agronomy

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Potassium and Water-Deficient Conditions Influence the Growth, Yield and Quality of Ratoon Sugarcane (*Saccharum officinarum* L.) in a Semi-Arid Agroecosystem

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Citation: Bhatt, R.; Singh, J.; Laing, A.M.; Meena, R.S.; Alsanie, W.F.; Gaber, A.; Hossain, A. Potassium and Water-Deficient Conditions Influence the Growth, Yield and Quality of Ratoon Sugarcane (*Saccharum officinarum* L.) in a Semi-Arid Agroecosystem. *Agronomy* **2021**, *11*, 2257. https://doi.org/10.3390/agronomy11112257

Academic Editors: Umberto Anastasi and Aurelio Scavo

Received: 11 September 2021
Accepted: 3 November 2021
Published: 8 November 2021

Abstract: Groundwater and soil potassium deficiencies are present in northern India. Sugarcane is a vital crop in the Indian Punjab; it is grown on approximately 91,000 hectares with an average yield of 80 tonnes ha^{-1} and a sugar recovery rate of 9.59%. The role of potassium (K) fertilizer under both sufficient and deficient irrigation in ratoon sugarcane crops is not well documented. We conducted a split-plot ratoon cane experiment during 2020–2021 at the Gurdaspur Regional Research Station of Punjab Agricultural University, India, on K-deficient soils. Main treatments were fully irrigated (I_1) and water stressed (I_0) conditions, with sub-treatments reflecting K fertilizer application rates of 0 (M_1), 67 (M_2), 133 (M_3), and 200 (M_4) kg K ha^{-1}. The ratoon sugarcane performance was assessed in terms of growth, productivity, sugar quality and incidence of key insect pests. At harvest, trends in the growth and yield parameters in I_1 were improved over the I_0 treatment, with cane height (+12.2%), diameter (+3.3%), number of internodes (+5.4%), biomass yield (+7.6%) and cane yield (+5.9%) all higher, although little significant difference was observed between treatments. Ratoon cane yield under irrigation was 57.1 tonnes ha^{-1}; in water-stressed conditions, it was 54.7 tonnes ha^{-1}. In terms of sugarcane quality parameters, measured 12 months after harvesting the initial seed crop, values of Brix (+3.6%), pol (+3.9%), commercial cane sugar percentage (+4.0%) and extractable sugar percentage (+2.8%) were all higher in the irrigated treatments than the water-stressed plot. Irrigated treatments also had a significantly lower incidence of two key insect pests: top borer (*Scirpophaga excerptalis*) was reduced by 18.5% and stalk borer (*Chilo auricilius*) by 21.7%. The M_3 and M_4 treatments resulted in the highest cane yield and lowest incidence of insect pests compared to other K-fertilizer treatments. Economic return on K-fertilizer application increased with increasing fertilizer dosage. Under the potassium-deficient water-stressed conditions of the region of north India, a fertilizer application rate of 133 kg K ha^{-1} is recommended to improve ratoon sugarcane growth, yield, and quality parameters and economic returns for sugarcane farmers.

Keywords: water stress; potassium fertilizer; Brix; sugarcane yield; insect-pest incidence

1. Introduction

The increase in intensive agricultural practices in northern India (i.e., Punjab, Haryana) over recent decades, combined with conventional crop establishment and irrigation methods, has resulted in the lowering of the underground water table and an increase in water-deficient conditions in which farmers produce crops [1–3]. Sugarcane (*Saccharum* spp. complex) is a commercially viable crop which is cultivated not only for edible-sugar products but also as a source of biomass for bioelectricity and second-generation bioethanol. Water stress has a negative impact on sugarcane development and productivity. Improving sugarcane survival and growth rates during periods of water stress is important to achieve sustainable agronomic production in northern India. Sugarcane quality and performance under water stress can be measured in terms of crop water use efficiency (WUE) [3]. Sugarcane plants have evolved a variety of molecular processes which limit the use of resources such as water and which regulate plant development in response to environmental conditions [4,5]. Water stress reduces the leaf-water potential and stomatal openings, resulting in down-regulation of photosynthesis-related genes and lower plant-CO_2 availability [6]. Stress responses involve several molecular networks including signal transduction [7–10]. Improved methods must be developed, tested, and recommended to farmers to reduce sugarcane WUE while improving plant quality and productivity.

Sugarcane is cultivated in north India under sub-tropical conditions. It is an important industrial and food crop with high sugar concentration, and it is extensively used commercially, e.g., as a source of ethanol to blend with petrol [11–13]. Average sugarcane production across the whole of India was around 362 M tonnes with productivity of 71.5 tonnes ha^{-1}. In the Indian Punjab, sugarcane is grown on 91,000 hectares with an average yield of 80.35 tonnes ha^{-1}, and a sugar recovery rate of 9.6%, similar to the national average but lower than that achieved in nearby states where more potassium fertilizer is applied [14].

To sustainably cultivate sugarcane, judicious use of nutrients is necessary as under-application may lead to significant yield and quality loss, as well as depleting the soil [13,15]. It is estimated that for every 100 tonnes of sugarcane produced, key nutrient requirements (i.e., those taken up by 100 tonnes of cane) are: nitrogen (N) 208 kg ha^{-1}, phosphorus (P) 53 kg ha^{-1}, potassium (K) 280 kg ha^{-1}, sulphur (S) 30 kg ha^{-1}, iron (Fe) 3.4 kg ha^{-1}, manganese (Mn) 1.2 kg ha^{-1}, and copper (Cu) 0.6 kg ha^{-1} [12]. While sugarcane K requirements are high (above those of N and P), in practice, little K is applied, even in K-deficient soils [16]. Potassium is an essential plant nutrient which improves plant nutrition and metabolism, N- and water-use efficiencies, root growth, and which regulates the opening of leaf stomata, particularly under water-stressed conditions [17,18]. Additionally, K aids in the functioning of plant enzymes, acting as a catalyst for the activation of around 60 [19–21]. K is also involved in seed germination, transport of photosynthate from leaves to rest plant [22–26], maintaining a balance of cations and anions within plant parts, protein synthesis, photosynthesis, energy transfer [16,27,28], and stress resistance [8,17,18]. K also interacts with other plant nutrients such as N to enhance their use efficiencies and reduce overall cultivation costs of sugarcane cultivation [28–32].

In northern India, sugarcane is grown from seed, and the initial harvest is called the "seed crop". Crops are not destroyed at this first harvest; instead, the sugarcane plant is managed to produce a subsequent "ratoon crop," which improves the economics of sugarcane production. Production costs are lower in ratoon crops than in seed crops, as the costs of land preparation and crop establishment are eliminated [12,13]. Furthermore, early tissue drying and nitrogen flushing mean that the ratoon crop is harvested over a longer window, extending the crushing schedule of sugar factories [33]. Yields of the ratoon crop are lower than those of the seed crop; this may be a result of increased bulk density [13,34,35], poor fertilizer use [14,36], and/or increased incidence of pests and diseases. Other factors which contribute to low ratoon-crop yields are a poor choice of cultivar, low air temperatures, poor quality irrigation water, and weed competition [37]. The relatively lower air temperature of northern India reduces the number of shoots that resprout after the harvest of the seed crop. Previous recommendations to increase the yields of ratoon sugarcane crops in northern India have included mulching the bare soil surface between plants with crop residues or intercropping short-duration vegetable or pulse crops between cane rows, but little success has been observed in reducing yield gaps [15,38,39].

Sugarcane plants have relatively high nutritional requirements [40], and a shortage in any one key nutrient can adversely affect plant performance in terms of productivity and cane juice quality [13]. It is important to maintain a balanced application of nutrients to the cane across both seed and ratoon crops [40]. K fertilizer application in K-deficient soils improves plant performance and reduces water, nutrient, and pesticide footprints by improving input use efficiency. Hence, for water- and K-deficient soils, quantifying the appropriate application rate of K fertilizer is important to ensure the sustainability of sugarcane production, and particularly of ratoon sugarcane production.

Given its importance in sugarcane production, applications of between 60 and 120 kg ha^{-1} K are recommended [41–43]. However, at some K-deficient sites, deficits of up to700 kg ha^{-1} have been recorded [38,44]. There are currently no standardized recommendations for K fertilizer application in north India, even on known K-deficient soils [13,15]. As groundwater levels in the region have also been observed to be low [1,2], the role of K fertilizer in K-deficient and water-stressed conditions is worthy of investigation. We conducted an experiment at the Gurdaspur Regional Research Station of Punjab Agricultural University during 2020–2021 on a ratoon sugarcane crop. Our objectives were to (1) identify standardized K-fertilizer recommendations in low K soils under water-stressed conditions to achieve improved ratoon-crop growth, yield and quality; (2) identify the optimal K-fertilizer dosage to reduce the incidence of insect pests; and (3) to calculate the benefit-to-cost ratio of K-fertilizer treatments.

Hypothesis: Judicious use of K fertilizer under I_1 and I_0 plots at deficient sites (<137.5 kg K_2O ha^{-1}) resulted in significantly lesser insect-pest incidence, and higher growth, yield and quality parameters which further add to the livelihoods of the cane farmers of the region.

2. Material and Methods

2.1. Experiment Location and Inherent Soil Fertility

The experiment was conducted between March 2020 and March 2021 at the Gurdaspur Regional Research Station of Punjab Agricultural University (PAU), India, in a split-plot design with irrigation as the main treatment and sub-treatments of different rates of K-fertilizer. The experimental site was located at 32°49.383′ N and 75°42.588′ E, at an elevation of 225 m. The soil was sandy loam in texture, with a neutral (7.3) pH, an EC of 0.045 dS m^{-1}, moderate soil organic carbon (0.65%), and relatively high in available phosphorus (26.5 kg P ha^{-1}) and low in available potassium (97.5 kg K ha^{-1}) using ammonium acetate method (using flame photometer), as previously reported [14,40]. The threshold value is 137.5 kg K_2O ha^{-1}. Further, soil bulk density was 1.62 g per cm^3 at the surface 0–15 cm.

2.2. Weather during the Experiment

A meteorological station at the site recorded daily maximum and minimum temperature, class A pan evaporation, and rainfall. During the experimental period 822.4 mm rain was received, evaporation 1419.3 mm, average maximum air temperature ranged between 17.1 to 35.9 °C, and average minimum air temperature between 7.4 and 25.7 °C (Figure 1).

2.3. Experimental Treatments and Recorded Observations

The experiment was a split-plot design, with irrigation level as the main treatment and applications of muriate of potassium fertilizer in the sub-plots. There were 24 treatment plots: (a) in 12 of these plots were water-stressed and (b) in 12 plots received the standard irrigation for sugarcane in this region. In both the water-stressed and unstressed plots, there were three replicates of four potassium-fertilizer treatments viz., 0, 40, 80, and 120 kg K ha^{-1}. Irrigation was either applied fully (I_1) or to achieve water-stressed plants (I_0). In the fully irrigated plots, sufficient water was applied throughout the experimental period to ensure it was non-limiting to ratoon-crop growth; however, if more than 20 mm rain was received in any 24 hours, irrigation was suspended. In the water-stressed plots, irrigation ceased at the key sugarcane growth stages of germination, tillering, and grand growth after three weeks. Sub-plots treatments were: 0 kg ha^{-1} K fertilizer (M_1), 67 kg ha^{-1} K fertilizer (M_2), 133 kg ha^{-1} (M_3) and 200 kg ha^{-1} K fertilizer (M_4). Excepting water and K fertilizer management, all other sugarcane agronomic practices followed the recommendations of PAU, Ludhiana [14].

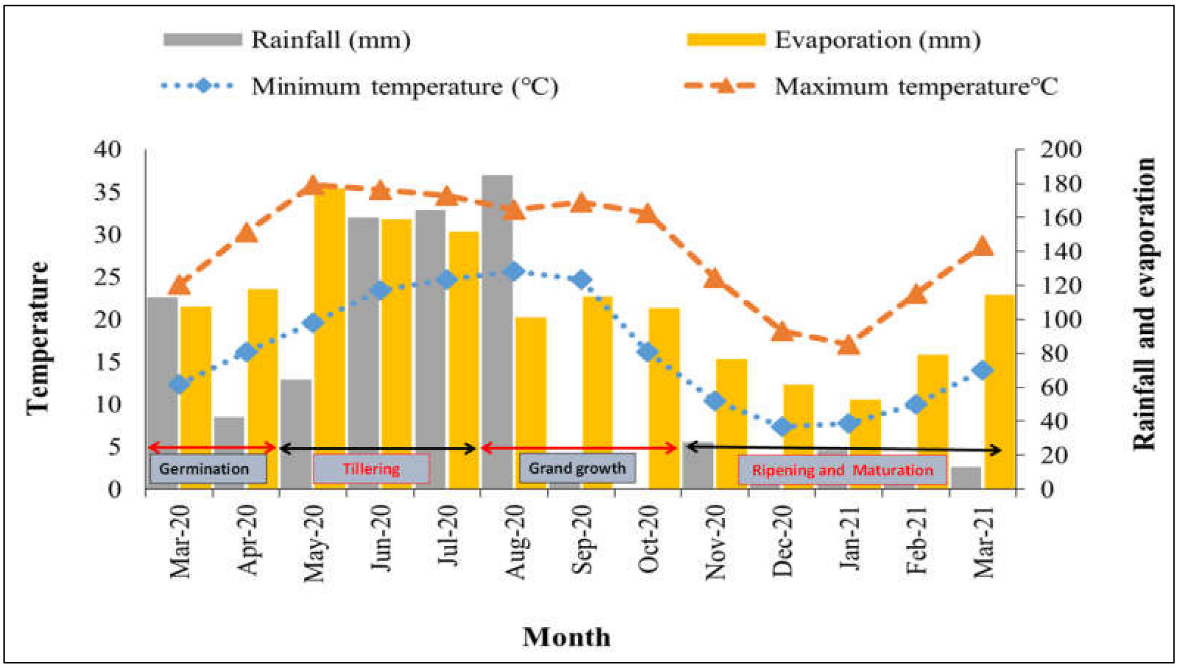

Figure 1. Weather conditions at the Gurdaspur Regional Research Station from March 2020 to March 2021.

The experimental treatments were applied to a ratoon crop of the sugarcane cultivar CoPb 91, which was planted at 75 cm inter-row spacing in 6 m long and 4.5 m broad plots following the harvesting of the seed crop on 15 March 2020. There were three replications of each treatment and sub-treatment plot.

Five canes were tagged in each experimental plot. Measurements of sugarcane growth were taken from these five canes of the number of resprouted canes (at 35 DAH, days after harvesting), average cane height (at 116, 155, 178, 200, 277, and 312 DAH), average cane stalk diameter in the middle of the stalk, the number of nodes per cane. Measurements of sugarcane quality (Brix, pol, percentage purity, extraction percentage, and commercial cane sugar (CCS) as both a percentage and a weight per hectare) were recorded from ten representative, pest- and disease-free, canes from each experimental plot 10 and 12 months after the harvest of the seed crop, on 13 November 2020 and 26 February 2021, respectively, following standard experimental protocols [13,15]. Sugarcane juice was extracted from the harvested canes using a cane crusher to assess Brix and other quality metrics, using standard protocols [41]. At maturity, the number of millable canes in each 27 m^2 plot was manually counted and each plot was manually harvested and processed to record final yield and biomass data in tonnes per hectare.

The presence of early shoot borer (*Chilo infuscatellus)* was manually observed and recorded at 65 DAH. The incidence of two other critical sugarcane pests, stalk borer (*Chilo auricilius*) and top borer (*Scirpophaga excerptalis*), was manually observed and recorded when the ratoon crop was harvested.

2.4. Calculations

The commercial cane sugar (CCS) percentage was calculated using Equation (1):

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

where, 0.4 is the multiplication factor and 0.74 is the crusher factor.

A weight-per-area CCS was determined using Equation (2), as reported in [29,45]:

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

The benefit-to-cost (B:C) ratio of additional applied K fertilizer in the ratoon canes was calculated using Equation (3), as reported by [15] and [31]:

$$\text{B:C} = \text{Value of sugarcane yield (Rs ha}^{-1})/\text{Cost of K fertilizer (Rs ha}^{-1}) \quad (3)$$

where, the cost of muriate of potassium fertilizer was 19,000 INR t^{-1} and the value of the sugarcane yield was the amount of sugarcane produced (tonnes ha^{-1}) multiplied by the sugarcane price, 2950 INR t^{-1}. The B:C ratio is dimensionless.

2.5. Statistical Analysis

Pooled data for the main and sub-plot treatments and their interactions were subjected to analysis of variance (ANOVA) using the STAR (Statistical Tool for Agricultural Research) software package. Statistical significance was inferred at $p \leq 0.05$. The cane growth, yield, and quality data were analysed as per the procedure given by Gomez and Gomez for split-plot design using OPSTAT program developed by Chaudhary Charan Singh Haryana Agricultural University, Hisar, India. R software [46] was used to investigate correlations between the different quality attributes.

3. Results

3.1. Ratoon Crop Productivity

The fully irrigated (I_1) plot fertilized with 133 kg K ha^{-1} (M_3) had more resprouted canes, more millable canes, greater cane length and diameter, more leaves, and higher Brix, yield and biomass (Table 1).

Table 1. Average sugarcane height under irrigation and potassium treatments.

Treatments	Cane Height (cm) at DAH					
	116	155	178	200	277	312
Irrigation treatment						
I_1	68.9 ^{a}	155.5 ^{a}	206.6 ^{a}	221.7 ^{a}	248.0 ^{a}	261.5 ^{a}
I_0	60.9 ^{b}	137.3 ^{b}	183.1 ^{a}	198.3 ^{a}	228.2 ^{b}	233.1 ^{a}
Significance level ($p \leq 0.05$)	**	**	SS	SS	**	NS
CV (%)	6.7	3.2	9.2	9.3	2.5	10.0
Potassium fertilizer treatment						
M_1	62.0 ^{a}	142.0 ^{a}	186.5 ^{a}	208.8 ^{b}	215.3 ^{c}	217.5 ^{c}
M_2	64.9 ^{a}	145.8 ^{a}	194.3 ^{a}	227.5 ^{ab}	233.3 ^{bc}	234.7 ^{bc}
M_3	65.5 ^{a}	147.8 ^{a}	197.0 ^{a}	239.5 ^{a}	248.0 ^{ab}	254.2 ^{ab}
M_4	66.7 ^{a}	150.0 ^{a}	201.5 ^{a}	246.7 ^{a}	260.3 ^{a}	260.0 $_a$
Significance level ($p \leq 0.05$)	SS	SS	SS	**	**	**
CV (%)	7.9	9.9	7.7	6.6	8.9	7.4
I × M	SS	SS	SS	SS	SS	SS

DAH, days after harvesting the initial seed crop of sugarcane; main plot treatments are I_1 (fully irrigated) and I_0 (water-stressed); subplot treatments are M_1 (0 kg K ha^{-1}), M_2 (67 kg K ha^{-1}), M_3 (133 kg K ha^{-1}), and M_4 (200 kg K ha^{-1}); CV, coefficient of variation; ** denotes significance at $p \leq 0.05$; SS, statistically similar. The superscript similar letter within a continuous column indicates no statistical difference while different letters denote significant differences at $p \leq 0.05$.

Average sugarcane height was significantly higher in this treatment than in the treatment with the same K fertilizer but with water stress (i.e., I_0 M_3); by 9.4% at 116 DAH, by 7.6% at 155 DAH, and by 12.2% at 312 DAH. There was no significant difference in average cane height between the zero-K control treatment (M_1) and plots where K fertilizer was applied at 116, 155 or 178 DAH. From 200 DAH onwards, there were clear differences between treatments, and by harvest (312 DAH) cane height was highest (19.5% above M_1) in M_4, and 7.9% to 16.9% higher in M_2 and M_3, respectively (Table 1). Further, I_1 plots had significantly higher cane height at 116, 155 and 277 DAH as compared to I_0 plots.

Average cane diameter did not differ significantly between irrigation treatments for most of the ratoon crop growing season, although greater measurements were recorded in the fully irrigated I_1 treatment (Table 2). Relative to the M_1 treatment average cane diameter differed from 237 DAH in the M_4 treatment; cane diameter in the M_2 and M_3 treatments was not always significantly different from the control treatment. At harvest, the average cane diameter in the M_4 treatment was 11.3% greater than in the M_1 treatment. There was no statistical difference in the number of leaves per plant between the irrigation treatments, nor between the K-fertilizer treatments, at any time from harvesting the seed crop to harvesting the ratoon crop (Table 2).

Table 2. Average sugarcane diameter and number of leaves under irrigation and potassium treatments.

Treatments	Cane Diameter (cm) at DAH				Leaves per Plant at DAH	
	200	237	277	312	200	237
	Irrigation treatment					
I_1	28.6 ^{a}	28.1 ^{a}	28.9 ^{a}	28.5 ^{a}	9.6 ^{a}	16.7 ^{a}
I_0	28.5 ^{a}	27.9 $_b$	28.2 ^{a}	27.6 ^{a}	9.4 ^{a}	15.6 ^{a}
F-test ($p \leq 0.05$)	SS	**	SS	SS	SS	SS
CV (%)	10.6	5.6	3.1	5.4	9.4	10.4
	Potassium fertilizer treatment					
M_1	27.8 ^{a}	26.6 ^{c}	27.4 -	26.5 ^{b}	9.3 ^{a}	15.3 ^{a}
M_2	28.5 ^{a}	27.5 ^{bc}	28.3 ^{ab}	27.7 ^{ab}	9.4 ^{a}	15.6 ^{a}
M_3	28.8 ^{a}	28.4 ^{ab}	29.2 ^{a}	28.4 ^{ab}	9.6 ^{a}	16.5 ^{a}
M_4	29.3 ^{a}	29.4 ^{a}	29.6 ^{a}	29.5 ^{a}	9.8 ^{a}	16.9 ^{a}
F-test ($p \leq 0.05$)	SS	**	**	**	SS	**
CV (%)	5.5	4.4	4.4	5.5	8.0	5.3
I × M	SS	SS	SS	SS	SS	SS

DAH, days after harvesting the initial seed crop of sugarcane; main plot treatments are I_1 (fully irrigated) and I_0 (water-stressed); subplot treatments are M_1 (0 kg K ha^{-1}), M_2 (67 kg K ha^{-1}), M_3 (133 kg K ha^{-1}), and M_4 (200 kg K ha^{-1}); CV, coefficient of variation; ** denotes significance at $p \leq 0.05$; SS, statistically similar. The superscript similar letter within a continuous column indicates no statistical difference while different letters denote significant differences at $p \leq 0.05$.

There were no statistical differences between irrigation treatments in the average number of internodes per plant or in the average Brix at any time during the ratoon crop growing season, although internodes were lower and Brix higher in the fully irrigated treatment (Table 3). Relative to the M_1 control, the M_4 fertilizer treatment had 12.5% and 12.0% more internodes at 200 and 237 DAH; however, at later samplings (277 and 312 DAH), there was no significant difference in the number of internodes per plant between any K-fertilizer treatments. There were no significant differences in Brix between any K-fertilizer treatments, although trends suggested that higher Brix was associated with greater K-fertilizer application.

Table 3. Average number of internodes per plant and average Brix under irrigation and potassium treatments.

Treatments	Internodes per Plant at DAH				Brix at DAH	
	200	237	277	312	277	312
			Irrigation treatment			
I_1	9.5 [a]	12.8 [a]	10.7 [a]	13.9 [a]	20.5 [a]	20.8 [a]
I_o	10.8 [a]	13.5 [a]	10.7 [a]	14.7 [a]	20.3 [a]	19.5 [a]
F-test ($p \leq 0.05$)	SS	SS	SS	SS	SS	SS
CV (%)	7.2	11.2	8.7	3.9	8.3	7.7
			Potassium fertilizer treatment			
M_1	9.6 [b]	12.5 [b]	10.1 [a]	12.7 [a]	19.5 [a]	18.1 [a]
M_2	9.9 [b]	12.7 [b]	10.5 [a]	14.5 [a]	20.0 [a]	19.5 [a]
M_3	10.3 [b]	13.5 [ab]	10.9 [a]	14.8 [a]	20.7 [a]	21.0 [a]
M_4	10.8 [a]	14.0 [a]	11.4 [a]	15.2 [a]	21.2 [a]	21.9 [a]
F-test ($p \leq 0.05$)	**	**	SS	**	NS	NS
CV (%)	6.6	6.5	8.5	5.6	14.7	11.7
I × M	SS	SS	SS	SS	SS	SS

DAH, days after harvesting the initial seed crop of sugarcane; main plot treatments are I_1 (fully irrigated) and I_0 (water-stressed); subplot treatments are M_1 (0 kg K ha^{-1}), M_2 (67 kg K ha^{-1}), M_3 (133 kg K ha^{-1}), and M_4 (200 kg K ha^{-1}); CV, coefficient of variation; ** denotes significance at $p \leq 0.05$; SS, statistically similar. The superscript similar letter within a continuous column indicates no statistical difference while different letters denote significant differences at $p \leq 0.05$.

There were no significant differences between irrigation treatments in terms of the number of resprouted shoots in the ratoon crop, the number of millable canes, or in the sugarcane biomass and yield at harvest, although in all parameters, observations were more favourable in the fully irrigated treatment (Table 4). Similarly, there were no significant differences in these parameters between any of the K-fertilizer treatments, although trends suggested improved outcomes with increasing K fertilizer application, with the greatest resprouted shoots (52.3%), number of millable canes (60,000 ha^{-1}), biomass yield (10.9 tonnes ha^{-1}) and cane yield (61.0 tonnes ha^{-1}) in the M_4 treatment.

Table 4. Sugarcane resprouting percentage, number of millable canes, and biomass and cane yields under irrigation and potassium treatments.

Treatments	Resprouted Ratoon 35 DAH (%)	NMC (000/ha)	Biomass Yield (t ha^{-1})	Cane Yield (t ha^{-1})
		Irrigation treatment		
I_1	40.1 [a]	55.4 [a]	10.53 [a]	57.1 [a]
I_0	37.1 [a]	47.2 [a]	9.79 [a]	54.7 [a]
F-test ($p \leq 0.05$)	SS	SS	SS	SS
CV (%)	14.6	7.6	5.0	3.5
		Potassium fertilizer treatment		
M_1	32.7 [a]	47.9 [a]	9.32 [a]	50.8 [b]
M_2	36.6 [a]	48.4 [a]	10.15 [a]	53.8 [b]
M_3	50.5 [a]	59.9 [a]	10.28 [a]	58.1 [a]
M_4	52.3 [a]	60.0 [a]	10.88 [a]	61.0 [a]
F-test ($p \leq 0.05$)	SS	SS	SS	**
CV (%)	10.6	8.7	8.8	6.2
I × M	SS	SS	SS	SS

DAH, days after harvesting the initial seed crop of sugarcane; NMC, number of millable canes; main plot treatments are I_1 (fully irrigated) and I_0 (water-stressed); subplot treatments are M_1 (0 kg K ha^{-1}), M_2 (67 kg K ha^{-1}), M_3 (133 kg K ha^{-1}), and M_4 (200 kg K ha^{-1}); CV, coefficient of variation; ** denotes significance at $p \leq 0.05$; SS, statistically similar. The superscript similar letter within a continuous column indicates no statistical difference while different letters denote significant differences at $p \leq 0.05$.

3.2. Insect Pest Occurrence

Under fully irrigated conditions, there was a significantly lower incidence of top borer (−18%) and stalk borer (−29%) than under water-stressed conditions, and no difference in the incidence of shoot borer (Table 5).

Table 5. The average incidence of key insect pests under irrigation and potassium treatments.

Treatments	Shoot Borer (%)	Top Borer (%)	Stalk Borer (%)
Irrigation treatment			
I_1	6.3 ^{a}	7.1 ^{b}	6.6 ^{b}
I_0	7.7 ^{a}	8.4 ^{a}	8.5 ^{a}
F-test ($p \leq 0.05$)	SS	**	**
CV (%)	5.2	8.6	3.7
Potassium fertilizer treatment			
M_1	7.7 ^{a}	8.3 ^{a}	8.2 ^{a}
M_2	6.8 ^{a}	7.7 ^{ab}	7.2 ^{a}
M_3	6.3 ^{a}	7.0 ^{b}	7.2 ^{a}
M_4	7.2 ^{a}	8.0 ^{a}	7.6 ^{a}
F-test ($p \leq 0.05$)	SS	**	SS
CV (%)	7.6	9.2	12.3
I × M	SS	SS	SS

Main plot treatments are I_1 (fully irrigated) and I_0 (water-stressed); subplot treatments are M_1 (0 kg K ha^{-1}), M_2 (67 kg K ha^{-1}), M_3 (133 kg K ha^{-1}), and M_4 (200 kg K ha^{-1}); CV, coefficient of variation; ** denotes significance at $p \leq 0.05$; SS, statistically similar. The superscript similar letter within a continuous column indicates no statistical difference while different letters denote significant differences at $p \leq 0.05$.

Under different K-fertilizer treatments, there was no significant difference in the incidence of shoot borer or stalk borer, although the trend was for higher levels of both pests under the M_1 (0 kg K ha^{-1}) treatment, and the M_2 (67 kg K ha^{-1}) and M_3 (133 kg K ha^{-1}) treatments had the lowest incidence of both shoot borer and stalk borer. The M_3 treatment had 15.6% less incidence of top borer than the M_1 treatment, while the M_1, M_2 and M_4 treatments did not differ significantly.

3.3. Ratoon Crop Quality

Irrigation treatment did not affect the Brix, purity, commercial cane sugar, or extractable sugar percentage at either 10 or 12 months after harvesting the seed crop (Tables 6 and 7). Pol was 4.1% higher in the fully irrigated (I_1) treatment 10 months after harvesting the seed crop, but this difference was no longer significant two months later. At 10 months after harvesting the seed crop, there was no significant difference in Brix between any irrigation treatment; however, two months later, the K-fertilized treatments had 4.5% (M_2), 7.5% (M_3) and 9.0% (M_4) higher Brix than the M_1 control treatment (Tables 6 and 7).

Similarly, at 10 months after seed crop harvest, the pol percentage was 5.5% higher in M_3 and M_4 than in M_1; at 12 months after seed crop harvest, the pol percentages were 7.1% and 9.8% higher in M_3 and M_4, respectively, than in M_1. The extractable sugar percentage was higher than M_1 in M_3 (+10.9%) and M_4 (+14.3%) 10 months after seed crop harvest; two months later, there was no significant difference between M_1, M_2, or M_3, while the extractable sugar percentage in M_4 was 11.3% higher than in M_1. The commercial cane sugar percentage was 4.5% to 9.0% higher than the control in all K-fertilizer treatments at 10 months after harvesting the seed crop; two months later there was no significant difference between CCS in M_1 and M_2, while M_3 (+7.0%) and M_4 (+10.0%) were higher than M_1. In the weight-per-area, CCS data, M_3 (+20.7%) and M_4 (+29.3%) were higher than the M_1 control at 10 months after harvesting the seed crop. Two months later, all K-fertilized treatments were higher than the control, by 10.5% (M_2), 23.1% (M_3), and 32.3% (M_4). There were no significant differences in purity between any fertilizer treatments at either sampling interval (Tables 6 and 7).

Table 6. Average sugarcane quality parameters 10 months after harvesting the seed crop under irrigation and potassium treatments.

Treatments	Average Sugarcane Quality Parameters 10 Months After Harvesting					
	Brix (º)	Pol (%)	Purity (%)	CCS (%)	Extraction (%)	CCS (Tonnes ha^{-1})
Irrigation treatment						
I_1	18.8 ^{a}	17.2 ^{a}	91.7 ^{a}	12.1 ^{a}	53.5 ^{a}	6.8 ^{a}
I_0	18.0 ^{a}	16.5 ^{b}	89.7 ^{a}	11.6 ^{a}	52.8 ^{a}	6.4 ^{a}
F-test ($p \leq 0.05$)	SS	**	SS	SS	SS	SS
CV (%)	4.6	1.0	4.6	3.4	6.7	7.4
Potassium fertilizer treatment						
M_1	17.5 ^{a}	16.3 ^{c}	89.2 ^{a}	11.1 ^{c}	49.6 ^{b}	5.8 ^{b}
M_2	18.2 ^{a}	16.6 ^{b}	91.4 ^{a}	11.6 ^{b}	53.2 ^{ab}	6.3 ^{b}
M_3	18.7 ^{a}	17.1 ^{a}	91.3 ^{a}	12.0 ^{ab}	55.0 ^{a}	7.0 ^{a}
M_4	19.1 ^{a}	17.3 ^{a}	90.8 ^{a}	12.1 ^{a}	56.7 ^{a}	7.5 ^{a}
F-test ($p \leq 0.05$)	SS	**	SS	**	**	**
CV (%)	7.7	2.2	5.2	2.4	6.5	7.3
I × M	SS	SS	SS	SS	SS	SS

CCS, commercial cane sugar; extraction, extractable sugar percentage; main plot treatments are I_1 (fully irrigated) and I_0 (water-stressed); subplot treatments are M_1 (0 kg K ha^{-1}), M_2 (67 kg K ha^{-1}), M_3 (133 kg K ha^{-1}), and M_4 (200 kg K ha^{-1}); CV, coefficient of variation; ** denotes significance at $p \leq 0.05$; SS, statistically similar. The superscript similar letter within a continuous column indicates no statistical difference while different letters denote significant differences at $p \leq 0.05$.

Table 7. Average sugarcane quality parameters 12 months after harvesting the seed crop under irrigation and potassium treatments.

Treatments	Average Sugarcane Quality Parameters 12 Months After Harvesting					
	Brix(º)	Pol (%)	Purity (%)	CCS (%)	Extraction (%)	CCS (Tonnes ha^{-1})
Irrigation treatment						
I_1	21.3 ^{a}	19.6 ^{a}	92.1 ^{a}	13.8 ^{a}	58.6 ^{a}	7.9 ^{a}
I_0	20.6 ^{a}	18.9 ^{a}	91.9 ^{a}	13.3 ^{a}	57.0 ^{a}	7.3 ^{a}
F-test ($p \leq 0.05$)	SS	SS	SS	SS	SS	SS
CV (%)	7.3	9.0	1.6	9.6	7.0	12.3
Potassium fertilizer treatment						
M_1	19.9 ^{c}	18.3 ^{c}	91.9 ^{a}	12.9 ^{b}	54.8 ^{b}	6.5 ^{c}
M_2	20.8 ^{b}	19.1 ^{b}	92.2 ^{a}	13.5 ^{ab}	56.6 ^{b}	7.2 ^{b}
M_3	21.4 ^{ab}	19.6 ^{ab}	91.5 ^{a}	13.8 ^{a}	58.8 ^{ab}	8.0 ^{a}
M_4	21.7 ^{a}	20.1 ^{a}	92.3 ^{a}	14.2 ^{a}	61.0 ^{a}	8.6 ^{a}
F-test ($p \leq 0.05$)	**	**	SS	**	**	**
CV (%)	3.1	2.4	3.4	3.5	6.0	7.3
I × M	SS	SS	SS	1.52	SS	SS

CCS, commercial cane sugar; extraction, extractable sugar percentage; main plot treatments are I_1 (fully irrigated) and I_0 (water-stressed); subplot treatments are M_1 (0 kg K ha^{-1}), M_2 (67 kg K ha^{-1}), M_3 (133 kg K ha^{-1}), and M_4 (200 kg K ha^{-1}); CV, coefficient of variation; ** denotes significance at $p \leq 0.05$; SS, statistically similar. The superscript similar letter within a continuous column indicates no statistical difference while different letters denote significant differences at $p \leq 0.05$.

3.4. Correlations between Quality Parameters

Ten months after harvesting the seed crop, Brix was moderately positively correlated with pol and the extractable sugar percentage, weakly positively correlated with both commercial cane sugar values, and moderately negatively correlated with purity (Table 8).

Table 8. Correlations between sugarcane quality parameters 10 and 12 months after harvesting the seed crop.

	10 Months after Harvesting the Seed Crop					
	Brix (○)	**Pol (%)**	**Purity (%)**	**CCS (%)**	**Extraction (%)**	**CCS (Tonnes ha^{-1})**
Brix (○)	1	0.6	−0.6	0.2	0.4	0.1
Pol (%)	0.6	1	0.2	0.9	0.5	0.5
Purity (%)	−0.6	0.2	1	0.6	0.1	0.4
CCS (%)	0.2	0.9	0.6	1	0.5	0.6
Extraction (%)	0.4	0.5	0.1	0.5	1	0.5
CCS (tonnes ha^{-1})	0.1	0.5	0.4	0.6	0.5	1
	12 Months after Harvesting the Seed Crop					
	Brix (○)	**Pol (%)**	**Purity (%)**	**CCS (%)**	**Extraction (%)**	**CCS (Tonnes ha^{-1})**
Brix (○)	1	0.8	−0.1	0.7	0.3	0.7
Pol (%)	0.8	1	0.5	1.0	0.2	0.8
Purity (%)	−0.1	0.5	1	0.6	−0.2	0.3
CCS (%)	0.7	1.0	0.6	1	0.1	0.8
Extraction (%)	0.3	0.2	−0.2	0.1	1	0.4
CCS (tonnes ha^{-1})	0.7	0.8	0.3	0.8	0.4	1

CCS, commercial cane sugar; extraction, extractable sugar percentage.

Strong positive correlations were observed between pol and the percentage CCS, with moderate positive correlations between pol and the extractable sugar percentage and the weight-per-area CCS, and a weak positive correlation between pol and purity. Moderate positive correlations were observed between purity and both CCS values and a weak positive correlation between purity and the extractable sugar percentage. The percentage CCS was associated with moderate positive correlations with both the extractable sugar percentage and the weight-per-area CCS, while the extractable sugar percentage was moderately positively correlated with the weight-per-area CCS.

Two months later, correlations between Brix and other parameters had become more positive: strong positive correlations were observed with pol and both CCS values, and a weak positive correlation was observed between pol and the extractable sugar percentage, while the correlation between Brix and purity was weakly negative (Table 8).

Correlations between pol and other parameters had also become more positive, except the correlation between pol and the extractable sugar percentage, which went from moderately to weakly positively correlated. There was no change in the correlation between purity and the percentage CCS, while the correlations between purity and extractable sugar percentage and between purity and weight-per-area CCS went from weakly positive to weakly negative and from moderately positive to moderately negative, respectively. The correlation between the percentage CCS and the extractable sugar percentage changed from moderately to weakly positive, while that between the percentage CCS and the weight-per-area CCS changed from moderately to strongly positive. The correlation between the extractable sugar percentage and the weight-per-area CCS did not change significantly between the sampling intervals.

3.5. Economic Analysis

Higher economic benefits were achieved under the fully irrigated treatments than under those with water stress (Table 9).

As well, yields increased with increasing K-fertilizer application. The highest yields were achieved in the I_1M_4 treatment; these were 25.5% higher than those of the I_1M_1 treatment. Similarly, yields in the I_0M_4 treatment were 14.2% higher than those of the I_0M_1 treatment. Increasing fertilizer resulted in increased income: the income achieved in I_1M_2 and in I_0M_2 was 9145 and 7965 INR ha^{-1} more than in the I_1M_1 and I_0M_1 treatments, respectively; however, at the maximum K-fertilizer rate, additional income was 38,350 INR ha^{-1} in I_1M_4 (above I_1M_1) and 21,240 INR ha^{-1} in I_0M_4 (above I_0M_1). The benefit-to-cost ratios reflected these data, and the highest B:C (10.1) was achieved in the fully irrigated treatment with the highest K-fertilizer applied (I_1M_4). The lowest B:C (6.3) was achieved in the water-stressed treatment with the lowest K-fertilizer applied (I_oM_2).

Table 9. Benefit-to-cost ratio of the ratoon crop under irrigation and potassium treatments.

Treatments	Fertilizer Cost (Rs ha^{-1})	Recorded Yield (Tonnes ha^{-1})	Reported Response	Additional Income due to Applied K (Rs ha^{-1})	Benefit-Cost Ratio	Overall Trend
I_1M_1	0	51.0	–	–	–	
I_1M_2	1273	54.1	3.1	9145	7.18	3.36
I_1M_3	2546	59.4	8.4	24,780	9.73	4.20
I_1M_4	3800	64.0	13.0	38,350	10.09	3.92
I_0M_1	0	50.7	–	–	–	
I_0M_2	1273	53.4	2.7	7965	6.26	
I_0M_3	2546	56.8	6.1	17,995	7.07	
I_0M_4	3800	57.9	7.2	21,240	5.59	

Change in cane yield is the change under different fertilizer treatments with irrigation treatment held constant.; I_1 is the fully irrigated treatment and I_0 the water-stressed treatment; the fertilizer treatments are M_1 (0 kg K ha^{-1}), M_2 (67 kg K ha^{-1}), M_3 (133 kg K ha^{-1}), and M_4 (200 kg K ha^{-1}); the cost of K fertilizer was 19,000 INR t^{-1}; sugarcane price was 2950 INR t$^{-1.}$

4. Discussion

4.1. Ratoon Sugarcane Performance under Irrigation

I_1 and I_0 treatment plots received a total of 13 and 10 irrigations, respectively, each with a depth of 50 mm. Thus, water stress equivalent to the lack of 150 mm irrigation water was expected in I_0 treatments; however, this stress was reduced due to receipt of 822.4 mm rainfall (Figure 1) during the experimental period, which largely coincided with the skipped irrigations. It is likely that differences between I_1 and I_0 treatments would have been stronger without this unforeseen rainfall.

Under fully irrigated conditions (all I_1 treatments), sugarcane growth parameters were improved, albeit not significantly different from the measurements observed under water-stressed conditions (all I_0 treatments; Tables 1–3). This may be a result of improved moisture availability [47,48], N use efficiency [49], significantly lower incidence of both stalk borer and top borer in I_1 plots (Table 5), all of which contribute to improving cane growth [50–52]. Under mild water stress, ratooned sugarcane has insect-pests incidence jumped while decreases are observed in stomatal conductance, transpiration rate, internal CO_2 concentration, and photosynthetic rate [53,54]. Water shortages result in cane yield reductions of up to 60% [55–57]. Sugarcane is most susceptible to water stress throughout the tillering and stem elongation phases [58,59], with stem and leaf growth being the most affected [55]. The physical responses to water stress in sugarcane are most commonly leaf rolling, stomatal closure, restriction of stalk and leaf growth, leaf senescence, and reduced leaf area [60]. Furthermore, both cell division and cell elongation are disrupted by water stress [59], with stem and leaf elongation being the most severely affected growth processes [61,62].

Irrigation did not affect the incidence of early shoot borer; however, stalk borer and top borer were observed in significantly higher numbers under water stress conditions (Table 5). This may be a consequence of poor nutrient movement from the leaves to other plant parts [13,14,53].

Under the fully irrigated conditions (I_1 treatments), ratoon sugarcane quality metrics at both 10 and 12 months after harvesting the seed crop were all better than metrics under the water-stressed conditions (I_0 treatments); albeit, the differences were not statistically significant (Tables 6 and 7). These trends may be the result of irrigation which improved metabolic and physiological activities, nutrient uptake and movement within the sugarcane plant from leaves, and higher fertilizer use efficiency [13,16,40,54–57,59]. At 12 months of ratoon canes, Brix relations with other quality parameters improved while remaining negative with purity (Table 8).

4.2. Ratoon Sugarcane Performance under Potassium Fertilizer

The M_3 treatment, with 133 kg K ha^{-1} performed better than any other K treatment in terms of shoot resprouting and other sugarcane performance metrics (Tables 1–4). Of the plant growth metrics recorded, treatments with both lower (i.e., M_2, 67 kg K ha^{-1}) and higher (i.e., M_4, 200 kg K ha^{-1}) rates of K fertilizer did not achieve as well as those recorded in the M_3 treatment. This may be a result of improved sugarcane metabolism [17,18,56], recorded significantly lower incidence of insect-pests (Table 5) which are further responsible for poor performance of canes in M_4 plots, better enzyme activation [19,21,58], carbohydrate transport [61], balancing of hormones and auxin levels [54], and sugarcane root growth and development [11,15,56,62]. Of the three insect pests studied, only the incidence of the top borer was significantly lower in M_3 as compared to M4 plots affected by the potassium fertilizer rate. Of the necessary plant nutrients, K is required in higher quantities. The performance of canes growing in K-deficient soils will be adversely affected by little or no K fertilizer [62]. Sugarcane productivity is influenced by the inherent capacity of the soil to supply K in the soil solution [63]. Consequently, K is a crucial element in achieving sustainable ratoon sugarcane production [64], as it activates photosynthesis, protein synthesis, starch production, and protein and sugar translocation [46,65]. The transfer of photosynthates in sugarcane is significantly reduced when K is in deficit [22,27,62]. Sugarcane crops react significantly to K fertilization only in soils with low available K [30].

Potassium deficiency reduces sugarcane growth, yields, and quality, while all are improved by applying sustainable fertilizer K to deficient soils [47]. Sugarcane responds to K fertilizers by increasing cane yield without changing the sucrose concentration in the cane [30]. In ratooned sugarcane, Shukla et al. [12] reported the following effects of K fertigation (66 kg K ha^{-1} administered with irrigation water): (i) enhanced dry matter accumulation at all development stages, (ii) increased the number of sprouted buds in ratoon cane stubble, and (iii) higher numbers of millable canes as a result of robust tillers generated in the ratooned cane. Moisture stress reduced cane yield when K was inadequate, while moisture stress had no effect on yield when sufficient K (above 133 kg K ha^{-1}) was supplied [65].

K-fertilization in K-deficient soils improves the transportation of nutrients from the leaves to the entire plant, resulting in comparatively fewer sweat leaves which are not preferred by sucking insect pests. This may explain why incidences of the major insect pests in stalk borer, early shoot borer, and top borer was reduced in the M_3 treatment (Table 5).

At both 10 and 12 months after harvesting the seed crop, higher K fertilizer application rates improved sugarcane quality parameters relative to the M_1 control (0 kg K ha^{-1} applied: Tables 6 and 7). The highest sugarcane juice quality was observed in the M_3 treatment, with 133 kg K ha^{-1} applied. This may be because the addition of K fertilizer improves sugarcane root growth and development (by improving input use efficiency), which might be due to translocation of photosynthates [22–27], which made the leaves bitter and reduced insect-pest incidence [13,14,62–64]. Further, K plays a key role in regulating stomatal openings through which water transpires from the plant to the atmosphere, thereby regulating transpiration losses under water stress [49].

Overall, the M_3 sub-treatment 133 kg K ha^{-1} performed best in terms of ratoon growth, and sugarcane production and quality, particularly under water stress conditions. The incidence of insect pests was also lowest in the M_3 treatment as compared to the other plots [15]. In general, in northern India, all sugarcane leaves are removed from the field prior to establishing the next crop: little of the K taken up by the plant is available to be returned to the soil after harvest. The importance of sufficient K-fertilizer application in sugarcane production on soils inherently low in K has been demonstrated here.

5. Conclusions

This experimental research has demonstrated that ratoon sugarcane performance in north India is somewhat affected by irrigation and potassium treatments. Under water-stress conditions, a trend for reduced ratoon productivity was observed, although this was not statistically significant. Relative to control treatments with no K fertilizer, adding K has elsewhere been reported to improve plant growth; however, in this experiment, no significant differences in average sugarcane height, diameter, or internodes per plant were observed in the ratoon crop. Adding K fertilizer improved sugarcane quality (e.g., measured in terms of Brix, pol, purity, extractable sugar percentage and commercial cane sugar) relative to a baseline with no K fertilizer. Significantly higher sugarcane quality and reductions in key insect pests were observed in the treatment where 133 kg K ha^{-1} was applied, in both irrigated and water-stressed plots. Further research to extend these experimental results and to examine, in more detail, relationships between key quality parameters such as pol and commercial cane sugar variables should be conducted to optimise ratoon quality and sugar recovery rate. We recommend that in the K-deficient soils of northern India, applications of 133 kg K ha^{-1} should be standard, regardless of irrigation application, to improve ratoon sugarcane growth, yield and quality, and ultimately to enable smallholder farmers to improve their livelihoods through more sustainable and climate-smart sugarcane production.

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

Funding: This research work was supported by the Director of the Regional Research Station, Gurdaspur Potassium Research Institute of India, and International Potassium Institute, Switzerland, for providing necessary support for carrying out these cane ratoon experiments during 2020–2021 and by the Taif University Researchers for funding this research with Project number (TURSP-2020/53), 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 Director, Regional Research Station, Gurdaspur Potassium Research Institute of India, and International Potassium Institute, Switzerland for providing necessary support for carrying out these cane ratoon experiments during 2020–2021. The authors also appreciate Taif University Researchers Supporting Project number (TURSP-2020/53), Taif University, Taif, Saudi Arabia.

Conflicts of Interest: The authors would hereby declare that there is no conflict of interest for the article.

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