mg ha^{-1}, (b) stover removal does not exceed 40% of the aboveground biomass (i.e., 3.5–4.0 Mg ha^{-1} yr^{-1}), and (c) plant nutrients (especially K) are closely monitored.

Sodium (Na) Stimulates Barley Growth in Potassium (K)-Deficient Soils by Improved K Uptake at Low Na Supply or by Substitution of K at Moderate Na Supply

Hussain, M., Q. Ma, and R. Bell. 2021. J Soil Sci Plant Nutr 21:1520–1530. DOI: 10.1007/s42729-021-00458-4.

Abstract: Sodium (Na) can alleviate potassium (K) limitations by either increasing K uptake or by substitution of K functions in plants, but there is limited information about the levels of soil Na and K at which these separate Na effects operate in cereals. Barley was grown in two sandy soils to assess plant growth and nutrient uptake responses with varying soil Na (5–95 mg kg^{-1}) and K (30, 90 mg kg^{-1}) treatments. Compared with very low Na (5 mg kg^{-1}), low Na (35, 65 mg kg^{-1}) enhanced barley tillering in low K soil (30 mg kg^{-1}) up to 6 weeks after sowing (WAS). Low K with 95 mg Na kg^{-1} or adequate K (90 mg kg^{-1}) with 65 mg Na kg^{-1} also produced more tillers at 6–7 WAS. Shoot dry weight of low K plants was significantly improved by low Na at 7 and 9 WAS and even by 95 mg Na kg^{-1} at 9 WAS. While low Na increased shoot K concentration and the K/Na ratio in low K plants, 95 mg Na kg^{-1} mainly increased shoot Na concentration at 7 and 9 WAS. By comparison, soil Na had less effect on shoot K concentration and dry weight of adequate K plants. Barley growth at low soil K was stimulated by increasing K uptake at low Na (35–65 mg Na kg^{-1}), but mainly by Na substitution of K at 95 mg Na kg^{-1}, i.e. the beneficial effect of Na on response of low K plants was attributed to two distinct mechanisms that operated at different soil Na levels.

Evaluation of Corn Response to In-Season Potassium Fertilization Using Dry Fertilizer

Charbonnier, D.A., and D.A. Ruiz Diaz. 2021. Kansas Agricultural Experiment Station Research Reports 7:8. DOI: 10.4148/2378-5977.8131.

Abstract: In-season application of potassium (K) fertilizer may offer an alternative to remediate deficiencies developed during the growing season. The objective of this study was to determine corn response to topdress K application under deficient K soil conditions. Treatments included a control and 50 lb K_2O/a in-season broadcasted at the V8 growth stage. The fertilizer source was potassium chloride (KCl). Measurements collected were plant biomass and tissue nutrient concentration at reproductive stage (R6), and grain yield. Potassium fertilization increased yield at the location evaluated in this study. The in-season fertilized treatment produced higher yield compared to the control ($P < 0.09$). The late K fertilization had higher K concentration and uptake in the plant at R6 ($P < 0.06$) with the same plant biomass as the control treatment. Also, broadcasting KCl at V8 resulted in a higher K/Mg ratio late in the season (R6). Preliminary results of this study suggest that in-season applications using dry K fertilizers could be used when pre-plant fertilization was not done. Nevertheless, for a dry growing season, corn response might be limited.

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Editors: Amnon Bustan, Israel; Patrick Harvey, Green Shoots, UK; Patricia Imas, IPI

Layout and design: Green Shoots, UK

Address: International Potash Institute
Industriestrasse 31
CH-6300 Zug, Switzerland

Telephone: +41 43 810 49 22
E-mail: ipi@ipipotash.org
Website: www.ipipotash.org

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