sustainability

Article

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

Rajan Bhatt [1], Paramjit Singh [1], Omar M. Ali [2], Arafat Abdel Hamed Abdel Latef [3,*], Alison M. Laing [4] and Akbar Hossain [5,*]

1 Regional Research Station, Kapurthala, Punjab Agricultural University, Ludhiana 141 004, India; rajansoils@pau.edu (R.B.); paramjit1963@pau.edu (P.S.)
2 Department of Chemistry, Turabah University College, Turabah Branch, Taif University, P.O. Box 11099, Taif 21944, Saudi Arabia; om.ali@tu.edu.sa
3 Botany and Microbiology Department, Faculty of Science, South Valley University, Qena 83523, Egypt
4 CSIRO Agriculture & Food, St. Lucia, QLD 4067, Australia; alison.laing@csiro.au
5 Department of Agronomy, Bangladesh Wheat and Maize Research Institute, Dinajpur 5200, Bangladesh
* Correspondence: moawad76@gmail.com (A.A.H.A.L.); akbarhossainwrc@gmail.com (A.H.)

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} (T_1) to potassium applied as MOP only at 80 kg K ha^{-1} (T_2) and at 120 kg K ha^{-1} (T_3), and potassium applied as an equal split of MOP and polyhalite at 80 kg K ha^{-1} (T_4) and at 120 kg K ha^{-1} (T_5). 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 T_2, T_3, T_4,, and T_5, respectively, than in T_1. 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.

Keywords: muriate of potash; polyhalite; sugarcane; potassium fertilizer; B:C ratio

Citation: Bhatt, R.; Singh, P.; Ali, O.M.; Abdel Latef, A.A.H.; Laing, A.M.; Hossain, A. Polyhalite Positively Influences the Growth, Yield and Quality of Sugarcane (*Saccharum officinarum* L.) in Potassium and Calcium-Deficient Soils in the Semi-Arid Tropics. *Sustainability* **2021**, *13*, 10689. https://doi.org/10.3390/su131910689

Academic Editor: Zakaria Solaiman

Received: 18 August 2021
Accepted: 23 September 2021
Published: 26 September 2021

1. Introduction

Sugarcane (*Saccharum* spp.) is an important industrial crop, grown in tropical to sub-tropical climates, between 36.7° north and 31.0° south of the Equator [1–3]. Sugarcane is grown for both sugar extraction (meeting 75% of global sugar requirements) and for ethanol production [4–6]. In the Indian Punjab, sugarcane is cultivated on 91,000 hectares, with an average cane yield of 80 tons per hectare and a sugar recovery of 9.59% [7]. Factors that limit yield and quality in this region are the poor use of nutrients, water stress, incidences of insect pests and disease, and poor-quality seed [8]. Of these, the unbalanced use of nutrients, and in particular of fertilizer potassium (potash), is a key challenge to achieving the potential yield of high-quality sugarcane [9]. Estimates suggest that for every 100 tons of sugarcane produced, inputs of 208 kg ha^{-1} nitrogen, 53 kg ha^{-1} phosphorus, 280 kg ha^{-1} potassium, and 30 kg ha^{-1} sulfur are required, along with smaller amounts of other elements [10].

Sugarcane grown in the Indian Punjab is produced with low applications of potassium (K) fertilizers on soils that are already inherently low in potassium, and also in calcium, magnesium, and sulfur. These deficiencies result in reductions in both sugarcane yield and quality. Potassium is necessary for the lignification of vascular bundles, reducing the risk of lodging and susceptibility to disease. In soil, potassium exists in four different pools: soil-soluble K (0.1–0.2% of total in-soil K), exchangeable K (1–2%), non-exchangeable K (1–10%), and mineral K (90–98%). When the equilibrium between these pools is disturbed by the removal or addition of potassium, potassium ions flow from one pool to another [11]. Equilibration of the soil-soluble and exchangeable potassium pools is quick, usually taking only a few hours. Some soils lose a large amount of potassium by leaching after being displaced from the clay exchange sites during flooding. In soils with low cation exchange capability, K leaching is a major issue [12,13]

To meet crop potassium requirements, muriate of potash (MOP) has traditionally been used in agriculture [6]. In sugarcane cultivation, the optimal dose of MOP has not been standardized [6,9]. Soils under continuous sugarcane production are often deficient in other nutrients as well as potassium. A multi-nutrient fertilizer, "polyhalite" ($K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$) contains potassium (14% K_2O), calcium (17% CaO), magnesium (6% MgO) and sulfur (48% SO_3) [14]. Polyhalite is mined 1200 m below the Earth's surface, in the North Sea, along the northeastern coast of the United Kingdom [15], and has lower environmental impacts than other fertilizers [16]. Polyhalite releases nutrients more slowly than traditional fertilizers [17], which may contribute to increased fertilizer use efficiency [18].

The efficacy of polyhalite has been examined for maize (*Zea mays*, L.) [19,20]; sorghum (*Sorghum bicolor*, L.) [21]; kiwifruit (*Actinidia deliciosa*) [22]; potato (*Solanum tuberosum*) [15]; tomato (*Solanum lycopersicum*) [23]; cabbage (*Brassica oleracea* var. capitata) [24]; and mustard (Brassica) [25]. Relative to fertilizer potassium in other forms, e.g., potassium chloride (KCl), polyhalite has been shown to increase the duration over which soil potassium is available to plants [26]. The effectiveness of polyhalite relative to conventional MOP has not, until now, been evaluated for semi-arid tropical sugarcane (*Saccharum officinarum*) cultivation in India [27].

Polyhalite supplies calcium (Ca), which is required for plant membrane stability, cell integrity, cell division, and elongation [28–30], as well as various signal transduction pathways and activation [28–31]. Further, as Ca be moved in plants through xylem sap, canes cannot remobilize calcium from older tissues and therefore the importance of a source of calcium fertilizer, such as polyhalite, is high in the Ca-deficient soils on which sugarcane is grown in the Indian Punjab. Magnesium (Mg), which is also supplied by polyhalite, is required for plant photosynthesis and glucose partitioning [32–34] which is also reported being significantly higher SPAD readings. Sulfur (S) contributes to increased crop yields [35,36] by improving the effectiveness of nitrogen fertilizers [37].

To sustainably increase sugarcane yield and quality, a balanced use of nutrients is necessary; ignorance of the appropriate nutrient balance is likely to reduce crop yields and deplete soil health [3,6]. Potassium fertilizer is important for the metabolic and physiological activity within sugarcane plants: potassium acts as a catalyst of many enzymes, controls stomatal openings, translocates plant resources throughout the entire plant, reduces the incidence and severity of attacks by insect pests, promotes root growth, and improves the nutrient-, pesticide- and water-use efficiencies while reducing the inputs required to produce a crop [8,9]. When potassium is deficient, translocation of photosynthates [38] and their movement throughout the whole sugarcane plant are severely affected [39].

This research compared the performance of sugarcane plants under MOP and the multi-nutrient fertilizer polyhalite on a potassium- and calcium-deficient soil in the Indian Punjab. Field experiments were conducted at the experimental farm of the Punjab Agricultural University Regional Research Station at Kapurthala, Punjab. We examined different applications of MOP and polyhalite to determine: (1) the optimal fertilizer potassium doses for improved sugarcane performance; (2) the incidence of insect-pest attacks under different fertilizer treatments; and (3) the benefit-to-cost (B:C) ratio under each treatment.

2. Material and Methods

2.1. Experimental Site

Experiments were conducted from March 2020 to March 2021 at the experimental farm of the Punjab Agricultural University Regional Research Station at Kapurthala, Punjab, 31°23.032′ N, and 75°21.647′ E, and altitude of 225 m above mean sea level (Figure 1). The sugarcane crop was established in March 2020.

Figure 1. The experimental location is in Kapurthala, Punjab (Source: Google Earth, Alphabet Company).

Daily climate data including maximum and minimum temperatures, rainfall, and pan evaporation were measured at the meteorological station near the experimental site. Annual class A pan evaporation was 1320.5 mm, average maximum air temperatures ranged between 19.2–37.5 °C, and average minimum air temperatures between 7.0–27.6 °C (Figure 2A,B). Maximum rainfall (969.5 mm) was received on 46 rainy days in July and August 2020, while least rainfall (0 mm) occurred in October 2020. During the dry season (December 2020 to February 2021), a total of 88 mm rainfall was recorded (Figure 2C). During the sugarcane growing season, the average pan evaporation was 102 mm, with a maximum (183 mm) in June 2020 and a minimum (30 mm) in January 2021 (Figure 2D).

2.2. Soil Characteristics

Representative, replicated soil samples were collected from the site using standard procedures [40]. Soil analysis showed that the experimental site was a sandy loam (sand 65–68%, clay 11–3%), neutral to slightly alkaline, non-saline, and with the topsoil (0–15 cm depth) low in potassium, calcium, and soil organic carbon, and high in phosphorus and magnesium (Table 1) Magnesium and sulfur (other nutrients within polyhalite fertilizer) are not limiting to sugarcane in the soil of the experimental site. There was no significant difference in soil properties across the experimental site.

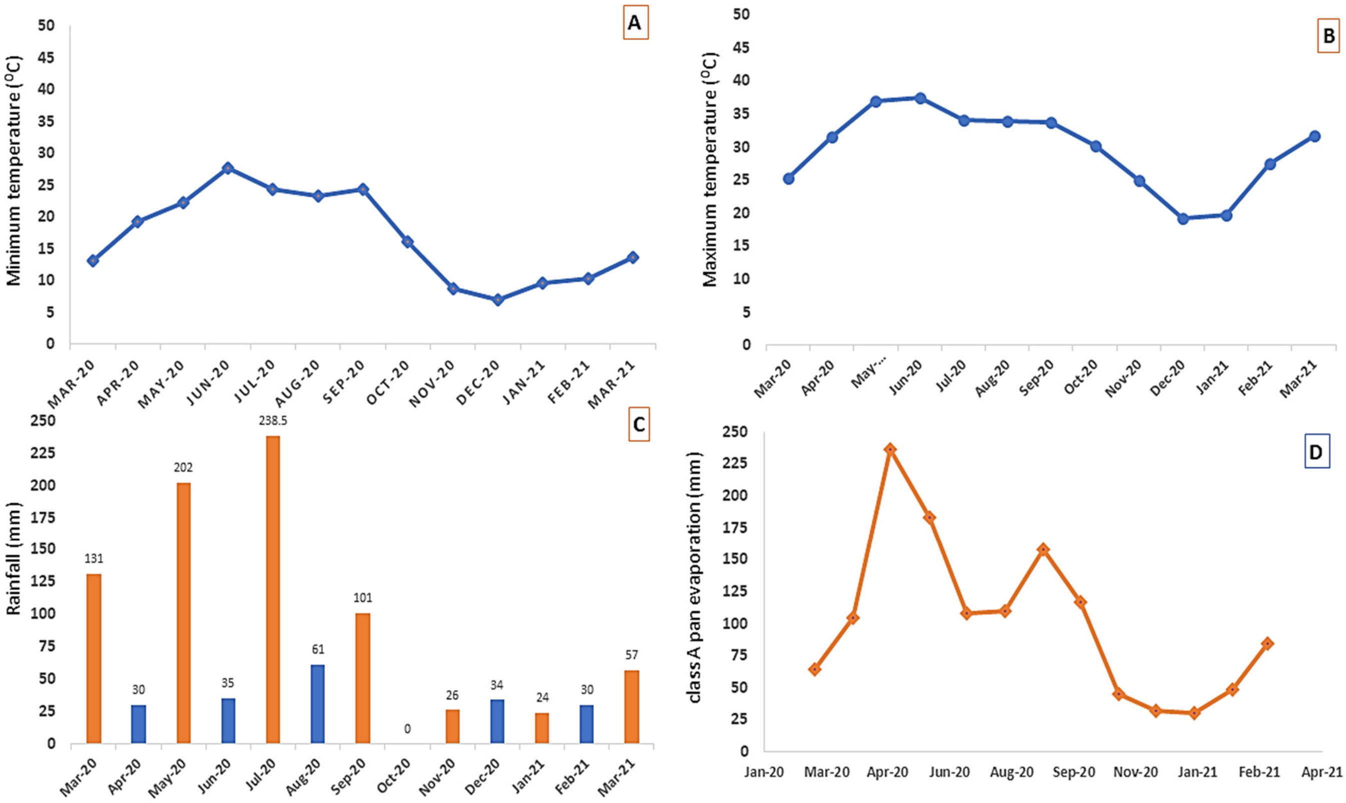

Figure 2. Minimum temperature (°C; (**A**)), maximum temperature (°C; (**B**)), rainfall (mm; (**C**)) and class A pan evaporation (mm; (**D**)) during the experimental period.

Table 1. Major soil properties at 0–15 cm depth at the experimental site.

Soil Properties	Values
Sand (%)	64.9
Clay (%)	11.5
pH (2:1)	8.64
EC (ds m^{-1})	0.20
°C (%)	0.34
Available nitrogen (Kg ha^{-1})	34.6
Available phosphorus (Kg ha^{-1})	54.2
Available potassium (Kg ha^{-1})	135.5
Available magnesium (ppm)	553.5
Available calcium (ppm)	140.0
Bulk density (Mg m^{-3})	1.65

2.3. Irrigation Water quality

Groundwater at the experimental site was at a depth of 26 m. Replicates of the irrigation water used on the crop were analyzed to determine their quality, with the results shown in Table 2. The water used for irrigating the canes was of good quality.

Table 2. Parameters of irrigation water quality at the experimental site.

Replications	Ca^{2+} + Mg^{2+}	Cl^{-1}	Residual	EC	$CO_3{}^{-2}$	$HCO_3{}^{-}$
	(meq L^{-1})	(meq L^{-1})	$NaHCO_3$	(ds m^{-1})	(meq L^{-1})	(meq L^{-1})
R_1	3.6	0.6	0	0.48	0	3.6
R_2	3.7	0.7	0	0.5	0	3.8
R_3	3.6	0.9	0	0.52	0	3.7
Mean	3.6	0.7	0	0.5	0.0	3.7

2.4. Treatments and Experimental Design

All the plots received the locally recommended dose (RDF) of non-potassium fertilizers [7]. Potassium fertilizer was applied as muriate of potash (MOP), or as a combination of MOP and the commercial preparation polyhalite ($K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$) according to the following treatments:

T_1: RDF non-K fertilizers + 0 kg K_2O ha^{-1};
T_2: RDF non-K fertilizers + 80 kg K_2O ha^{-1} as MOP;
T_3: RDF non-K fertilizers + 120 kg K_2O ha^{-1} as MOP;
T_4: RDF non-K fertilizers + 80 K_2O ha^{-1} half applied as MOP and half as polyhalite;
T_5: RDF non-K fertilizers + 120 K_2O ha^{-1} half applied as MOP and half as polyhalite.

The treatments are summarized in Table 3.

Table 3. Fertilizer used in each experimental treatment.

Treatment	Major Non-K Fertilizer (%)	Potassium Fertilizer			
		Polyhalite (%)	Polyhalite (kg K_2O ha^{-1})	MOP (%)	MOP (kg K_2O ha^{-1})
T_1	100	0	0	0	0
T_2	100	0	0	66	80
T_3	100	0	0	100	120
T_4	100	33	40	33	40
T_5	100	50	60	50	60

Treatments were laid out in a randomized block design in plots 6 m × 4.5 m (i.e., 27 m^2), with three replicates in each treatment. The mid-long duration sugarcane cultivar CoPb 93, which is a common variety grown in the Indian Punjab, was sown at 75 cm row spacing on 6 April 2020 in soils that were deficient in potassium and calcium. Best agronomic practices for sugarcane cultivation and insect-pest control were followed, using recommendations from Punjab Agricultural University, Ludhiana [7].

2.5. Data Collection and Calculations

The germination percentage of the sown setts was counted in each plot 45 days after sowing (DAS) the crop, following the recommended approach [6,9].

The number of tillers was assessed at 200 and 329 DAS by counting the total number of single plant tillers in a randomly selected 5 m^2 area within each treatment plot [6].

The number of millable sugarcane stalks was recorded at 334 DAS. Well-matured canes fit for milling were visually assessed and counted from within the total plot area, and expressed as thousands per hectare [6,9].

Five randomly selected sugarcane stalks were tagged in each plot. Of these stalks, the shoot length from the soil surface top the top growing point was measured at 113, 127, 152, and 198 DAS using a long rule.

The cane diameter of the five randomly selected sugarcane stalks was measured at 99, 152, 179, and 262 DAS using Vernier calipers. The mean value of the stalk diameter at the top, middle, and bottom was calculated to determine average cane stalk diameter [6,9].

The total number of internodes on each of the five randomly selected sugarcane stalks was counted at 152, 200, 261, and 297 DAS in each plot and averaged for a value in each treatment plot.

Leaf chlorophyll concentration was measured at 219, 267, and 298 DAS using a SPAD-502+ chlorophyll meter.

The weight of all sugarcane stalks in each treatment plot was measured at harvest and expressed as cane yield in tons per hectare.

2.6. Sugarcane Quality Parameters

Five randomly selected sugarcane stalks were harvested from each experimental plot in the 10th and 12th months after planting. A cane-crusher was used to extract juice, which was analyzed for quality following standard methods [41].

Brix and the percentage of sucrose in the cane juice were measured using a digital refractometer following the procedure outlined in [41]. The percentage commercial cane sugar (CCS) content was calculated using the equation:

$$\text{CCS (\%)} = [\text{Sucrose \%} - (\text{Brix \%} - \text{Sucrose \%}) \times 0.4] \times 0.74 \quad (1)$$

In Equation (1), 0.4 and 0.74 are the multiplication and crusher factors, respectively.

Using the cane yield and percentage CCS content, the CCS content in tons per hectare was calculated as follows:

$$\text{CCS (t ha}^{-1}) = [\text{CCS (\%)} \times \text{sugarcane yield (t ha}^{-1})]/100 \quad (2)$$

2.7. Incidence of Insect-Pests

Three key sugarcane insect pests which adversely affect yield quality and quantity were visually monitored: early shoot borer (*Chilo infuscatellus*), top borer (*Scirpophaga excerptalis*) and stalk borer (*Chilo auricilius*). The top borer and early shoot borer populations in each treatment plot were recorded in June, 60 DAS. At harvesting, the population of stalk borer in 100 plants in each plot was recorded.

2.8. Benefit-to-Cost Ratio of Additional Fertilizer

The calculation of the benefit-to-cost (B:C) ratio used the costs of the applied MOP and polyhalite, and the minimum support price (MSP) of sugarcane cane [6,9,42]. The B:C ratio was calculated using the equation:

$$\text{B:C ratio} = \text{Economic benefit from additional K (INR ha}^{-1})/\text{Cost of additional K (INR ha}^{-1}) \quad (3)$$

2.9. Statistical Analysis

The online OPSTAT program developed by Chaudhary Charan Singh of Haryana Agricultural University, Hisar, India, was used to analyze cane yield and quality data. Statistical significance was inferred when $p \leq 0.05$. R was used to analyze correlations between different quality parameters in the experimental treatments [43].

3. Results

3.1. Growth and Yield Parameters

Germination, cane height, cane width, the number of internodes per plant, the number of millable canes, the number of tillers per plant, the leaf-chlorophyll concentration, and the cane yield were all higher in experimental treatments which received potassium fertilizer (T_2–T_5) than in the control (T_1), regardless of the type of potassium fertilizer applied (Tables 4 and 5).

Table 4. Germination, sugarcane stalk height, and sugarcane stalk diameter under fertilizer treatments.

Treatment	Germination		Sugarcane Stalk Height (cm)			Sugarcane Stalk Diameter (cm)			
	35 DAS	113 DAS	127 DAS	152 DAS	198 DAS	99 DAS	152 DAS	179 DAS	262 DAS
T_1	40.9d	101.6a	115.4c	175.2b	206.4a	2.27b	2.47c	2.51d	2.75c
T_2	46.1c	103.8a	119.9bc	176.5b	211.5a	2.34b	2.53bc	2.54c	2.79bc
T_3	50.8b	106.7a	122.4ab	179.1b	212.1a	2.39b	2.56ab	2.57b	2.81b
T_4	54.4a	107.9a	127.0a	182.1ab	216.2a	2.56a	2.63a	2.61a	2.88a
T_5	55.2a	111.9a	127.4a	187.4a	217.3a	2.58a	2.60ab	2.62a	2.89a
F-test ($p \leq 0.05$)	2.36	NS	6.48	7.69	NS	0.18	0.78	0.02	0.05
SE (±)	0.71	2.22	1.96	2.32	2.96	0.053	0.005	0.005	0.015
CV (%)	2.48	3.61	2.80	2.20	2.41	3.78	1.60	0.33	0.90

DAS = days after sowing. In all treatments, the recommended dose of non-K fertilizers was applied. T_1: 0 kg K_2O ha^{-1}; T_2: 80 kg K_2O ha^{-1} as MOP; T_3: 120 kg K_2O ha^{-1} as MOP; T_4: 80 K_2O ha^{-1} as MOP + polyhalite (50% each); T_5: 120 K_2O ha^{-1} as MOP + polyhalite (50% each). Within each column different letters indicate statistical difference.

Table 5. Growth and yield parameters of sugarcane under different rates and types of potassium fertilizer.

Treatments	Nodes Cane^{-1}				NMC (000 ha^{-1})	Tillers		Leaf Chlorophyll Concentration			Yield (t ha^{-1})
	Days after Sowing										
	152	200	261	297	334	200	329	219	267	298	
T_1	15.5a	21.3a	23.6a	24.9a	3.41c	5.00a	7.40a	69.1a	44.5a	45.3a	68.40b
T_2	16.9a	21.0a	24.1a	25.3a	3.88b	5.67a	7.87a	62.9b	37.2b	42.8b	71.41a
T_3	16.3a	21.3a	23.9a	24.3a	4.18b	5.53a	8.27a	57.5c	32.9c	42.9b	72.63a
T_4	16.4a	21.8a	24.2a	24.7a	4.68a	5.50a	8.87a	47.6d	36.3bc	39.2c	74.02a
T_5	16.3a	21.5a	24.3a	25.2a	4.81a	5.43a	8.73a	48.4d	33.1c	42.4b	75.16a
F-test ($p \leq 0.05$)	NS	NS	NS	NS	0.36	NS	NS	2.8	3.5	2.1	1.40
SE (±)	0.62	0.34	0.31	0.69	0.11	0.34	0.51	0.87	1.10	0.63	0.42
CV (%)	6.5	2.73	2.24	4.76	4.44	10.9	10.6	2.6	5.1	2.6	1.00

NMC = number of millable canes. In all treatments, the recommended dose of non-K fertilizers was applied. T_1: 0 kg K_2O ha^{-1}; T_2: 80 kg K_2O ha^{-1} as MOP; T_3: 120 kg K_2O ha^{-1} as MOP; T_4: 80 K_2O ha^{-1} as MOP + polyhalite (50% each); T_5: 120 K_2O ha^{-1} as MOP + polyhalite (50% each). Within each column different letters indicate statistical difference.

Relative to the control treatment, the cane germination rate at 35 DAS was higher in T_2 (by 12.7%), in T_3 (by 24.2%), in T_4 (by 33.0%), and in T_5 (by 35.0%; Table 4). Sugarcane stalk length at 113 DAS was not significantly different between the control and all K treatments. Significant differences in stalk length were observed at 127 DAS (stalks in T_3, T_4, and T_5 were significantly higher than those in T_1) and 152 DAS (stalks in T_5 were significantly higher than those in T_1 to T_3), however by 198 DAS there were no significant differences in stalk height between any treatments.

Sugarcane stalk diameter was greater in both T_4 and T_5 than in any of T_1, T_2, or T_3 (Table 4). Differences in stalk diameter were largest at 99 DAS, where the increase above T_1 was up to 13.7% in T_5. At 262 DAS, the greatest increase in stalk diameter above the control treatment was 5.1% in T_5. Across all three growth and yield parameters the differences from the baseline treatment were statistically similar in the T_4 and T_5 treatments, and greater than those in treatments T_1, T_2, or T_3.

There were no significant differences between treatments on the number of internodes per sugarcane stalk or the number of tillers per plant were (Table 5).

In terms of the number of millable canes (NMC) in each experimental treatment, all K treatments had higher NMC than the T_1 control at 334 DAS (Table 5). The MOC-only treatments (T_2 and T_3) had 23–33% more NMC than T_1, while the combined MOC and polyhalite treatments (T_4 and T_5) had 49–53% more NMC than T_1.

Leaf chlorophyll concentration was lower in all K treatments than in the baseline T_1 treatment at 219, 267, and 298 DAS (Table 5). At 298 DAS the leaf chlorophyll concentrations in T_2 (−5.5%), T_3 (−5.3%), and T_5 (−6.4%) were all lower than those in T_1; and the leaf chlorophyll concentration in T_4 (−13.5%) was lower again.

The average yield in the baseline treatment was 68.4 t ha^{-1}: yields in all K treatments were higher than the baseline regardless of K fertilizer type, and ranged between 71.4 t ha^{-1} in T_2 to 75.2 t ha^{-1} in T_5, although there was no significant yield difference between K treatments (Table 5).

3.2. Quality Parameters

At 10 months after sowing, the T_2 and T_4 treatment plots had higher purity (by 2.6 and 3.3%, respectively) than in the T_1 control treatment (Table 6). In contrast, T_3 and T_5 did not differ significantly from T_1 in terms of purity. Pol was statistically similar in the T_1 and T_3 treatments while T_2 (+0.9%), T_4 (+1.1%), and T_5 (+0.8%) had higher pol than in the T_1 control. Similarly, in terms of the commercial cane sugar content (CCS), T_1 and T_3 had comparable CCS percentages (10.56 and 10.91%, respectively), while CCS was higher in T_2 (+0.8%), T_4 (+1.0%), and T_5 (+0.6%). There were no significant differences between any treatments in terms of Brix (which ranged between 18.4° in T_1 to 19.2° in T_5) or the percentage of sugar extracted (which varied between 46.7% in T_3 to 50.1% in T_4). Results across all five quality metrics examined were statistically similar in T_2 and

T_4, which both received 66% of the recommended dose of potassium fertilizer, either as 80 kg MOP ha^{-1} (T_2) or as 40 kg MOP ha^{-1} and 40 kg polyhalite ha^{-1} (T_4). T_3 and T_5, the potassium treatments with the full recommended fertilizer dose (i.e., 120 Kg K ha^{-1}) did not always differ in quality from the control treatment (Table 6).

Table 6. Sugarcane quality parameters 10 months after sowing under potassium fertilizer treatments.

Treatments	Brix (°)	Pol (%)	Purity (%)	CCS (%)	Sugar Extraction (%)
T_1	18.40a	15.59c	84.75c	10.56c	46.99a
T_2	18.83a	16.45ab	87.34ab	11.31ab	48.38a
T_3	18.67a	16.01bc	85.76bc	10.91bc	46.72a
T_4	18.97a	16.70a	88.07a	11.53a	50.10a
T_5	19.17a	16.40ab	85.56c	11.17ab	48.58a
F-test ($p \leq 0.05$)	NS	0.57	1.77	0.45	NS
SE (±)	0.18	0.17	0.53	0.14	1.29
CV (%)	1.66	1.83	1.07	2.13	2.67

CCS = commercial cane sugar content. In all treatments, the recommended dose of non-K fertilizers was applied. T_1: 0 kg K_2O ha^{-1}; T_2: 80 kg K_2O ha^{-1} as MOP; T_3: 120 kg K_2O ha^{-1} as MOP; T_4: 80 K_2O ha^{-1} as MOP + polyhalite (50% each); T_5: 120 K_2O ha^{-1} as MOP + polyhalite (50% each). Within each column different letters indicate statistical difference.

At 12 months after sowing, T_2, T_4, and T_5 all had greater purity (by 2.4%, 2.8%, and 2.0%, respectively) than T_1 or T_3, which were statistically similar (Table 7). In terms of pol, no K treatments differed from the T_1 control, although T_5 (18.9% pol) was significantly greater than any of the T_2 to T_4 treatments (pol range of 18.1 to 18.5%). The CCS percentage was similar in treatments T_1 to T_4 (range between 12.5 and 12.7%) which were all less than the CCS in T_5 (13.1%). When expressed as a weight per area, CCS was significantly higher in both T_4 (9.4 t ha^{-1}) and T_5 (9.8 t ha^{-1}) than in any of T_1 to T_3, which ranged in CCS between 8.6 and 9.2 t ha^{-1}. Only T_2 (20.5°) and T_4 (20.7°) were significantly lower in Brix than in the T_1 control (21.5°). There was no significant difference between treatments in the percentage of sugar extracted, which varied between 48.9% in T_1 to 50.7% in T_4 (Table 7) and which has been previously observed by [44–46]. As at the earlier quality sampling, the T_2 and T_4 treatments, with 80 kg ha^{-1} potassium fertilizer, had greater differences from the T_1 control in terms of the quality parameters examined than was observed in the T_3 and T_5 treatments, which received 120 kg ha^{-1} potassium fertilizer. Other research has reported similar results [47,48].

Table 7. Sugarcane quality parameters 12 months after sowing under potassium fertilizer treatments.

Treatments	Brix (°)	Pol (%)	Purity (%)	CCS (%)	Sugar Extraction (%)	CCS (t ha^{-1})
T_1	21.53a	18.49ab	85.89b	12.62b	48.86a	8.63b
T_2	20.53b	18.13b	88.33a	12.54b	49.04a	8.95b
T_3	21.50a	18.48ab	85.94b	12.61b	49.27a	9.15b
T_4	20.67b	18.33b	88.68a	12.70b	50.70a	9.40a
T_5	21.53a	18.93a	87.91a	13.06a	50.06a	9.75a
F-test ($p \leq 0.05$)	0.67	0.46	1.66	0.33	NS	0.38
SE (±)	0.20	0.14	0.50	0.10	1.00	0.11
CV (%)	1.66	1.31	0.99	1.36	2.49	1.90

CCS = commercial cane sugar content. In all treatments, the recommended dose of non-K fertilizers was applied. T_1: 0 kg K_2O ha^{-1}; T_2: 80 kg K_2O ha^{-1} as MOP; T_3: 120 kg K_2O ha^{-1} as MOP; T_4: 80 K_2O ha^{-1} as MOP + polyhalite (50% each); T_5: 120 K_2O ha^{-1} as MOP + polyhalite (50% each). Within each column different letters indicate statistical difference.

3.3. Insect-Pest Infestation

The incidence of early shoot borer (*Chilo infuscatellus*) was reduced under all potassium treatments relative to the control (Table 8).

Table 8. Insect–pest incidence in sugarcane under potassium fertilizer treatments.

Treatments	Early Shoot Borer	Top Borer	Stalk Borer
T_1	10.3a	11.0a	10.3a
T_2	8.3b	9.33a	8.7a
T_3	8.7b	9.67a	9.0a
T_4	8.3b	8.67a	7.7a
T_5	7.7b	9.33a	9.0a
F-test ($p \leq 0.05$)	1.5	NS	NS
SE (±)	0.45	0.51	0.50
CV (%)	8.90	9.20	9.60

In all treatments, the recommended dose of non-K fertilizers was applied. T_1: 0 kg K_2O ha^{-1}; T_2: 80 kg K_2O ha^{-1} as MOP; T_3: 120 kg K_2O ha^{-1} as MOP; T_4: 80 K_2O ha^{-1} as MOP + polyhalite (50% each); T_5: 120 K_2O ha^{-1} as MOP + polyhalite (50% each). Within each column different letters indicate statistical difference.

Reductions were greatest in T_5 (−25.2%) and least in T_3 (−15.5%). There was no significant difference in the incidence of either top borer (*Scirpophaga excerptalis*) or stalk borer (*Chilo auricilius*) between the control and any potassium treatments, although the incidence of both pests was highest in the control and least in T_4. While there were no significant differences in insect pests between potassium treatments, T_5 had the lowest incidence of early shoot borer, and T_4 had the lowest incidence of both top borer and stalk borer. T_3 had the highest incidence of all three insect pests among the potassium treatments; T_5 also had the highest incidence of stalk borer.

Further, comparing rates of insect pests in T_2 to those in $T_{3,}$ $T_{4,}$ and T_5, there was less (by −4.82, −4.6, and −7.2%, respectively) incidence of early shoot borer (*Chilo infuscatellus*), less (by 0, −7.1, and −11.5%, respectively) incidence of top borer (*Scirpophaga excerptalis*), and less (by −3.3, −11.5 and −16.1%, respectively) incidence of stalk borer (*Chilo auricilius*) (Table 8). The T_4 treatment (80 kg K_2O ha^{-1} as MOP and polyhalite combined) recorded the lowest incidence of insect-pest attacks, although no statistical difference from any other potassium fertilizer treatment was observed.

3.4. Correlation between Quality Variables

Ten months after sowing brix was strongly positively correlated with pol and CCS, moderately positively correlated with the extractable sugar percentage, and weakly positively correlated with purity (Table 9). Pol was strongly correlated with brix, purity and CCS, and moderately positively correlated with the extractable sugar percentage. Purity was strongly positively correlated with pol and CCS, and weekly positively correlated with brix and the extractable sugar percentage, while CCS was strongly positively correlated with brix, pol and purity, and moderately positively correlated with the extractable sugar percentage (Table 9).

Table 9. Correlation analysis of sugarcane quality parameters at eight and ten months after sowing.

10 Months after Sowing					
	Brix	**Pol**	**Purity**	**CCS (%)**	**Sugar Extraction (%)**
Brix		0.83	0.24	0.73	0.47
Pol	0.83		0.74	0.99	0.52
Purity	0.24	0.74		0.83	0.34
CCS (%)	0.73	0.99	0.83		0.51
Sugar extraction (%)	0.47	0.52	0.34	0.51	
12 months after sowing					
	Brix	Pol	Purity	CCS (%)	Sugar extraction (%)
Brix		0.79	−0.73	0.46	0.16
Pol	0.79		−0.15	0.91	0.27
Purity	−0.73	−0.15		0.27	0.04
CCS (%)	0.46	0.91	0.27		0.28
Sugar extraction (%)	0.16	0.27	0.04	0.28	

CCS = commercial cane sugar content.

Twelve months after sowing, brix remained positively correlated with pol, but correlations with other parameters had altered: brix was strongly negatively correlated with purity, moderately positively correlated with CCS, and weakly positively correlated with the extractable sugar percentage (Table 9). Pol remained strongly positively correlated with brix and CCS but was now weakly negatively correlated with purity and weakly positively correlated with the extractable sugar percentage. CCS remained strongly positively correlated with pol, but only moderately positively correlated with brix and was now weakly positively correlated with purity and the extractable sugar percentage.

3.5. Benefit-to-Cost Ratio

The cost of potassium fertilizers was lowest in T_2 (80 kg K ha^{-1}, applied as MOP only) and highest in T_5 (120 kg K ha^{-1}, applied as MOP and polyhalite combined; Table 10). Sugarcane yields were lowest in T_1 (68.4 t ha^{-1}) and highest in T_5 (75.2 t ha^{-1}). The economic benefit from the potassium fertilizer applied was 9331, 13,114, 17,422, and 20,956 INR ha^{-1} for T_2, T_3, T_4, and T_5, respectively.

Table 10. The benefit-to-cost ratio in sugarcane under potassium fertilizer treatments.

Treatments	Cost of K Fertilizer (INR ha^{-1})	Sugarcane Yield (t ha^{-1})	Yield Change from T_1 (t ha^{-1})	Economic Benefit from Applied K (INR ha^{-1})	Benefit-to-Cost Ratio
T_1	0	68.40	0.0	0	0.0
T_2	2533	71.41	3.01	9331	3.68
T_3	3800	72.63	4.23	13,113	3.45
T_4	5542	74.02	5.62	17,422	3.14
T_5	8328	75.16	6.76	20,956	2.52

K = potassium, INR = Indian rupee, sugarcane price: INR 3100 t^{-1}, MOP cost: INR 19,000 t^{-1}, polyhalite cost: 30,000 t^{-1}. In all treatments, the recommended dose of non-K fertilizers was applied. T_1: 0 kg K_2O ha^{-1}; T_2: 80 kg K_2O ha^{-1} as MOP; T_3: 120 kg K_2O ha^{-1} as MOP; T_4: 80 K_2O ha^{-1} as MOP + polyhalite (50% each); T_5: 120 K_2O ha^{-1} as MOP + polyhalite (50% each).

Benefit-to-cost (B:C) ratios were highest in T_2 (3.7) and T_3 (3.5), and lower in T_4 (3.1) and T_5 (2.5). Polyhalite is an effective multi-nutrient fertilizer in soils deficient in both potassium and calcium, however, its higher cost (30,000 INR t^{-1} compared to 19,000 INR t^{-1} for MOP) means that it results in lower immediate economic benefits to farmers (longer-term benefits resulting from improved soil health are outside the scope of this paper). A higher fertilizer application (120 kg K ha^{-1} rather than 80 kg K ha^{-1}), regardless of potassium fertilizer type, did not increase the economic benefits for farmers. This was a consequence of the higher production costs of the higher application of potassium fertilizer, which were exacerbated in the combined MOP and polyhalite treatment (T_5) relative to the sole-MOP treatment (T_3) (Table 10). Rather than increasing economic benefits, treatments with 120 kg ha^{-1} had fewer economic benefits than those at the lower (80 kg ha^{-1}) potassium-fertilizer rate. This may be due to higher insect-pest infestations, limited yield response and increased fertilizer costs when comparing between T_2 and T_3, and T_4 and T_5, respectively (Tables 5 and 8) [9,44–46].

4. Discussion

4.1. Sugarcane Growth and Yield

Improvements relative to the zero-potassium control treatment (T_1) in sugarcane germination, stalk height and stalk width (Table 1), and in the number of nodes per cane, the number of millable canes, and leaf chlorophyll content (Table 2) are likely a result of improved metabolic and physiological processes, including improved photosynthesis, protein synthesis, starch production, and protein and sugar translocation [49]. Additionally, potassium fertilizer has been shown to reduce the adverse effects of water stress and improve root growth [6,9,27]. Potassium fertilizer also catalyzes enzymes and improves water and nutrient use efficiencies [50], in particular the efficient use of N fertilizer, resulting in improved root growth which facilitates improved plant extraction of water and key nutrients [48–53].

The improved sugarcane performance from T_2 (80 kg K ha^{-1} of sole MOP) to T_4 (80 kg K ha^{-1} of MOP and polyhalite) and from T_3 (120 kg K ha^{-1} of sole MOP) to T_5 (120 kg K ha^{-1} MOP and polyhalite) may be a consequence of reduced competition between chloride and sulfate anions for absorption by plant roots in the partial polyhalite treatments [54,55]. Because of the presence of chloride anions and the lack of sulfur in the soil or the MOP fertilizer, this competition may be more severe in MOP-only treatments. In treatments containing polyhalite and MOP, calcium, potassium, and sulfur are all added to the soil, reducing competition from soil chloride ions. As well, potassium in MOP fixes more strongly to clay particles in the soil than does potassium released from polyhalite, due to the competition between monovalent (K^+) and divalent (Ca^{2+}, Mg^{2+}) cations. Managing nutrient availability with times of crop nutrient demand, as well as variability in the availability of calcium affects crop performance, especially in the treatments fertilized with MOP alone [56]. Polyhalite provided a sustainable supply of calcium in the calcium-deficient experimental soil which enhanced sugarcane performance (Table 1) and which has been observed elsewhere [57,58]. The experimental soil was not deficient in magnesium or sulfur, and thus it is likely that the benefits of polyhalite were from the additional calcium provided. Increasing the potassium and calcium available to sugarcane plants extends the shelf life of harvested canes and reduces post-harvest losses [59]. Further, polyhalite is a slow-release fertilizer with a low chloride concentration [59] which reduces the risk of salinity stress and rapid potassium depletion from the rhizosphere.

The benefit-to-cost ratio declined as the amount of potassium fertilizer applied increased from 80 to 120 kg K ha^{-1}: this is due to higher fertilizer costs (Table 10) and lower yields under increased attack by insect pests (Table 8). While polyhalite is initially expensive relative to traditional MOP fertilizer, it provides a lasting contribution to edaphic health and sustainable sugarcane production on potassium- and calcium-deficient soils. Consideration for government subsidies to increase the sustainability of sugarcane production in the region should be considered.

4.2. Sugarcane Juice Quality

Sugarcane quality parameters were higher in the treatment with 80 kg K ha^{-1} applied as MOP and polyhalite in combination than in the treatment with 80 kg K ha^{-1} applied as MOP alone (Tables 6 and 7). This is likely a result of an improved and more sustainable supply of key nutrients (potassium and calcium) by polyhalite which is critical in the nutrient-deficient soils of the experimental site, and which deficiency is widespread throughout the sugarcane-growing region of northern India. K^+ adsorbs less strongly to mineral soil surfaces than Ca^{2+} or Mg^{2+}, and the total adsorption capacity of the soil increases as the clay mineral concentration increases [60,61]. Relative to the control treatment, all potassium treatments had improved sugarcane quality as a result of increases in dry matter accumulation, the number of sprouted buds, the number of millable canes, and in improved root growth [62]. Potassium mitigates the adverse effect of water stress and thus promotes an environment that is more conducive to plant development and biomass accumulation [6,9,49].

4.3. Incidence of Insect Pests

Crop resistance to most pests and diseases improves under balanced plant nutrition because the healthier a plant is the more resilient it is to attack [54,55]. The incidence of three key insect pests in sugarcane, early shoot borer (*Chilo infuscatellus*), top borer (*Scirpophaga excerptalis*) and stalk borer (*Chilo auricilius*), reduced (although not significantly) with sole MOP applied at 80 kg K ha^{-1}, and further reduced with an application at the same rate of MOP and polyhalite combined (Table 8). The potassium fertilizer may have facilitated an improved transfer of photosynthates across the whole plant [38], resulting in comparatively bitter leaves and thereby reducing the incidence of insect–pest attack [6,9,62,63]

5. Conclusions

Nutrients, including potassium, calcium, magnesium, and sulfur, are limiting in agricultural soils in key sugarcane growing regions of the semi-arid tropics including the Indian Punjab, in part due to agricultural intensification over the last three decades. This lack of key nutrients limits sugarcane yield and juice quality. Traditional potassium fertilizers such as MOP are insufficient to overcome these soil nutrient deficiencies. Instead, multi-nutrient fertilizers, such as polyhalite, have the potential to sustainably increase sugarcane growth, yield and quality across the region. We have shown that potassium fertilizer applied as 80 kg K ha^{-1} of MOP alone improved sugarcane growth, yield, and quality parameters relative to a 0 kg K ha^{-1} control treatment and that these benefits were further enhanced when potassium fertilizer was applied at the same rate, but at an equal concentration (i.e., 40 kg K ha^{-1} for each) of MOP and polyhalite. We recommend sugarcane farmers in the potassium- and calcium deficient soils of the Indian Punjab combine MOP and polyhalite equally to achieve an application rate of 80 kg K ha^{-1}, in addition to other fertilizers applied as recommended. Increasing potassium fertilizer applications to 120 kg K ha^{-1} reduced the benefits observed at the lower potassium fertilizer application rate. The benefits of polyhalite combined with MOP are likely to result from the addition of calcium into these calcium-deficient soils. Further, longer-term research is necessary to quantify the optimum amounts of key nutrients, e.g., calcium, magnesium, and sulfur, and to establish precise fertilizer management strategies for different edaphic conditions across the sugarcane production region.

Author Contributions: Conceptualization, R.B., P.S. and A.H.; methodology and visualization, R.B. and P.S.; software, R.B. and A.H.; validation, R.B. and P.S.; formal analysis, R.B., P.S. and A.H.; investigation, R.B. and P.S.; resources, R.B.; data curation, R.B., P.S. and A.H.; writing—original draft preparation, R.B., P.S. and A.H.; writing—review and editing, O.M.A.; A.A.H.A.L.; A.H. and A.M.L.; supervision and project administration, R.B., A.H. and O.M.A.; funding acquisition, R.B., A.H., A.A.H.A.L. and O.M.A. All authors have read and agreed to the published version of the manuscript in 'Sustainability'.

Funding: The current work was financially supported by the Potash Research Institute of India, Gurgaon and International Potash Institute, Switzerland for supporting the project with no. Misc. 168 (PC 5034) entitled, "Assessment of POLYHALITE in improving yield and quality of sugarcane in Punjab, India". The work was also funded by the Taif University Researchers Supporting Project number (TURSP-2020/81), Taif University, Taif, Saudi Arabia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Most of the data are available in all tables and figures of the manuscripts.

Acknowledgments: The authors want to acknowledge the support received from the Potash Research Institute of India, Gurgaon and International Potash Institute, Switzerland for supporting the project with no. Misc. 168 (PC 5034) entitled, "Assessment of POLYHALITE in improving yield and quality of sugarcane in Punjab, India". The authors also extend their appreciation to Taif University for funding the current work through the Taif University Researchers Supporting Project number (TURSP-2020/81), Taif University, Taif, Saudi Arabia.

Conflicts of Interest: Authors declare that there are no conflict of interest in the article.

References

1. Bhatt, R.; Singh, P.; Hussain, A.; Tamsina, J. Rice-wheat system in the north-west Indo-Gangetic Plains of South Asia: Issues and technological interventions for increasing productivity and sustainability. *Paddy Water Environ.* **2021**, *19*, 345–365. [CrossRef]
2. Choudhary, H.R.; Singh, R.K. Effect of sequential application of herbicides on weeds and productivity of spring-planted sugarcane (*Saccharum officinarum* L.). *Int. J. Life Sci.* **2016**, *11*, 687–690.
3. Bhatt, R. Resources management for sustainable sugarcane production. In *Resources Use Efficiency in Agriculture*; Kumar, S., Meena, S.R., Jhariya, K.M., Eds.; Springer: Singapore, 2020; pp. 650–685.
4. O'Hara, I.M.; Edye, L.A.; Doherty, W. Towards a commercial lignocellulosic ethanol industry in Australia: The Mackay renewablebio commodities pilot plant. In Proceedings of the Australian Society of Sugarcane Technologists, Balina, Australia, 5–8 May 2009; Volume 31, pp. 11–17.
5. Singh, J.; Singh, R.D.; Anwar, S.I.; Solomon, S. Alternative sweeteners production from sugarcane in India: Lump sugar (Jaggery). *Sugar Tech.* **2011**, *13*, 366–371. [CrossRef]
6. Bhatt, R.; Singh, P. Sugarcane response to irrigation and potash levels in subtropics. *Agric. Res. J. PAU* **2021**, in press.
7. PAU. *Package of Practices for Crops of Punjab-Kharif*; Punjab Agricultural University: Ludhiana, India, 2021; pp. 55–66.
8. Bhatt, R.; Oliveira, M.W.; Silva, V.S.G. Sugarcane nutrition for food and environmental security. *Brazi. J. Dev.* **2021**, *6*, 64431–64467. [CrossRef]
9. Bhatt, R.; Singh, P.; Ali, O.M.; Latef, A.A.H.A.; Laing, A.M.; Hossain, A. Yield and Quality of Ratoon Sugarcane Are Improved by Applying Potassium under Irrigation to Potassium Deficient Soils. *Agronomy* **2021**, *11*, 1381. [CrossRef]
10. Shukla, S.K.; Solomon, S.; Sharma, L.; Jaiswal, V.P.; Pathak, A.D.; Singh, P. Green technologies for improving cane sugar productivity and sustaining soil fertility in sugarcane-based cropping system. *Sugar Tech* **2019**, *21*, 186–196. [CrossRef]
11. Barber, S.A. *Soil Nutrient Bioavailability: A Mechanical Approach*, 2nd ed.; Wiley: New York, NY, USA, 1995.
12. Bijay-Singh.; Yadvinder-Singh.; Imas, P.; Xie, J. Potassium nutrition of the rice-wheat cropping system. *Adv. Agron.* **2004**, *81*, 203–259.
13. Fageria, N.K.; Baligar, V.C.; Wright, R.J.; Carvalho, J.R.P. Lowland rice response to potassium fertilization and its effect on N and P uptake. *Fertil. Res.* **1990**, *21*, 157–162. [CrossRef]
14. Minerals, S. POLY4 Brochure. Available online: http://www.siriusminerals.com/ (accessed on 21 December 2016).
15. Garnett, S. Potential of polyhalite fertilizers to enhance potato yield and quality in the United Kingdom. *e-ifc Int. Potash Inst.* **2021**, *63*, 18–27.
16. Pavinato, P.S.; Corá, J.E.; Santos, C.; Herrera, A.; Pavuluri, W.F.B.; Pierce, F.J. Sugarcane response to polyhalite fertilizer in Brazilian Oxisols. *Agron. J.* **2020**, *112*, 5264–5278. [CrossRef]
17. Vale, F. Calcium and magnesium movement in soil profile with polyhalite as potassium fertilizer for soybean crop. In Proceedings of the FERTBIO 2016, Goiana, Brazil, 16–20 October 2016.
18. Bhatt, R.; Singh, M. Comparative efficiency of polymer-coated urea for lowland rice in semi-arid tropics. *Commun. Soil Sci. Plant Anal.* **2021**, *52*. [CrossRef]
19. Fraps, G.S. *Availability to Plants to Potash in Polyhalite*; Texas Agricultural Experiments Station Bulletin. No. 449; Texas FARMER Collection: Collegs Station, TX, USA, 1932.
20. Tien, T.M.; Trang, T.T.T.; Ha, P.T.N.; Chien, D.T.; Thai, T.T.; Thang, D.T.; Thu, T.T.M. Polyhalite effects on winter maize crop performance on degraded soil in Northern Vietnam. *e-ifc Int. Potash Inst.* **2020**, *62*, 3–12.
21. Barbarick, K.A. Polyhalite application to sorghum-sudangrass and leaching in soil columns. *Soil Sci.* **1991**, *151*, 159–166. [CrossRef]
22. Zhao, N.; Guo, H.; Suo, J.; Lei, Y.; Li, G.; Imas, P.; Magen, H. Impact of alternative polyhalite fertilizers on 'xu xiang' kiwifruit yield and quality in Shaanxi Province, China. *e-ifc Int. Potash Inst.* **2020**, *62*, 13–23.
23. Sacks, M.; Gantz, S.; Mezuman, U.; Peled, L.; Imas, P. Polyhalite—A multi-nutrient fertilizer preventing ca and mg deficiencies in greenhouse tomatoes under desalinized irrigation water. *e-ifc Int. Potash Inst.* **2017**, *51*, 24–30.
24. Tien, T.M.; Trang, T.T.T.; Ha, P.T.N.; Thu, T.T.M. Effects of polyhalite application on yield and quality of cabbage grown on degraded soils in Northern Vietnam. *e-ifc Int. Potash Inst.* **2021**, *63*, 3–10.
25. Tiwari, D.D.; Pandey, S.B.; Katiyar, N.K. Effects of polyhalite as a fertilizer on yield and quality of the oilseed crops mustard and sesame. *e-ifc Int. Potash Inst.* **2015**, *42*, 10–17.
26. Lewis, T.D.; Hallett, P.D.; Paton, G.I.; Harrold, L. Retention and release of nutrients from polyhalite to soil. *Soil Use Manag.* **2020**, *36*, 117–122. [CrossRef]
27. Bhatt, R.; Singh, P.; Kumar, R. *Assessment of Polyhalite in Improving Yield and Quality of Sugarcane in Punjab, India*; Project submitted to Indian Potash Limited (IPL): Gurgaon, India, 2020.

28. Steward, F.C. Mineral nutrition of plants: Principles and perspectives. *Emanuel Epstein Q. Rev. Biol.* **1974**, *49*, 353–354. [CrossRef]
29. Kirkby, E.A.; Pilbeam, D.J. Calcium as a plant nutrient. *Plant Cell Environ.* **1984**, *7*, 397–405. [CrossRef]
30. White, P.J.; Broadley, M.R. Calcium in Plants. *Ann. Bot.* **2003**, *92*, 487–511. [CrossRef] [PubMed]
31. Monshausen, G.B. Visualizing Ca^{2+} Signatures in Plants. *Curr. Opin. Plant Biol.* **2012**, *15*, 677–682. [CrossRef] [PubMed]
32. Cakmak, I.; Yazici, A.M. Magnesium: A forgotten element in crop production. *Better Crops.* **2010**, *94*, 23–25.
33. Farhat, N.; Elkhouni, A.; Zorrig, W.; Smaoui, A.; Abdelly, C.; Rabhi, M. Effects of Magnesium Deficiency on Photosynthesis and Carbohydrate Partitioning. *Acta Physiol. Plant* **2016**, *38*, 145. [CrossRef]
34. Gransee, A.; Führs, H. Magnesium mobility in soils as a challenge for soil and plant analysis, magnesium fertilization and root uptake under adverse growth conditions. *Plant Soil* **2013**, *368*, 5–21. [CrossRef]
35. Khan, N.A.; Mobin, M.; Samiullah. The influence of gibberellic acid and sulfur fertilization rate on growth and S-use efficiency of mustard (*Brassica juncea*). *Plant Soil* **2005**, *270*, 269–274. [CrossRef]
36. Kovar, J.L.; Grant, C.A. Nutrient cycling in soils: Sulfur. In *Soil Management: Building a Stable Base for Agriculture*; U.S. Department of Agriculture: Lincoln, Nebraska, 2011; pp. 103–115. [CrossRef]
37. Jamal, A.; Moon, Y.S.; Abdin, M.Z. Sulphur—a general overview and interaction with nitrogen. *Aust. J. Crop Sci.* **2010**, *4*, 523–529.
38. Hartt, C.E. Some effects of potassium upon the amounts of protein and amino forms of nitrogen, sugars and enzyme activity of sugarcane. *Plant Physiol.* **1969**, *9*, 452–490. [CrossRef]
39. Quampah, A.; Wang, R.M.; Shamsi, I.H.; Jilani, G.; Zhang, Q.; Hua, S.; Xu, H. Improving water productivity by potassium application in various rice genotypes. *Int. J. Agric. Biol.* **2011**, *13*, 9–17.
40. Bhatt, R.; Sharma, M. *Importance of Soil Testing and Techniques of Soil Sampling*; Chisinau-2068, str. A. Russo 15, of.61; Lap Lambert Academic Publishing: Chișinău, Republic of Moldova, 2014; pp. 1–48. ISBN 978-3-659-53555-0.
41. Meade, G.P.; Chen, J.C.P. *Can Sugar Handbook*, 10th ed.; Wiley-Inter-Science: New York, NY, USA, 1977; p. 405.
42. Kumar, A.; Babar, L.; Mohan, N.; Bansal, S.K. Effect of Potassium Application on Yield, Nutrient Uptake and Quality of Sugarcane and Soil Health. *Indian J. Fertil.* **2019**, *15*, 782–786.
43. Olivoto, T.; Dal'Col Lúcio, A. Metan: An R package for multi-environment trial analysis. *Methods Ecol. Evol.* **2020**, *11*, 783–789. [CrossRef]
44. Filho, J.O. Potassium nutrition of sugarcane. In *Potassium in Agriculture*; Munson, R.D., Ed.; American Society of Agronomy; Crop Science Society of America; Soil Science Society of America: Madison, WI, USA, 1985; pp. 1045–1062.
45. Wood, R.A. The roles of nitrogen, phosphorus and potassium in the production of sugarcane in South Africa. *Fertil. Res.* **1990**, *26*, 87–98. [CrossRef]
46. Chapman, L.S. Long term responses in cane yields and soil analyses from potassium fertilizer. In Proceedings of the 1980 Conference of the Australian Society of Sugar Cane Technologists, Cairns, Australia, 28 April–2 May 1980; pp. 63–68.
47. Sudama, S.; Tiwari, T.N.; Srivastava, R.P.; Singh, G.P.; Singh, S. Effect of potassium on stomatal behaviour, yield and juice quality of sugarcane under moisture stress conditions. *Ind. J. Plant Physiol.* **1998**, *3*, 303–305.
48. Singh, K.D.N.; Mishra, G.K.; Ojha, J.B. Effect of potassium on yield and quality of sugarcane in calciothents. *Ind. Sugar* **1999**, *49*, 499–507.
49. Wood, A.W.; Schroeder, B.L. Potassium: A critical role in sugarcane production, particularly in drought conditions. In Proceedings of the Australian Society of Sugarcane Technologists, Brisbane, Australia, 4–7 May 2004. Available online: http://www.cabdirect.org/abstracts/20043079912.html/ (accessed on 7 May 2020).
50. Korndörfer, G.H.; Oliveira, L.A. Potassium in sugarcane crops. In *Potassium in Brazilian Agriculture*; Yamada, T., Roberts, T.L., Eds.; Esalq/USP: Piracicaba, Brazil, 2005.
51. Schultz, N.; Lima, E.; Pereira, M.G.; Zonta, E. Residual effects of nitrogen, potassium and vinasse, fertilization on cane plant and ratoon harvested with and without straw burning. *Rev. Bras. Ciência Solo* **2010**, *34*, 811–820. [CrossRef]
52. Kwong, K.F. The effects of potassium on growth, development, yield and quality of sugarcane. In *Potassium for Sustainable Crop Production and Food Security, Proceedings of the First National Potash Symposium, Dar es Salaam, Tanzania, 28–29 July 2015*; International Potash Institute: Zug, Switzerland, 2002; pp. 430–444.
53. Ashraf, M.Y.; Hussain, F.; Akhter, J.; Gul, A.; Ross, M.; Ebert, G. Effect of different sources and rates of nitrogen and supra optimal level of potassium fertilization on growth, yield and nutrient uptake by sugarcane. Grown under saline conditions. *Pak. J. Bot.* **2008**, *40*, 1521–1531.
54. Huber, D.; Römheld, V.; Weinmann, M. Relationship between Nutrition, Plant Diseases and Pests. In *Marschner's Mineral Nutrition of Higher Plants*; Academic Press: Cambridge, MA, USA, 2012; pp. 283–298.
55. Dordas, C. Role of nutrients in controlling plant diseases in sustainable agriculture: A review. *Agron. Sustain. Dev.* **2008**, *28*, 33–46. [CrossRef]
56. Pavuluri, K.; Malley, Z.; Mzimbiri, M.K.; Lewis, T.D.; Meakin, R. Evaluation of polyhalite in comparison to muriate for corn grain yield in the Southern Highlands of Tanzania. *Afr. J. Agron.* **2017**, *5*, 325–332.
57. Smith, G.S.; Clark, C.J.; Henderson, H.V. Seasonal Accumulation of Mineral Nutrients by Kiwifruit I. Leaves. *New Phytol.* **1987**, *106*, 81–100. [CrossRef]
58. Clark, C.J.; Smith, G.S. Seasonal accumulation of mineral nutrients by kiwifruit 2. fruit. *New Phytol.* **1988**, *108*, 399–409. [CrossRef]
59. Yermiyahu, U.; Zipori, I.; Omer, C.; Beer, Y. Solubility of granular polyhalite under laboratory and field conditions. *Electron. Int. Fertil. Corresp. e-ifc* **2019**, *58*, 3–9.

60. Mengel, K.; Haeder, H.E. Effect of potassium supply on the rates of phloem sap exudation and the composition of phloem sap of Ricinis communis. *Plant Physiol.* **1977**, *59*, 282–284. [CrossRef] [PubMed]
61. Rabindra, B.; Kumaraswamy, S. Potash and eye spot disease in sugarcane. *Ind. Potash J.* **1978**, *3*, 15–18.
62. Elwan, E.A.; Abazied, A.A.; Youssef, L.A.; Sakr, H.E.A. Influence of some agricultural practices on the infestation with lesser sugarcane borer, Chilo agamemnon Bles. in the autumn plant cane and its 1st ratoon in upper Egypt. *Egypt. J. Agric. Res.* **2008**, *86*, 1801–1826.
63. Shukla, S.K.; Yadav, R.L.; Singh, P.N.; Singh, I. Potassium nutrition for improving stubble bud sprouting, dry matter partitioning, nutrient uptake and winter initiated sugarcane (*Saccharum* spp. hybrid complex) ratoon yield. *Eur. J. Agron.* **2009**, *30*, 27–33. [CrossRef]