Research Findings

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

Polyhalite Effects on Corn and Bean Performance in Guanajuato, Mexico

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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

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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

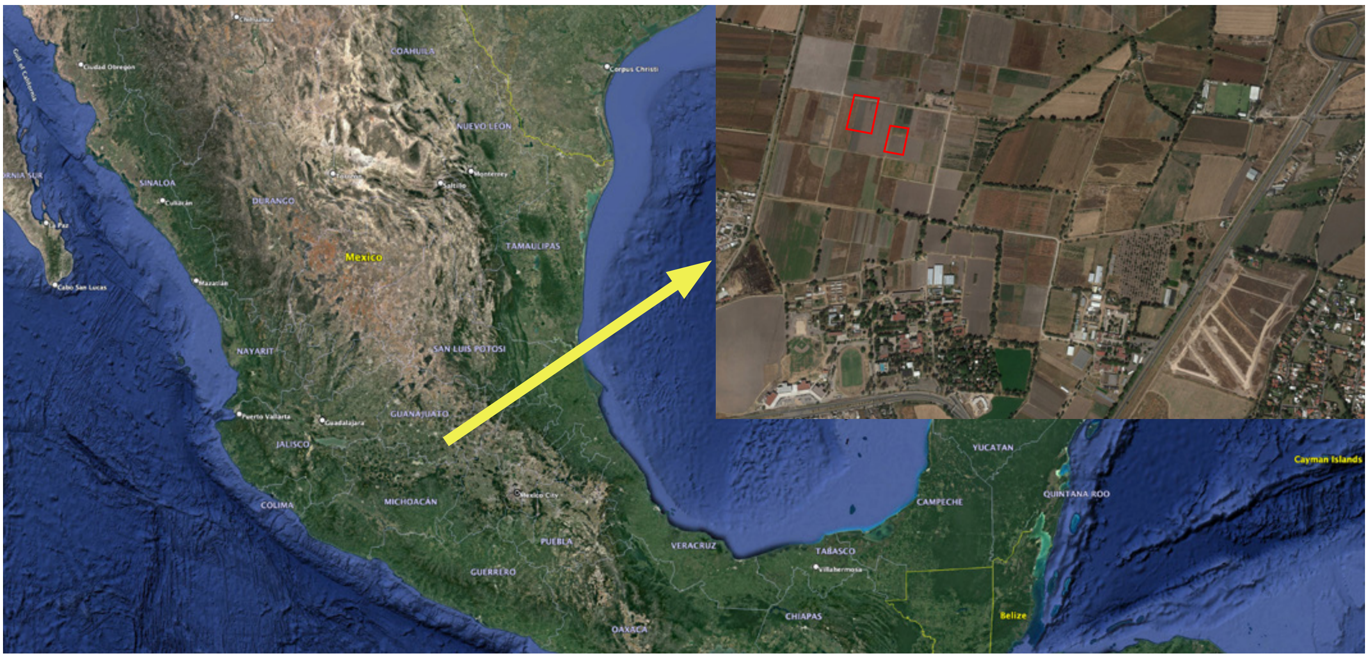

Fig. 1. Location of INIFAP's Bajío experiment field in Celaya, Guanajuato State, Mexico. Source: Google Earth.

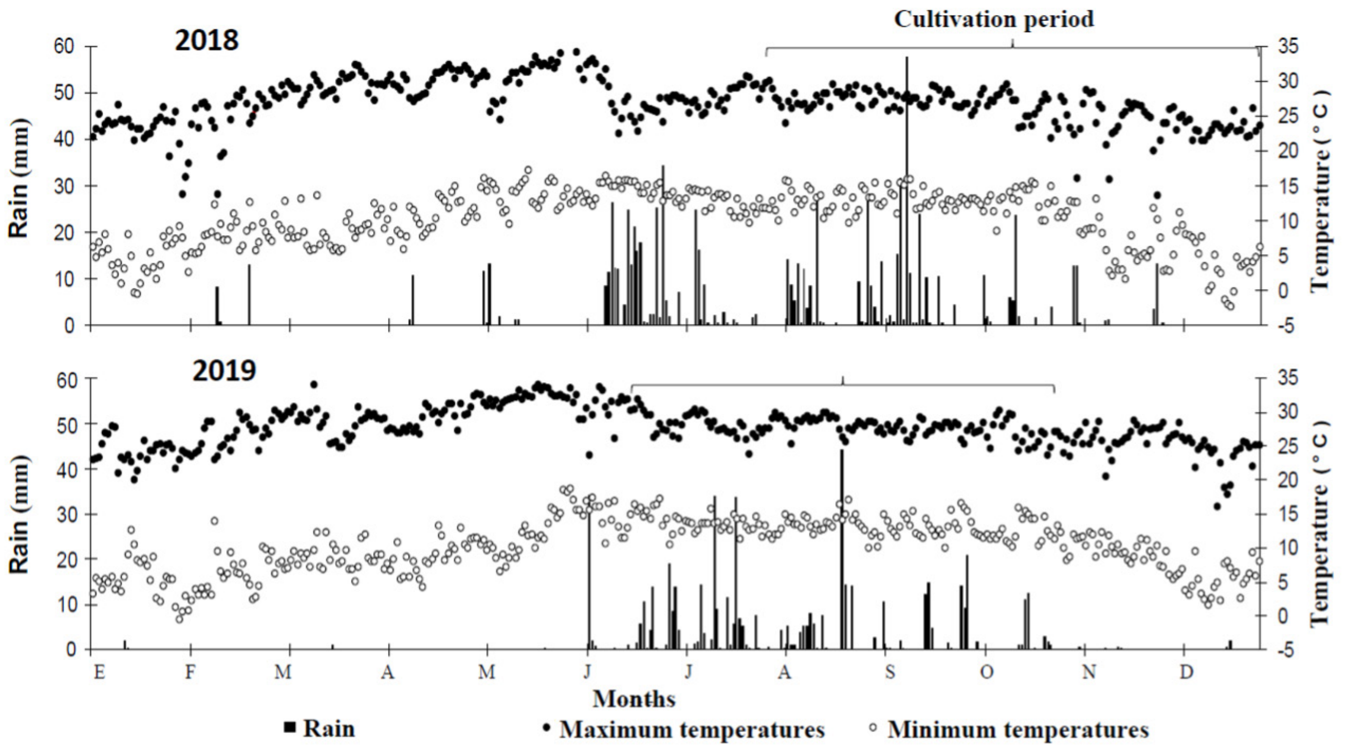

Fig. 2. Daily rain, and maximum and minimum temperatures at Bajío experiment field, Celaya, Guanajuato, Mexico, in 2018 and 2019.

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

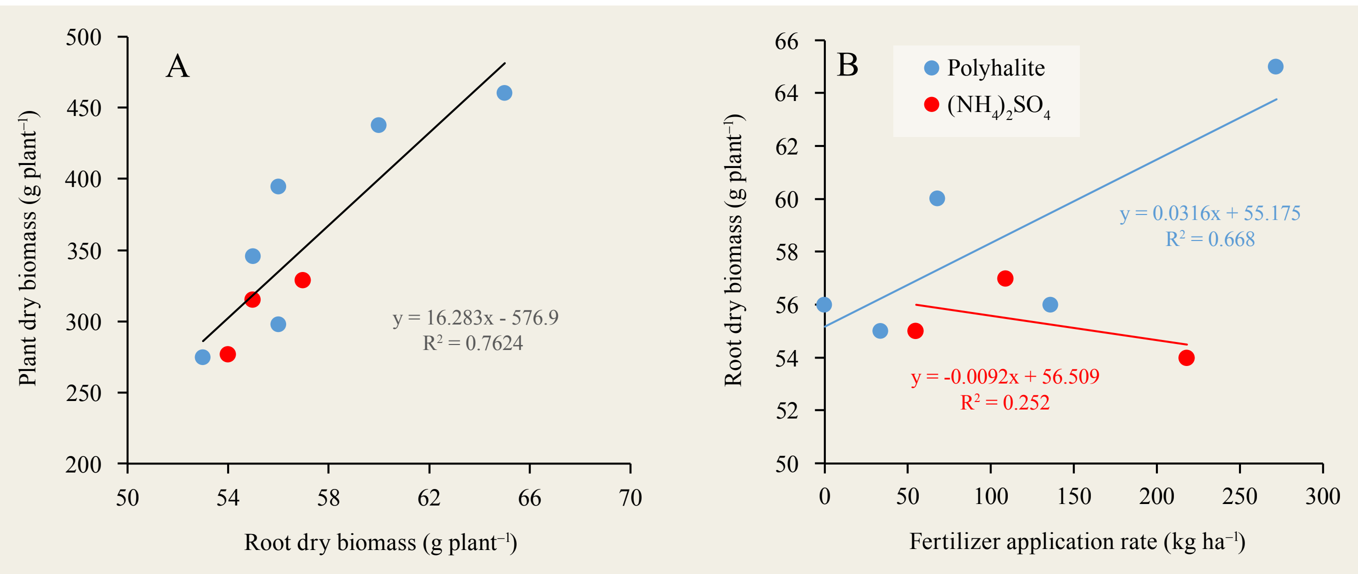

Fig. 3. The relationship between root biomass and plant biomass (A), and the effect of the fertilizer type and application rate on these parameters (B).

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.

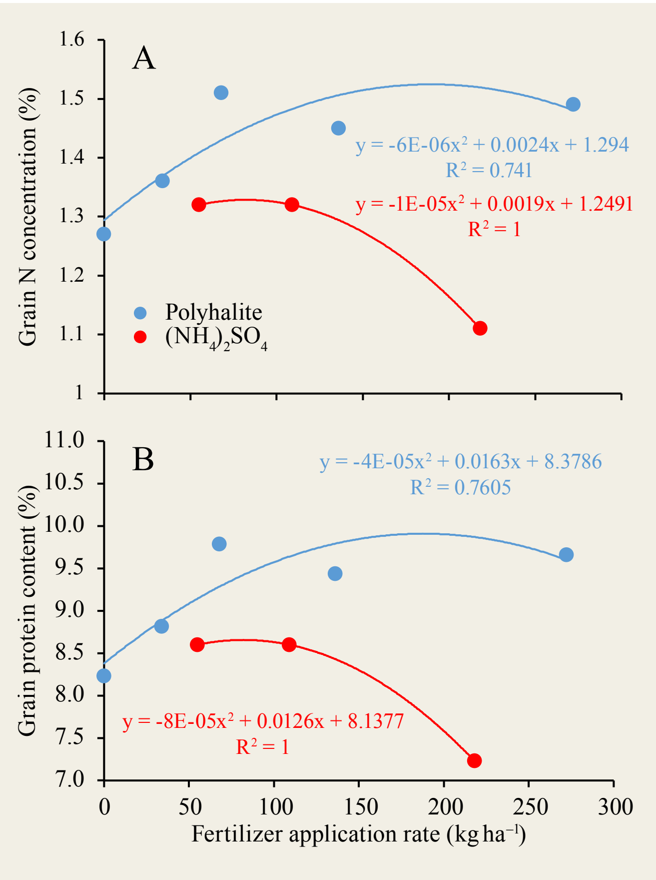

Fig. 4. Effects of fertilizer treatments on the grain N (A) and protein (B) contents in the 2018 corn crop season (Experiment A).

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

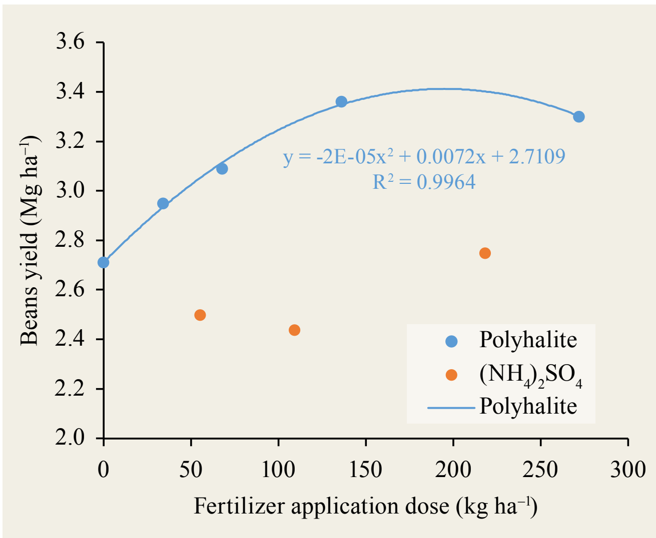

Fig. 5. Residual effect of the 2018 fertilizer application rate on bean yield in 2019.

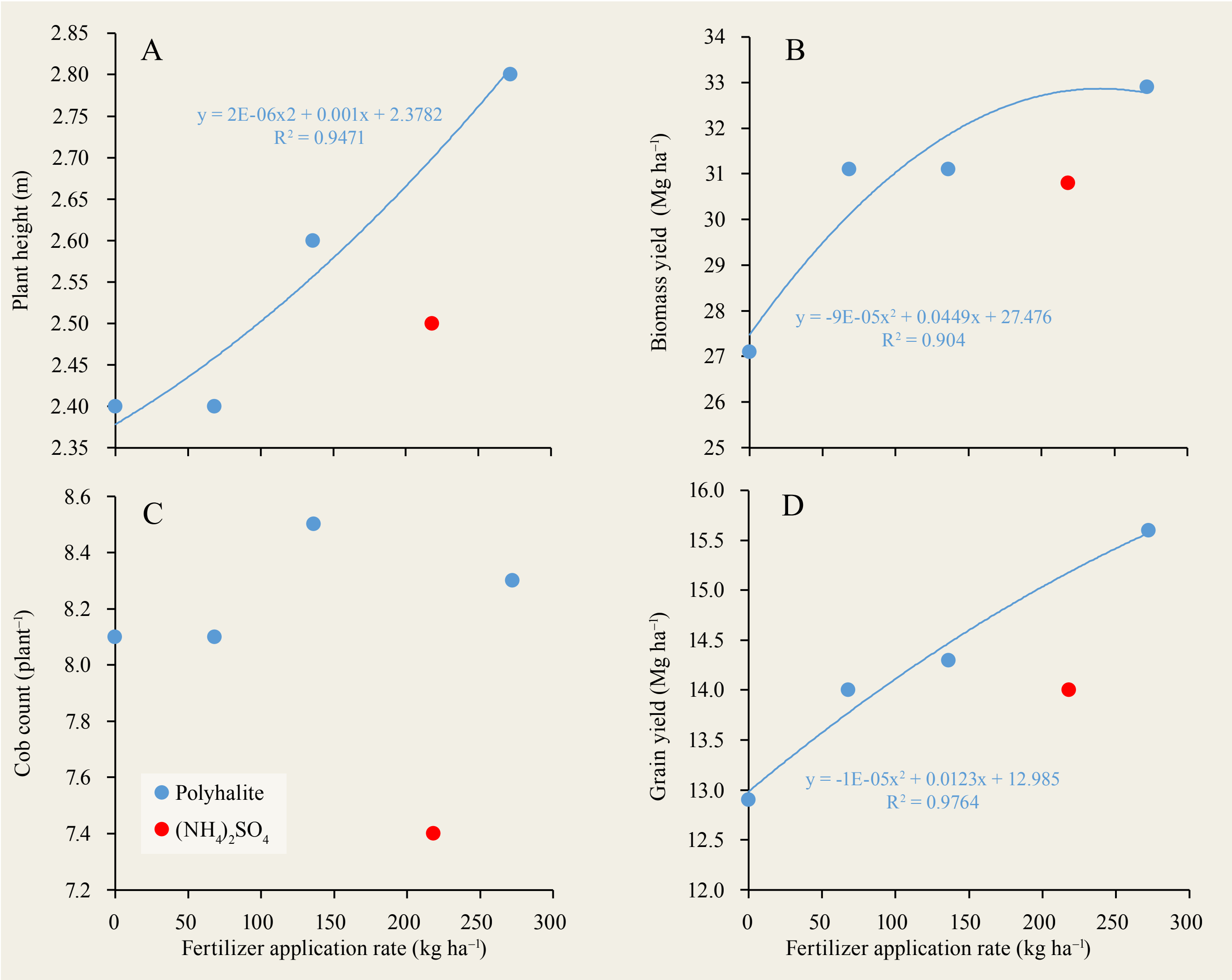

Fig. 6. Effects of fertilizer treatments on corn crop performance in 2019 (Experiment B)

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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