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Balanced Use of Zn, Cu, Fe, and B Improves the Yield and Sucrose Contents of Sugarcane Juice Cultivated in Sandy Clay Loam Soil

Abdul Majeed [1], Imran Rashid [1], Abid Niaz [2], Allah Ditta [3,4,*], Aysha Sameen [5], Asma A. Al-Huqail [6] and Manzer H. Siddiqui [6]

1 Sugarcane Research Institute, Ayub Agricultural Research Institute, Faisalabad 38040, Pakistan; drmajeed1805@gmail.com (A.M.); imransoilchemist@gmail.com (I.R.)
2 Provincial Reference Fertilizer Testing Laboratory, Raiwind Near, Government Degree College for Women, Raiwind, Lahore 55150, Pakistan; draniaz@gmail.com
3 School of Biological Sciences, The University of Western Australia, 35 Stirling Highway, Perth, WA 6009, Australia
4 Department of Environmental Sciences, Shaheed Benazir Bhutto University, Sheringal, Upper Dir 18000, Pakistan
5 National Institute of Food Science and Technology, Faculty of Food, Nutrition & Home Sciences, University of Agriculture Faisalabad, Faisalabad 38040, Pakistan; ayshasameen@uaf.edu.pk
6 Department of Botany and Microbiology, College of Science, King Saud University, Riyadh 11451, Saudi Arabia; aalhuqail@ksu.edu.sa (A.A.A.-H.); mhsiddiqui@ksu.edu.sa (M.H.S.)
* Correspondence: allah.ditta@sbbu.edu.pk or allah.ditta@uwa.edu.au

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Abstract: Balanced use of micronutrients in soils is essential for optimized nutrient use efficiency, environmental conservation and long-term sustainability of agro-ecological systems. As a result, maintaining correct micronutrient levels in the soil is essential not only to meet plant needs and maintain agricultural productivity but also to avoid nutrient build-up. The present study aimed to investigate the effect of micronutrient application on the yield and sucrose content expressed as the polarization of sugar cane juice (POL%) under field conditions. There were seven treatments, viz. T_0 = No micronutrient application (control); T_1 = $ZnSO_4$ at the rate of 30 kg ha^{-1}; T_2 = $CuSO_4$ at the rate of 10 kg ha^{-1}; T_3 = $FeSO_4$ at the rate of 30 kg ha^{-1}; T_4 = borax at the rate of 2 kg ha^{-1}; T_5 = half dose of $ZnSO_4$, $CuSO_4$, $FeSO_4$ and borax at the rate of 15, 5, 15 and 1 kg ha^{-1} and T_6 = full dose of $ZnSO_4$, $CuSO_4$, $FeSO_4$ and borax at the rate of 30, 10, 30 and 2 kg ha^{-1}, arranged in randomized complete block design in triplicate. With the application of $ZnSO_4$ at 30 kg ha^{-1} along with recommended doses of NPK, 30% more income was generated as compared with the control. Fist plant and ratoon crop yields were 19.08% and 22.03% higher, respectively, than in the control. Similarly, Zn application resulted in 5.91% and 8.64% greater sucrose contents (POL%) in plant and ratoon crops, respectively, when compared with the control. The application of $ZnSO_4$ at the rate of 30 kg ha^{-1} along with recommended doses of NPK had a significant impact on the yield and sucrose contents of sugarcane.

Keywords: micronutrients; zinc; boron; iron; sucrose contents; cane yield; BCR

1. Introduction

Sugarcane (*Saccharum officinarum* L.) is a sustainable agricultural resource that produces sugar, ethanol, manure and fiber. It is one of the world's most important commercial sugar crops [1–3]. It is a key cash crop, which contributes greatly to the economic prosperity of farmers around the world. Crop output per hectare must be raised to meet the needs of an ever-growing population, with the possibility of developing cultivable land in remote locations. Even though the present cultivars have a high production potential, yet more could be achieved with the use of balanced fertilizers [3]. Soil micronutrient deficiency is one of the yield-limiting variables. Organic matter depletion and micronutrient shortages were caused by intensive farming, mono-cropping without appropriate crop rotation and the adoption of high-yield hybrid varieties [4].

Various soil problems such as salinity and an abundance of carbonates and bicarbonates worsen micronutrient deficits. Aside from these aspects, a lack of understanding among farmers about crop micronutrient requirements is another major cause of low yields. For best sugarcane growth and development, an optimum supply of micronutrients is required. These elements, though in smaller amounts, are just as vital for plant development as phosphorus, potassium and nitrogen. Furthermore, a deficiency of micronutrients in both the soil and the plants reduces agricultural productivity [5,6]. Micronutrient deficiency negatively affects crop yield and quality, can cause a widespread infestation of a variety of diseases and pests, and can cause low nutrient use efficiency. Micronutrient requirements for sugarcane vary depending on soil texture and local climatic zones. Micronutrient deficiency in sugarcane is evident under light-textured, calcareous, and heavily farmed soils [5,7].

Zinc (Zn) is necessary for tryptophan production that produces indole acetic acid, which is necessary for protein metabolism. Iron (Fe) shortage is widespread in sugarcane crops, particularly in ratoons, even though it is the fourth most common nutrient in the soil [8–10]. Chlorophyll synthesis necessitates the presence of Fe. It acts as a stimulant in respiration and photosynthesis. Boron (B) is required for sugar transport and the development of cell walls [11]. Micronutrients affect the majority of the crop's physiological functions by interfering with the amount of chlorophyll in the leaves, which in turn affects the plant's photosynthetic activity. Micronutrients aid in the absorption and transport of essential plant nutrients such as nitrogen, phosphorus and potassium. Micronutrients improve sugarcane juice quality in addition to increasing yields. In addition to the primary and secondary nutrients, Zn and Fe minerals are indispensable for high-quality, long-term cane production [5,12]. Based on this discussion, the present study was based on the hypothesis that an optimum supply of micronutrients enhances the sugarcane yield and its juice quality. It is important to find out the optimum ratios of micronutrients for optimum productivity of crops, especially for sugarcane juice quantity and quality. To our knowledge, no study has been conducted in finding the optimum ratios of different macro-and micronutrients for enhanced productivity in terms of crop yield, sugar yield and percentage of sugar contents. Therefore, the present study was conducted to investigate the effect of micronutrient application on the growth, yield and sucrose content expressed as the polarization of sugar cane juice (POL%) under field conditions in sandy clay loam soil for two years.

2. Materials and Methods

The present study was carried out at Sugarcane Research Institute (31°24′24.8904″ N, 73°3′0.882″ E), Ayub Agricultural Research Institute Faisalabad, Pakistan during 2019–2020 and 2020–2021.

2.1. Soil Analysis

Soil samples (0–30 cm) were taken from the field area before the start of the experiment and after two years at the end of the study. The collected samples of soil were dried, ground, sieved (2 mm) and analyzed regarding various physicochemical properties. The particle size distribution for soil textural analysis was determined by the hydrometer method as described by Bouyoucos [13] and Page [14]. Electrical conductivity (EC) and pH were measured by following the method of Nelson and Sommers [15] using electrical conductivity (Jenway 3520 Cole-Parmer, Staffordshire, UK) and pH meter (Jenway 4520 Cole-Parmer, Staffordshire, UK), respectively. The pH was measured from 1:2.5 soil water ratio, respectively, whereas the extract from the soil saturated paste was used for EC determination. Total N by Kjeldahl process, available P [16] and extractable K by using PFP-7 Jenway Flame photometer (Table 1). Soil organic carbon contents were estimated following the aforementioned method [17]. The extractable and available micronutrients

(Zn, Cu, Fe, and Mn) were determined by using the DTPA method [18]. The soil at the experimental area was sandy clay loam in texture as per the USDA soil taxonomy and WRB soil classification systems, non-saline, low in organic matter and total nitrogen, medium in phosphorus and zinc and sufficient in potassium, copper, iron, and boron.

Table 1. Physicochemical properties of soil used in the present study.

Properties	Before the Start of the Experiment	At the End of the Experiment
Sand (%)	51	54.5
Silt (%)	25	20.5
Clay (%)	24	25
Textural Class	Sandy clay loam	Sandy clay loam
ECe (dS m^{-1})	2.10	2.22
pH	8.30	8.26
Soil organic carbon contents (%)	0.278	0.296
Available P (mg kg^{-1})	7.80	7.74
Extractable K (mg kg^{-1})	160	164
Extractable Zn (mg kg^{-1})	0.32	0.52
Extractable Cu (mg kg^{-1})	0.49	0.51
Extractable Fe (mg kg^{-1})	4.55	4.54
Available B (mg kg^{-1})	0.53	0.52

2.2. Field Experiment

The series of field experiments were performed in a randomized complete block design (RCBD) with seven treatments replicated in triplicate during 2019–2020 and 2020–2021. The weather data regarding temperature, relative humidity and rainfall during the study period are presented in Figure 1. There were seven treatments viz., T_0 = No micronutrient application (control); T_1 = $ZnSO_4$ at the rate of 30 kg ha^{-1}; T_2 = $CuSO_4$ at the rate of 10 kg ha^{-1}; T_3 = $FeSO_4$ at the rate of 30 kg ha^{-1}; T_4 = borax at the rate of 2 kg ha^{-1}; T_5 = half dose of $ZnSO_4$, $CuSO_4$, $FeSO_4$ and borax at the rate of 15, 5, 15 and 1 kg ha^{-1} and T_6 = full dose of $ZnSO_4$, $CuSO_4$, $FeSO_4$ and borax at the rate of 30, 10, 30 and 2 kg ha^{-1}, respectively. The application doses of different micronutrients were based on previous studies conducted [3,19–21]. A mid-maturing sugarcane variety, i.e., CPF-253, was used in the present study. For the first plantation, three-budded double setts were placed end-to-end with a row-to-row distance of 1 m after proper seedbed preparation. The seed rate was about 85 mounds setts per acre. The same field was used for the ratoon crop and the recommended doses of NPK were added. All of the treatments received the recommended fertilizer doses, i.e., pure NPK 168:48.9:92.6 kg ha^{-1}, respectively. Urea ($CO(NH_2)_2$) 46% N, diammonium phosphate ($(NH_4)_2(HPO_4)$) 18:46 N and P_2O_5, respectively, and muriate of potash (KCl) 60% K_2O were used as N, P, and K sources. The entire phosphorus (P) and potash (K) doses were applied at the time of planting, whereas N was applied in two equivalent splits: first at 50 days and the remaining at 95 days after planting. At the time of planting, micronutrients were applied to the soil according to the treatments. Recommended agronomic practices such as earthing up, weeding and irrigation practices were regularly followed across all the treatments.

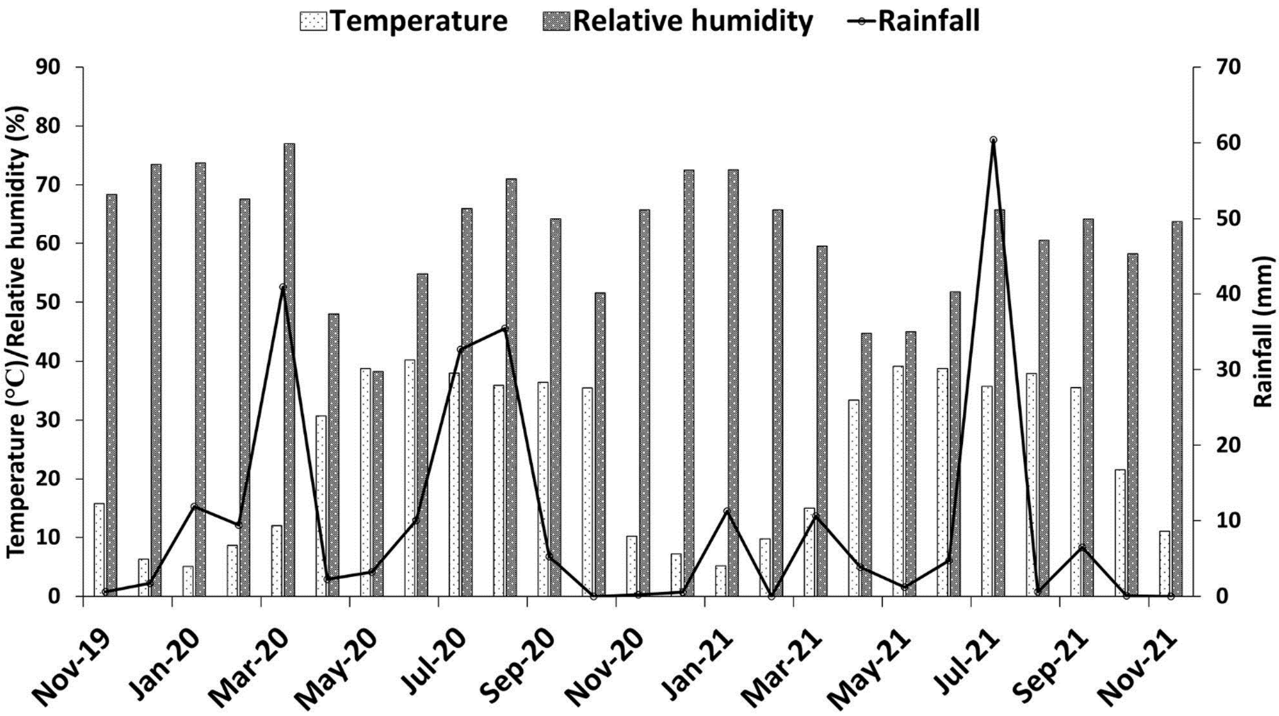

Figure 1. Weather data during the study period from November 2019 to November 2021. Source: https://namc.pmd.gov.pk/monthly-bulletins.php (accessed on 27 January 2022).

2.3. Data Collection

In the present study, the data presented as the 1st year (2019–2020) is of plant crop and that of the 2nd year (2020–2021) is of ratoon crop. At maturity after twelve months, data on yield metrics such as stripped cane weight, stripped cane height, stripped cane girth and stripped cane yield were recorded at the time of harvest. Sucrose contents were noted by using a polarimeter [22]. Sugar yield (t ha^{-1}) was calculated by the following formula:

$$\text{Sugar yield } (\text{t ha}^{-1}) = \frac{\text{Stripped cane yield } (\text{t ha}^{-1}) \times \text{Sugar recovery } (\%)}{100} \quad (1)$$

2.4. Economic Analysis

For the calculation of total cost, fixed cost (seed sowing, land preparation, irrigation, plant protection, harvesting charges, etc.) and variable cost (fertilizers) were added together. For economic analysis, the net benefits and benefit-cost ratio (BCR) were determined as described by CIMMYT [23]. The total fixed cost was the same for all treatments and BCR was calculated by dividing gross income by total expenditure (Table 2).

Table 2. Correlation among different growth and yield parameters of sugarcane during 2019–20 and 2020–21.

	2019–2020				
	Sucrose Contents	**Stripped Cane Girth**	**Stripped Cane Height**	**Sugar Yield**	**Single Stripped Cane Weight**
Stripped cane girth	0.7142 ***				
Stripped cane height	0.3888 NS	0.5875 **			
Sugar yield	0.7863 ***	0.8592 ***	0.6117 **		
Single stripped cane weight	0.7786 ***	0.7990 ***	0.5620 **	0.9293 ***	
Cane yield	0.6859 ***	0.8248 ***	0.6328 **	0.9853 ***	0.9136 ***

Table 2. *Cont.*

2020–2021					
	Sucrose Contents	**Stripped Cane Girth**	**Stripped Cane Height**	**Sugar Yield**	**Single Stripped Cane Weight**
Stripped cane girth	0.8814 ***				
Stripped cane height	0.5221 *	0.7685 ***			
Sugar yield	0.8554 ***	0.8705 ***	0.5675 **		
Single stripped cane weight	0.8004 ***	0.8686 ***	0.6363 **	0.9327 ***	
Cane yield	0.7987 ***	0.8391 ***	0.5574 **	0.9935 ***	0.9300 ***

Where * = $p < 0.05$, ** = $p < 0.01$, and *** = $p < 0.001$ ($n = 3$) and NS = Non-significant $p \leq 0.05$.

2.5. Statistical Analysis

The experimental data were analyzed regarding analysis of variance (ANOVA) using the computer software Statistix 8.1 (Analytical Software, Statistix; Tallahassee, FL, USA, 1985–2003). At a probability level of 5%, the least significant difference (LSD) test was employed to compare treatment means [24]. The Figures were prepared using GraphPad Prism Version 8.0 software (GraphPad Software LLC, CA, USA).

3. Results and Discussion

3.1. Growth and Yield Parameters

Stripped cane height was enhanced non-significantly with the application of micronutrients under almost all treatments compared with the control (Figure 2). Overall, in treatment T_1, 8.35% and 3.55% higher stripped cane height was noted in plant and ratoon crop, respectively, than control. Crusciol et al. [11] also found a positive association between micronutrients and stripped cane height. As Zn plays a vital role in the enhancement of plant growth, the increase in stripped cane height could be attributed to more vegetative development due to the availability of balanced Zn nutrition [25]. Similarly, the addition of micronutrients increased stripped cane height over the control treatment [26]. Earlier, it has been found that Zn plays a key role in tryptophan synthesis involved in protein metabolism. Similarly, Fe enhances chlorophyll synthesis and acts as a stimulant in respiration and photosynthesis [8–10].

Data depicted that the stripped cane girth was significantly improved with the use of micronutrients under different treatments, especially with the application of Zn (Figure 2). Overall, in treatment T_1, 27.3% and 36.7% higher stripped cane girth was noted in plant and ratoon crop, respectively, than un-amended control. Similarly, in treatment T_6, 30.3% and 40.0% higher stripped cane girth was noted in plant and ratoon crop, respectively, over control. These outcomes are consistent with those of Crusciol et al. [11] and Oliva et al. [27]. The application of micronutrients, particularly Zn, improved stripped cane girth [25]. It was revealed that optimal application of these micronutrients, particularly Zn, is required for better sugarcane growth and development [11,28]. Zinc (Zn) application to the plant and ratoon crop resulted in a significant increase in stripped cane weight (SCW). In comparison with the normal control, the application of Zn in the form of $ZnSO_4$ to the soil at a rate of 30 kg ha^{-1} showed a significant increase in various growth and yield parameters. In comparison with the control, treatment T_1 showed a 33.7% and 68.2% increase in stripped cane weight (SCW) in the plant and ratoon crop, respectively. Similarly, in treatment T_6, SCW was found to be 41.5% and 75.0% greater in the plant and ratoon crop, respectively, when compared with the control (Figure 3). The outcomes are consistent with Singh et al. [29]. Fertilizers containing Fe and Cu improved SCW in the plant and ratoon crop, but not significantly when compared with the control, and both treatments were equivalent (Figure 3). It was revealed that by applying micronutrients, particularly Zn, the SCW can be greatly improved, resulting in increased cane yield [4]. Boron, on the other hand, had no influence on SCW when compared with other micronutrients and was equivalent to control [25]. A positive correlation was observed between cane yield and SCW (Table 2).

Cane yield (CY) was significantly increased with the addition of micronutrients. The highest CY was documented in plant and ratoon crops with the application of Zn (Figure 3). The results depicted that in T_1, 19.1% and 22.0% higher CY was recorded in plant and ratoon crops, respectively, over control. In addition, in treatment T_6, 24.7% and 26.7% higher CY was noted in plant and ratoon crops, respectively, over control (Figure 3). A significant rise in CY with the addition of micronutrients has also been observed by many researchers around the world [5,28,30,31]. With the addition of copper, iron and boron in both the plant and the ratoon crop, there was a lesser increase in cane production. The use of micronutrients, particularly Zn, has a beneficial effect on all yield-contributing attributes such as stripped cane height, stripped cane girth, and stripped cane weight [25,32].

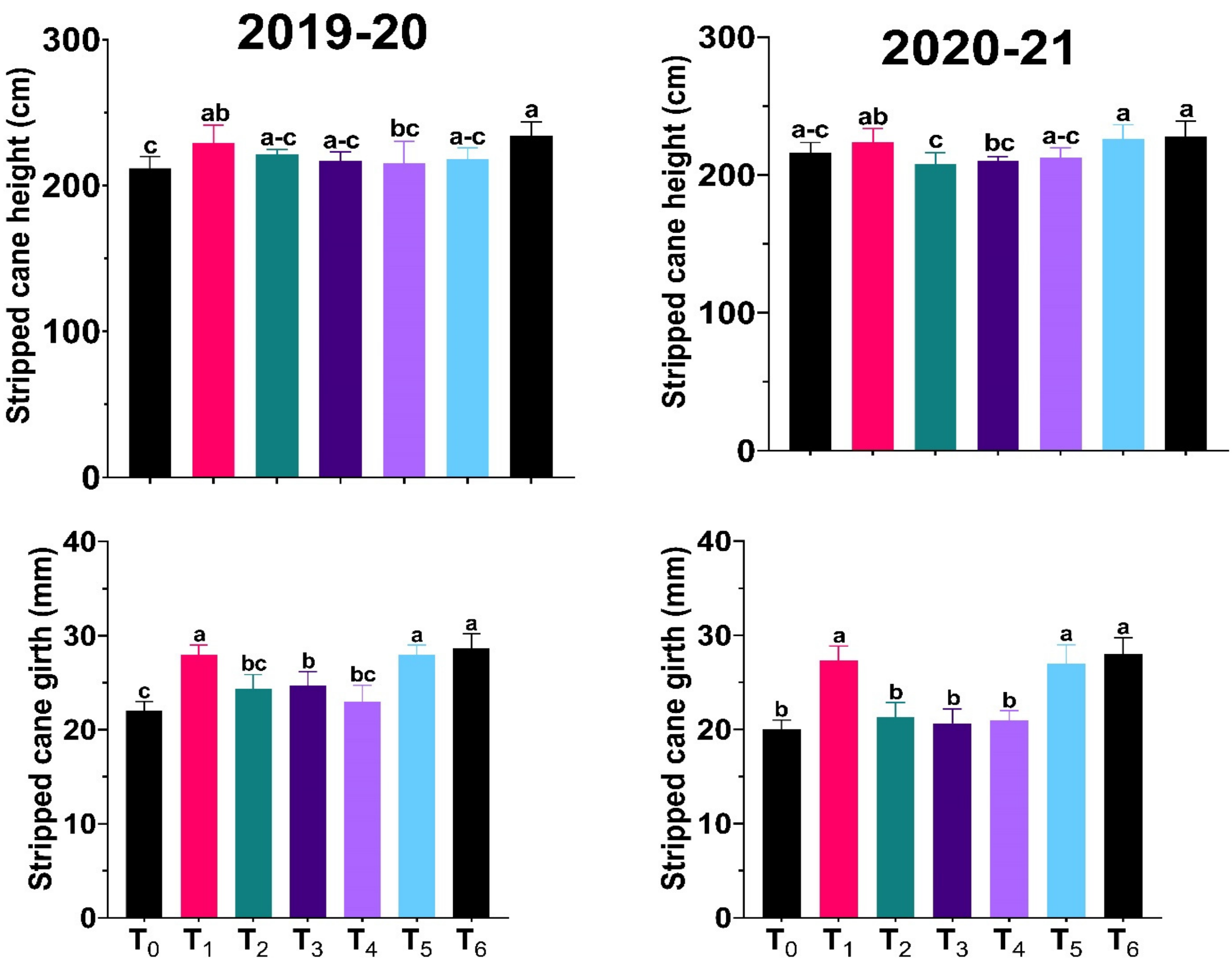

Figure 2. Impact of different treatments on stripped cane height and girth during 2019–2020 and 2020–2021. T_0 = No micronutrient application (control); T_1 = $ZnSO_4$ at the rate of 30 kg ha^{-1}; T_2 = $CuSO_4$ at the rate of 10 kg ha^{-1}; T_3 = $FeSO_4$ at the rate of 30 kg ha^{-1}; T_4 = borax at the rate of 2 kg ha^{-1}; T_5 = half dose of $ZnSO_4$, $CuSO_4$, $FeSO_4$ and borax at the rate of 15, 5, 15 and 1 kg ha^{-1} and T_6 = full dose of $ZnSO_4$, $CuSO_4$, $FeSO_4$ and borax at the rate of 30, 10, 30 and 2 kg ha^{-1}, respectively. Each bar indicates the mean values with standard error of means (SEM) where $n = 3$. The bars sharing the same letter(s) are statistically non-significant with each other at $p < 0.05$.

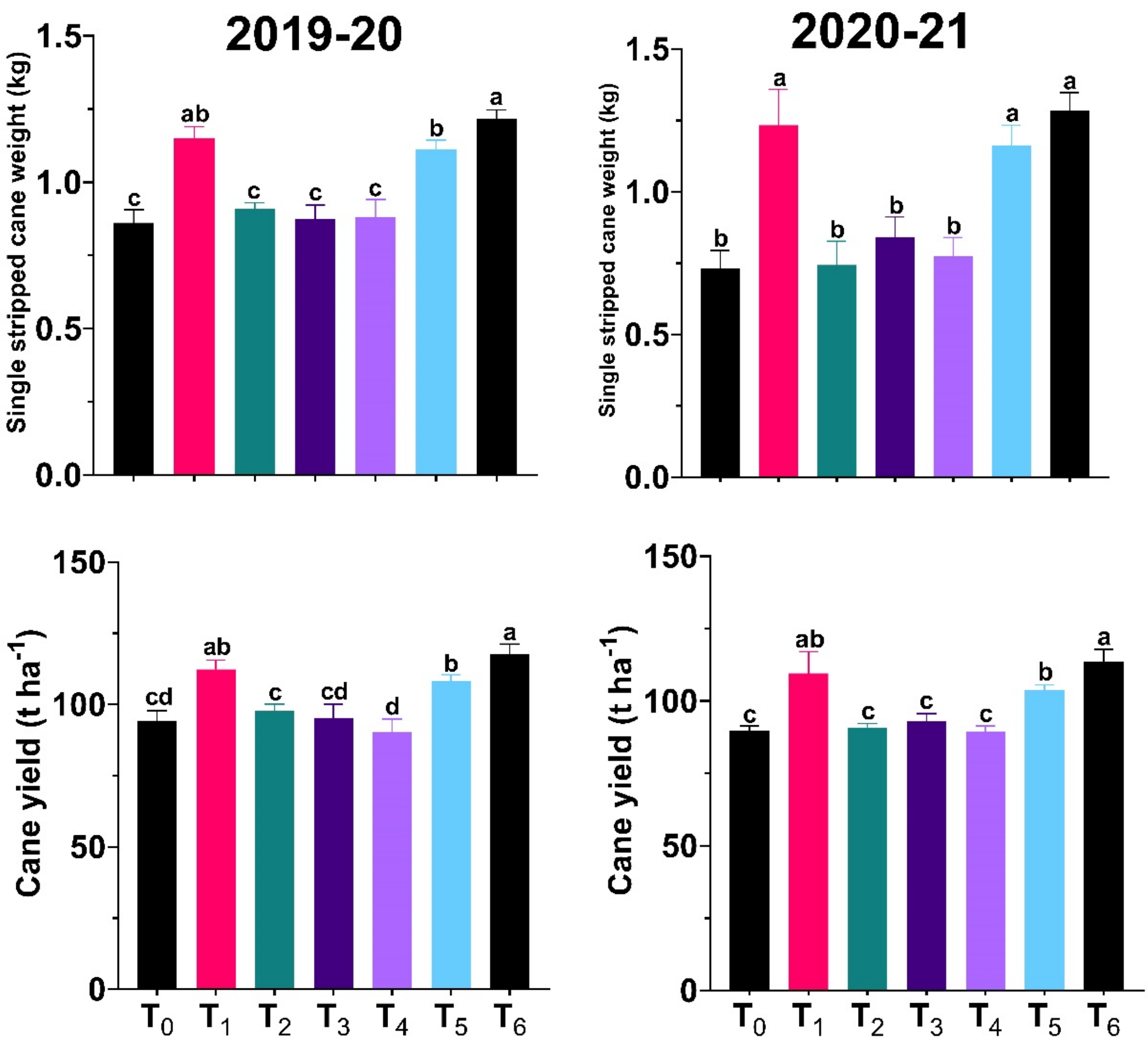

Figure 3. Impact of different treatments on single stripped cane weight and cane yield during 2019–2020 and 2020–2021. T_0 = No micronutrient application (control); T_1 = $ZnSO_4$ at the rate of 30 kg ha^{-1}; T_2 = $CuSO_4$ at the rate of 10 kg ha^{-1}; T_3 = $FeSO_4$ at the rate of 30 kg ha^{-1}; T_4 = borax at the rate of 2 kg ha^{-1}; T_5 = half dose of $ZnSO_4$, $CuSO_4$, $FeSO_4$ and borax at the rate of 15, 5, 15 and 1 kg ha^{-1} and T_6 = full dose of $ZnSO_4$, $CuSO_4$, $FeSO_4$ and borax at the rate of 30, 10, 30 and 2 kg ha^{-1}, respectively. Each bar indicates the mean values with standard error of means (SEM) where $n = 3$. The bars sharing the same letter(s) are statistically non-significant with each other at $p < 0.05$.

3.2. Quality Parameter

Sucrose contents, i.e., polarization percentage (POL%) of sugarcane juice was considerably affected with the addition of micronutrients, especially Zn. The highest sucrose contents were noted with the addition of Zn over control treatment (Figure 4).

The results revealed that in T_1, 5.9% and 8.6% higher sucrose contents were recorded in plant and ratoon crops, respectively, over control (Figure 4). In addition, in treatment T_6, 7.0% and 9.1% higher sucrose contents were recorded in plant and ratoon crops, respectively, over control (Figure 4). No positive response was observed with the sole application of Cu, Fe, and B for sucrose contents of sugarcane juice (Figure 4). Earlier, it has been found that micronutrients have a significant impact on the majority of the crop's physiological functions by interfering with the amount of chlorophyll in the leaves, which in turn affects the plant's photosynthetic activity. These also aid in the absorption and transport of essential plant macronutrients such as nitrogen, phosphorus, and potassium. Balanced use of micronutrients improves sugarcane juice quality in terms of sucrose contents in addition to increasing yields. Overall, a balanced supply of micro-and macro-nutrients is indispensable for high-quality, long-term cane production [5,12].

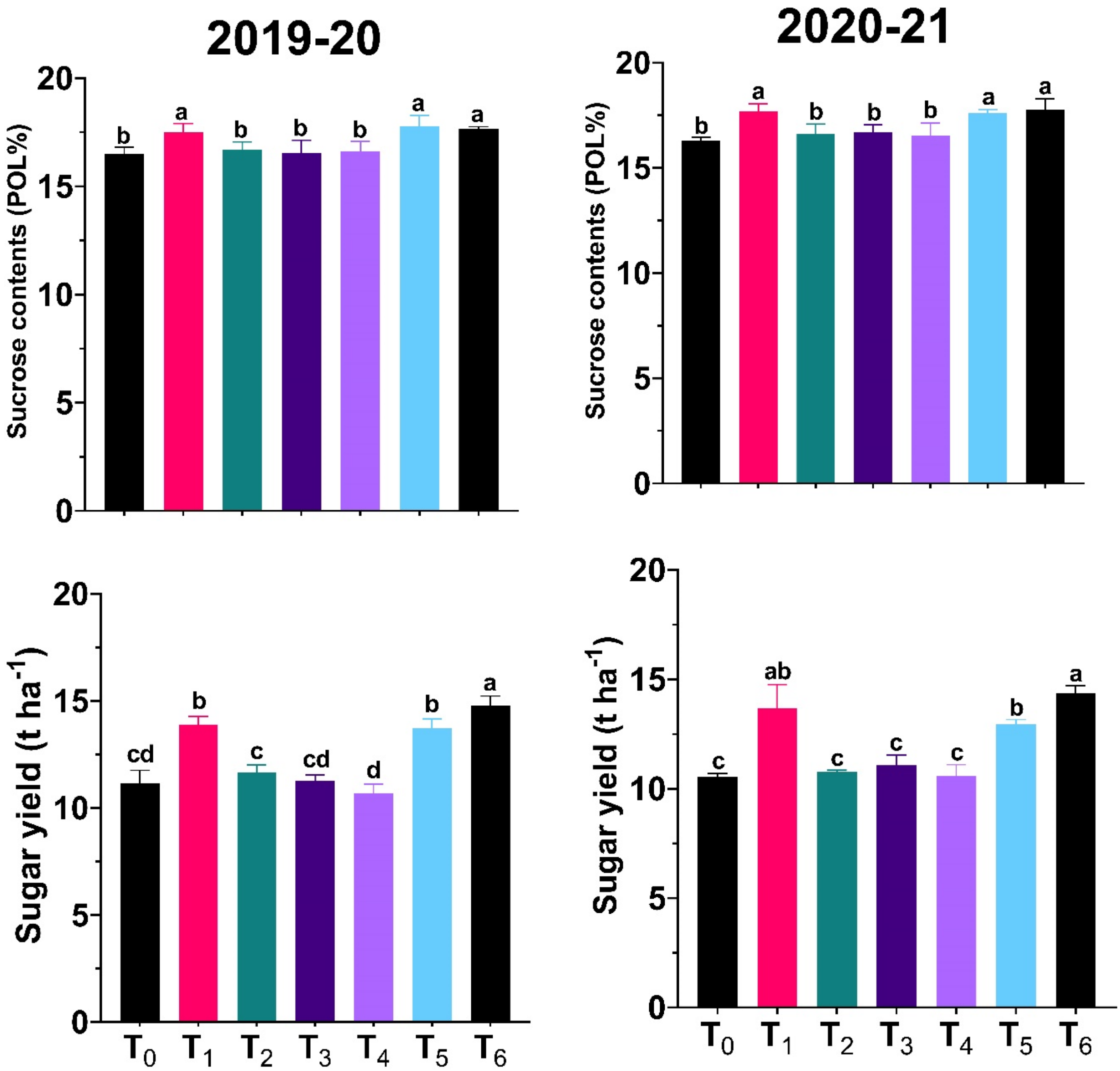

Figure 4. Impact of different treatments on sucrose contents (POL%) and sugar yield during 2019–2020 and 2020–2021. T_0 = No micronutrient application (control); T_1 = $ZnSO_4$ at the rate of 30 kg ha^{-1}; T_2 = $CuSO_4$ at the rate of 10 kg ha^{-1}; T_3 = $FeSO_4$ at the rate of 30 kg ha^{-1}; T_4 = borax at the rate of 2 kg ha^{-1}; T_5 = half dose of $ZnSO_4$, $CuSO_4$, $FeSO_4$ and borax at the rate of 15, 5, 15 and 1 kg ha^{-1} and T_6 = full dose of $ZnSO_4$, $CuSO_4$, $FeSO_4$ and borax at the rate of 30, 10, 30 and 2 kg ha^{-1}, respectively. Each bar indicates the mean values with standard error of means (SEM) where $n = 3$. The bars sharing the same letter(s) are statistically non-significant with each other at $p < 0.05$.

The use of Zn caused an increase in sucrose content, which may be related to an increase in sucrose synthase activity as reported by Pawar et al. [33]. The addition of Zn fertilizer along with main N, P, and K fertilizers significantly raised the sucrose percent of cane juice than control [34,35]. Similarly, cane juice quality parameters were significantly improved with the application of Zn [25,36]. On the other hand, El-Mageed et al. [37] found a non-significant increase in sucrose percent of cane juice with the addition of Zn and Fe fertilizer.

The results depicted that sugar yield (SY) was significantly influenced by the addition of micronutrients, especially Zn (Figure 4). Overall, in treatment T_1, 24.5% and 29.8% higher SY was recorded in plant and ratoon crop, respectively, over control. Similarly, in treatment T_6, 32.4% and 36.5% higher SY was noted in plant and ratoon crops, respectively, compared with the control (Figure 4). No significant increase in SY was observed with the sole applications of Cu, Fe and B (Figure 4). Significant and maximum SY was recorded with Zn fertilizer application over control [38]. El-Mageed et al. [37], on the other hand, found that adding Zn fertilizer to the sugarcane crop had no effect on SY. The significant difference in SY with the addition of micronutrients, particularly Zn, could be related to the high cane production [4,30,34]. Despite the impact of four micronutrients investigated in the present study, there is a potential influence of other elements such as iodine, silicon, vanadium, and selenium on the sugar contents [39–43] and needs to be investigated in future studies.

3.3. Economic Analysis

The average economic analysis (Table 3) of two-year experiments showed that the micronutrients, especially Zn, in the form of $ZnSO_4$ application to sugarcane crop resulted in the highest benefit to cost ratio (BCR), i.e., 2.18 as compared with the control with BCR = 1.76. Earlier, Paul and Mannan [44] reported similar results regarding the benefit to cost ratio and sugarcane productivity with the combined application of organic and inorganic fertilizers.

Table 3. Economic analysis average of 2 years.

Treatments	Cost of Fertilizer ha^{-1} (US$)	Fixed Cost ha^{-1} (US$)	Total Expenditure ha^{-1} (US$)	Sugarcane Yield (kg ha^{-1})	Total Income ha^{-1} (US$)	Gross Income ha^{-1} (US$)	BCR	Increase over Control
Recommended NPK (Control)	275.26	519.38	794.63	92,035	2189.37	1394.74	1.76	-
Recommended NPK + Zn	309.48	519.38	828.86	110,922	2638.65	1809.79	2.18	30
Recommended NPK + Cu	283.81	519.38	803.19	94,290	2243.01	1439.82	1.79	3
Recommended NPK + Fe	303.78	519.38	823.16	94,142	2239.49	1416.33	1.72	2
Recommended NPK + B	278.11	519.38	797.48	89,877	2138.03	1340.55	1.68	−4
Recommended NPK + (Zn + Cu + Fe + B as basal Half Dose)	312.34	519.38	831.71	106,088	2523.68	1691.96	2.03	21
Recommended NPK + (Zn + Cu + Fe + B as basal Full Dose)	349.42	519.38	868.79	115,683	2751.93	1883.14	2.17	35

US$ = 175.295 Pakistani rupee November 15, 2021; BCR = Benefit-cost ratio.

4. Conclusions

The present study showed that the application of micronutrients, particularly Zn, had a substantial impact on all sugarcane growth metrics and yield, whereas the application of Fe, Cu, and B had no effect on sugarcane yield features or sugar output. The use of micronutrients had a good impact on all quality indicators. The highest sugar yield was achieved by applying 30 kg Zn ha^{-1} to the soil. The highest BCR, i.e., 2.18 was recorded with the application of Zn as compared with the control with BCR = 1.76. Based on these findings, it is concluded that Zn addition to the soil at 30 kg ha^{-1} improves growth, yield and sucrose contents in sugarcane.

Author Contributions: Conceptualization, A.M. and A.N.; Data curation, A.A.A.-H. and A.M.; Formal analysis, A.M., I.R., A.D., A.S., A.A.A.-H. and M.H.S.; Funding acquisition, A.A.A.-H. and M.H.S.; Project administration, A.N. and A.D.; Resources, A.M., I.R., A.N. and A.A.A.-H.; Software, I.R., A.D. and A.S.; Supervision, A.N.; Validation, A.N., A.D., A.S., A.A.A.-H. and M.H.S.; Visualization, I.R., A.D., A.S., A.A.A.-H. and M.H.S.; Writing—original draft, A.M.; Writing—review and editing, A.M., I.R., A.N., A.D., A.S., A.A.A.-H. and M.H.S. All authors have read and agreed to the published version of the manuscript.

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