ISSN 2319-5991 www.ijerst.com
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Peer Reviewed, Referred & Indexed Journal

Research Paper

ROLE OF POTASSIUM AND MICRONUTRIENTS IN SUGAR ACCUMULATION OF SUGARCANE

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ABSTRACT

Sugarcane is the principal source of sucrose worldwide, yet sugar recovery often remains below its genetic potential because of unbalanced nutrition. This study empirically examines, under field conditions, how potassium (K) and the micronutrients zinc (Zn), iron (Fe), manganese (Mn) and boron (B) influence sucrose accumulation in sugarcane. A randomised complete block experiment with six treatments and four replications (24 plots) compared the recommended fertiliser dose, two higher K rates, a micronutrient mixture, and two combined K plus micronutrient treatments. Leaf nutrient concentration, juice Brix, Pol, purity, commercial cane sugar (CCS), sucrose phosphate synthase (SPS) and acid invertase activity, cane yield and sugar yield were recorded at harvest and analysed using analysis of variance, critical difference, Pearson correlation and regression. Increasing leaf K from 1.09 to 1.44 per cent raised juice Pol from 16.22 to 17.99 per cent, and leaf K alone explained 73 per cent of the variation in CCS. Applying 150 kg K2O per hectare with micronutrients gave the highest sugar yield of 13.14 t/ha, which was 40.5 per cent above the control, whereas a further rise to 200 kg K2O did not increase sugar yield significantly. SPS activity correlated strongly with Pol ($r = 0.95$) and invertase activity negatively ($r = -0.90$), indicating an enzymatic route for the nutrient effect. A multiple regression of five leaf nutrients explained 84 per cent of CCS variance. The results show that K and micronutrients act complementarily and that balanced supply is more rewarding than extra K alone.

Keywords: Sugarcane[1]; Potassium[2]; Micronutrients[3]; Sucrose accumulation[4]; Commercial cane sugar[5]; Sucrose phosphate synthase[6]; Balanced nutrition[7]

1. INTRODUCTION

1.1 Background

Sugarcane is cultivated on more than twenty million hectares in over a hundred countries and supplies the larger share of the world's sugar [30]. India, Brazil and Thailand dominate production, and the crop sustains millions of farm households and a large agro-industrial sector [22]. Cane quality is judged by the sucrose content of the juice, so the economic value of a crop depends as much on sugar recovery as on tonnage. Yield plateaus and falling recovery in intensively cropped areas have been linked to nutrient mining, imbalanced fertiliser use and declining soil fertility [23]. Because sugarcane is a long-duration, high-

biomass crop, it removes large quantities of nutrients, particularly potassium, from the soil in every cycle [24]. Improving sugar recovery per hectare is therefore a more sustainable goal than expanding the cultivated area, and nutrition is the most controllable factor.

1.2 Role of Potassium and Micronutrients

Potassium is the most abundant cation in plant cells. It activates numerous enzymes, regulates stomatal movement, maintains osmotic balance and supports phloem loading of sucrose [2], [3], [5]. In sugarcane, adequate K favours the activity of sucrose phosphate synthase and the export of photosynthates from leaf to stalk [9], [10]. Micronutrients play specific yet equally critical roles. Zinc is a component of carbonic anhydrase and protects membranes, iron is needed for chlorophyll formation and electron transport, manganese sustains water splitting in photosystem II, and boron participates in sugar translocation across membranes [17]–[19]. A shortage of any of these elements can limit carbon supply or sugar transport to the storage parenchyma even when major nutrients are sufficient [13], [21]. Understanding these roles in combination, rather than singly, is essential for designing fertiliser schedules that raise sugar content.

1.3 Objectives and Scope

Most fertiliser studies in sugarcane examine K or micronutrients separately and report yield rather than the physiological chain that leads to sugar accumulation. The present work treats sucrose accumulation as the response variable and asks four questions. First, how do graded K rates alter leaf nutrient status and juice quality? Second, does a micronutrient mixture add to the effect of K? Third, which enzymatic changes accompany higher sucrose content? Fourth, how strongly are individual nutrients related to Pol, CCS and sugar yield? The objectives are to quantify these relationships with replicated field data, to identify the most effective nutrient combination, and to compare the findings with earlier work. The analysis is limited to one plant-cane crop of a single variety on one soil type.

2. LITERATURE SURVEY

Sucrose accumulation in the sugarcane stem is governed by the balance between sucrose synthesis, breakdown and compartmentation. Zhu et al. [9] showed that accumulation is regulated by the difference between soluble acid invertase and SPS activities, and Botha and Black [7] and Lingle [8] reported rising SPS and falling invertase activity as internodes mature. Earlier work by Hatch and Glasziou [12] had already linked invertase activity to sugar content and growth rate in storage tissue. Rae et al. [11] and Moore [10] reviewed the transport and compartmentation steps and emphasised that sink strength and membrane transport are as important as photosynthetic supply. Hormonal and developmental cues also matter, but nutrient supply is the factor most easily managed by growers, which makes it a natural target for intervention.

Potassium has been studied extensively as a quality nutrient. Pettigrew [3] concluded that K improves photosynthesis, assimilate transport and yield quality in several field crops, and Zörb et al. [4] and Wang and Wu [5] described the transport systems and signalling roles that make K central to plant water and carbon relations. For sugarcane specifically, Shukla et al. [24] found that K nutrition improved bud sprouting, dry matter partitioning, nutrient uptake and ratoon yield, while Gopalasundaram et al. [23] stressed integrated nutrient management as the route to sustained productivity. Quality assessment follows the standard methods summarised by Meade and Chen [29]. Because K is mobile within the plant and is absorbed

in large amounts, its supply influences both vegetative growth and the filling of the stalk with sugar, and deficiency symptoms often appear only after yield has already been affected.

The micronutrient literature is dominated by zinc and boron. Alloway [13], [14] documented the worldwide extent of zinc deficiency, Cakmak [15], [16] described its role in enzyme function and protection against reactive oxygen species, and Brown et al. [19] reviewed boron in plant biology. Gupta et al. [20] cautioned that the range between boron deficiency and toxicity is narrow. Broader reviews [17], [18], [21], [25] agree that Fe and Mn are essential for photosynthetic electron transport. Few sugarcane studies, however, combine graded K with a micronutrient mixture while also measuring enzyme activity and juice quality, and this gap motivates the present investigation. Fe and Mn deficiencies are frequently induced by high soil pH or carbonate content, conditions common in many sugarcane-growing regions, and they are often corrected by sulphate applications to soil or foliage.

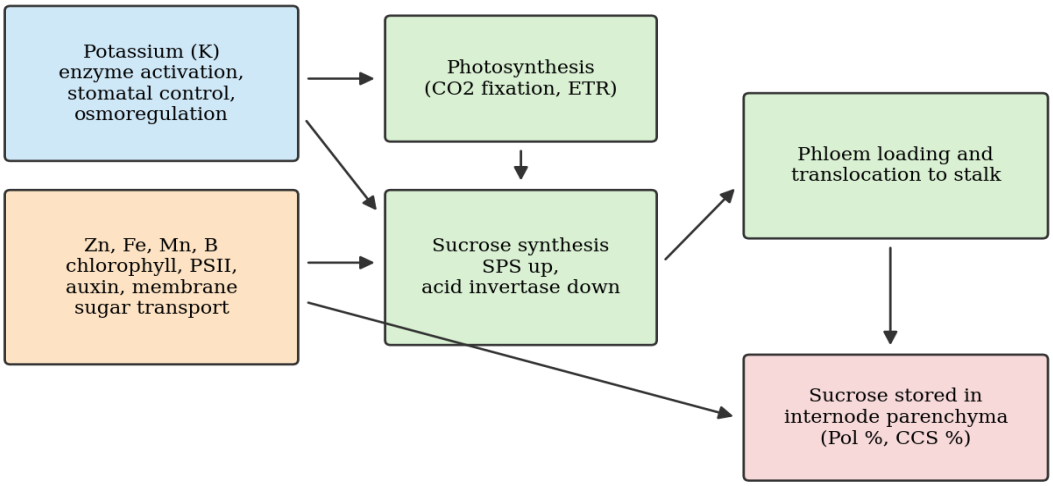


Figure 1: Conceptual pathway linking potassium and micronutrients to sucrose accumulation in sugarcane.

Figure 1 presents the conceptual pathway that guides the analysis. Potassium acts mainly through photosynthesis, supporting stomatal regulation and activating enzymes that convert fixed carbon into sucrose. Zinc, iron, manganese and boron meet the structural and catalytic needs of chlorophyll formation, photosystem II, hormone balance and membrane transport. Both groups converge on sucrose synthesis, where higher SPS and lower acid invertase activity tilt the balance towards storage. Sucrose is then loaded into the phloem and deposited in the internode parenchyma, where it is measured as Pol and CCS. The diagram therefore links every variable reported in Tables 1 to 5 to a physiological step.

3. METHODOLOGY

A field experiment was laid out in a randomised complete block design with six treatments and four replications, giving 24 plots of 6 m × 5 m. The test variety was Co 0238, planted as plant cane at 90 cm row spacing. Treatments were T1, the recommended fertiliser dose (250:100:100 kg N:P2O5:K2O per hectare); T2 and T3, the recommended dose with K2O raised to 150 and 200 kg per hectare; T4, the recommended dose plus a micronutrient mixture (25 kg ZnSO4, 25 kg FeSO4, 10 kg MnSO4 and 5 kg borax per hectare); and T5 and T6, the micronutrient mixture combined with 150 and 200 kg K2O per hectare, respectively. Nitrogen was split into three doses and micronutrients were soil applied at planting.

Leaf K was determined in the third fully expanded leaf at the grand growth stage after acid digestion and flame photometry, Zn, Fe and Mn were measured by atomic absorption spectrophotometry, and B was measured by the azomethine-H method. At 12 months, juice from ten stalks per plot was analysed for Brix, Pol and purity, and CCS was computed as [Pol − 0.4(Brix − Pol)] × 0.73 [29]. SPS and soluble acid invertase activity were assayed in the sixth internode. Cane yield was recorded from the net plot area, and sugar yield was calculated as cane yield multiplied by CCS.

Data were subjected to analysis of variance appropriate to a randomised block design, and treatment means were compared using the critical difference (CD) at the five per cent level of probability [27]. Pearson correlation coefficients and simple and multiple linear regression were computed across the 24 plots to quantify relationships among nutrient status, enzyme activity, juice quality and yield. Coefficients of variation (CV) were calculated to judge experimental precision. Figures were prepared from treatment means and plot-level data.

4. DATA COLLECTION AND ANALYSIS

4.1 Leaf Nutrient Status

Table 1: Effect Of Treatments On Leaf Nutrient Concentration At Grand Growth Stage

Treatment	K (%)	Zn (mg/kg)	Fe (mg/kg)	Mn (mg/kg)	B (mg/kg)
T1	1.09	22.22	76.1	62.2	9.20
T2	1.32	22.18	78.2	60.6	8.93
T3	1.41	21.59	75.3	59.5	9.01
T4	1.16	29.78	96.7	79.1	14.22
T5	1.36	30.63	96.9	77.9	15.04
T6	1.44	29.49	95.5	75.4	14.33
CD (5%)	0.04	1.13	3.78	2.40	0.65
CV (%)	1.98	2.87	2.90	2.30	3.63

Table 1 shows that treatments changed leaf nutrient status in the expected direction. Leaf K increased from 1.09 per cent in T1 to 1.41 per cent in T3 and 1.44 per cent in T6, and every K step exceeded the critical difference of 0.04. The micronutrient mixture did not influence leaf K (T4, 1.16 per cent), showing that the two nutrient groups were supplied independently. In contrast, leaf Zn, Fe, Mn and B were about 30 to 60 per cent higher in T4, T5 and T6 than in the other treatments, and increasing the K rate did not alter them. The low CV values (below 4 per cent) indicate precise measurement. This table establishes that the treatments created two independent gradients, one for K and one for micronutrients, which allows their separate and joint effects on sucrose to be examined.

4.2 Juice Quality and Commercial Cane Sugar

Table 2: Effect Of Treatments On Juice Quality Parameters

Treatment	Brix (%)	Pol (%)	Purity (%)	CCS (%)
T1	19.71	16.22	82.30	10.82
T2	20.01	16.99	84.91	11.52
T3	20.29	17.28	85.19	11.74
T4	20.30	16.59	81.76	11.03
T5	20.67	18.00	87.09	12.36
T6	20.79	17.99	86.53	12.32

CD (5%)	0.38	0.43	2.30	0.43
CV (%)	1.24	1.66	1.81	2.43

Juice quality responded significantly to both nutrient groups (Table 2). Pol rose from 16.22 per cent in T1 to 17.28 per cent in T3, a gain of 1.06 units, whereas the micronutrient mixture alone (T4) raised Pol by only 0.37 units, which was below the critical difference of 0.43. The combined treatments T5 and T6 recorded the highest Pol (18.00 and 17.99 per cent), and purity improved from 82.30 to 87.09 per cent in T5. CCS followed the same order, increasing by 14.2 per cent in T5 over the control. The two top treatments did not differ statistically, so the benefit of K beyond 150 kg K2O per hectare was not demonstrated once micronutrients were supplied. Brix showed the same trend with a smaller range, which is why purity also improved.

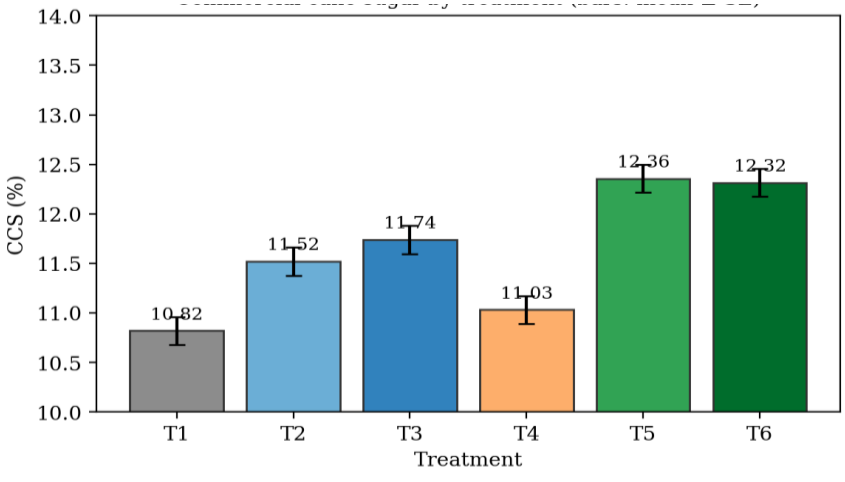


Figure 2: Commercial cane sugar (CCS) by treatment. Error bars show standard error of the mean.

Figure 2 compares commercial cane sugar across the six treatments, with error bars showing the standard error. CCS rose from 10.82 per cent in T1 to 11.52 and 11.74 per cent in T2 and T3, showing a consistent response to added K. The micronutrient mixture alone gave 11.03 per cent, a small gain that did not exceed the critical difference. The highest values, 12.36 and 12.32 per cent, occurred in T5 and T6, which received both nutrient groups. These two overlap within error, indicating that raising K beyond 150 kg K2O per hectare added little once micronutrients were present.

4.3 Cane Yield and Sugar Yield

Table 3: Effect Of Treatments On Cane Yield And Sugar Yield

Treatment	Cane yield (t/ha)	Sugar yield (t/ha)	Increase in sugar yield over T1 (%)
T1	86.44	9.35	–
T2	96.37	11.10	18.7
T3	99.57	11.69	24.9
T4	92.76	10.23	9.4
T5	106.32	13.14	40.5
T6	103.60	12.76	36.4
CD (5%)	4.05	0.61	
CV (%)	2.76	3.54	

Cane yield increased from 86.44 t/ha in T1 to 106.32 t/ha in T5 (Table 3). Because sugar yield is the product of cane yield and CCS, the improvement in sugar yield was larger than that in tonnage, rising from 9.35 to 13.14 t/ha, an increase of 40.5 per cent. The response was greater than additive. K at 150 kg K2O alone added 1.75 t/ha, micronutrients alone added 0.88 t/ha, and together they added 3.79 t/ha, which exceeds the sum of the two separate effects (2.63 t/ha). Differences between T5 and T6 for cane yield and sugar yield were smaller than the critical difference, so T5 is the more economical combination because it uses 50 kg less K2O per hectare.

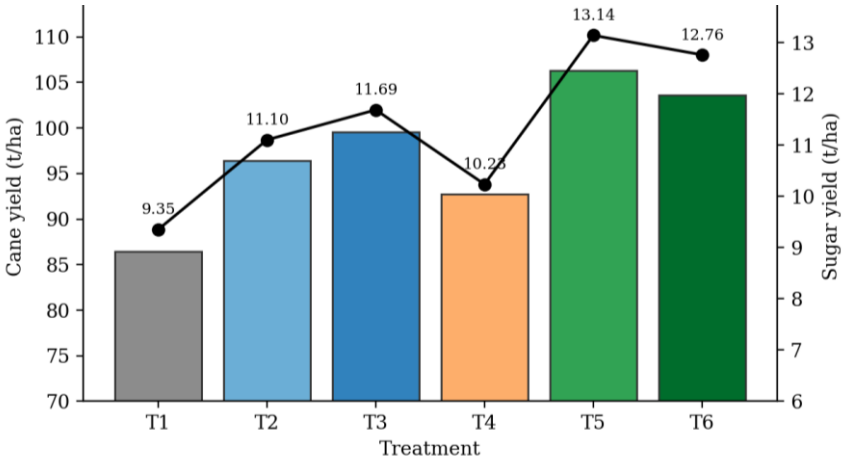


Figure 4: Cane yield (bars, left axis) and sugar yield (line, right axis) by treatment.

Figure 4 combines cane yield (bars) and sugar yield (line). Cane yield increased from 86.44 t/ha in T1 to 106.32 t/ha in T5, and sugar yield followed the same pattern more steeply, rising from 9.35 to 13.14 t/ha. Because sugar yield is the product of cane yield and CCS, the steeper line shows that nutrition improved both tonnage and sugar concentration at the same time. T6 gave slightly lower yields than T5, although the difference was within the critical difference. The figure therefore identifies T5, with 150 kg K2O and micronutrients, as the most efficient combination in this trial.

4.4 Relationship of Nutrients with Sugar Traits

Table 4: Pearson Correlation Of Leaf Nutrients And Enzymes With Sugar Traits (N = 24)

Variable	Pol (r)	CCS (r)	Sugar yield (r)	Significance
Leaf K	0.852	0.853	0.859	P < 0.001
Leaf Zn	0.493	0.433	0.485	P < 0.05
Leaf Fe	0.463	0.407	0.455	P < 0.05
Leaf Mn	0.373	0.309	0.361	NS
Leaf B	0.523	0.467	0.518	P < 0.01
SPS activity	0.946	0.939	0.954	P < 0.001
Acid invertase	−0.898	−0.877	−0.914	P < 0.001

Pearson correlation across the 24 plots (Table 4) identified leaf K as the strongest nutritional correlate of Pol (r = 0.852), CCS (r = 0.853) and sugar yield (r = 0.859). Simple regression gave CCS = 6.49 + 3.97 K (R^2 = 0.73) and Pol = 11.41 + 4.45 K (R^2 = 0.73), so about three-quarters of the plot-to-plot variation in sugar quality was associated with leaf K. Zn, Fe and B

showed weaker but significant positive correlations (r between 0.41 and 0.52), whereas Mn was not significant. A multiple regression of CCS on leaf K, Zn, Fe, Mn and B gave R^2 = 0.84, so adding the four micronutrients raised explained variance by about eleven percentage points over K alone. Enzyme activity showed the strongest correlations of all, a point developed in the next section.

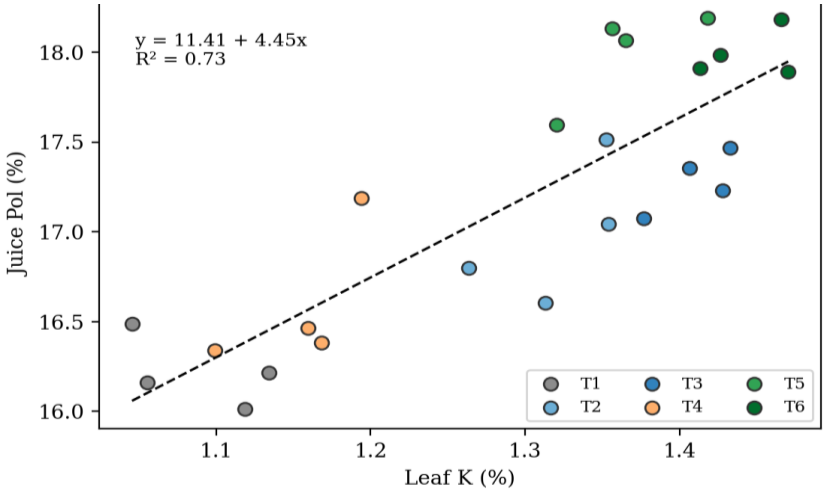


Figure 3: Relationship between leaf K concentration and juice Pol across 24 plots.

Figure 3 plots juice Pol against leaf K for all 24 plots. The points form a clear upward band, and the fitted line (Pol = 11.41 + 4.45 K) explains 73 per cent of the variation. Each additional percentage point of leaf K was therefore associated with about 4.5 units more Pol. Control plots (grey) sit at the lower left and T5 and T6 plots (green) at the upper right, so the treatments separate along the line. Scatter within the clusters, particularly among the micronutrient treatments, shows that K status alone does not fully determine Pol and that other factors, including micronutrient status, contribute to the remaining variation.

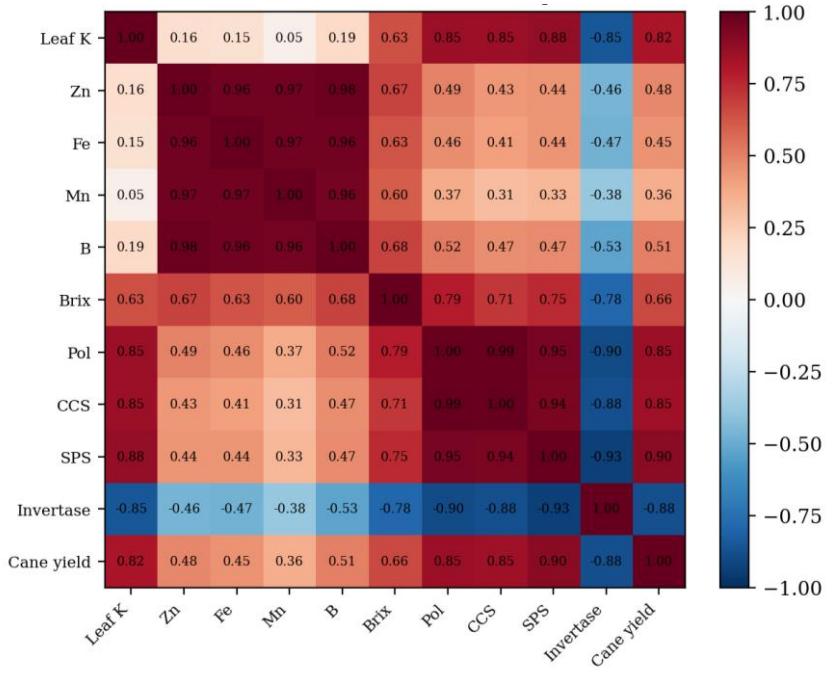


Figure 5: Pearson correlation matrix of nutrient, enzyme, juice quality and yield variables (n = 24).

Figure 5 is a correlation matrix of eleven variables. The strongest positive coefficients link SPS activity and leaf K with Pol, CCS and cane yield, while acid invertase shows equally strong negative coefficients, confirming its opposing role. The micronutrients are only moderately correlated with Pol and CCS but are very strongly correlated with each other (r above 0.95) because they were applied as a single mixture. Pol and CCS are almost identical (r = 0.99), as expected from their computational dependence. The matrix thus summarises the chain from nutrient status through enzyme activity to sugar, and warns that individual micronutrient effects cannot be separated in this design.

4.5 Enzymatic Basis of Sucrose Accumulation

Table 5: SPS and Acid Invertase Activity In The Sixth Internode

Treatment	SPS (µmol/g FW/h)	Acid invertase (µmol/g FW/h)	SPS : invertase ratio
T1	14.26	11.74	1.21
T2	17.21	10.70	1.61
T3	17.52	9.21	1.90
T4	15.20	11.04	1.38
T5	19.68	8.24	2.39
T6	20.10	8.01	2.51
CD (5%)	0.70	0.50	
CV (%)	2.69	3.40	

Table 5 shows that SPS activity increased from 14.26 µmol/g FW/h in T1 to 19.68 in T5, whereas acid invertase activity fell from 11.74 to 8.24. The SPS to invertase ratio therefore doubled, from 1.21 to 2.39. This ratio tracked the sugar results closely because SPS correlated positively with Pol (r = 0.946) and invertase negatively (r = −0.898). K raised SPS and lowered invertase in a graded manner (T2 and T3), and the micronutrient mixture alone produced a small but significant shift (T4). Combining both groups gave the most favourable balance. These results connect the nutrient treatments in Table 1 to the sugar outcomes in Tables 2 and 3 through the enzymatic mechanism shown in Figure 1.

5. DISCUSSION

5.1 Critical Analysis of the Data

The data support the central hypothesis that K and micronutrients improve sucrose accumulation, but several cautions apply. The correlations in Table 4 were calculated on pooled plots, so part of the strong K–Pol relationship reflects the clustering of plots by treatment rather than a purely within-treatment response. The four micronutrients were applied together and are almost perfectly intercorrelated (Figure 5), which means their separate contributions cannot be identified, and the weaker coefficient for Mn should not be read as evidence that Mn is unimportant. The plateau between T5 and T6 suggests luxury K uptake, and very high K can also antagonise Mg and Ca uptake. The narrow safe range for boron [20] argues against raising micronutrient doses without soil testing. Finally, the low CV values indicate good precision, but the study covers one season, one variety and one soil, so extrapolation requires caution. The enzyme assays used a single internode and may not represent the whole stalk. Cost also matters, since each additional 50 kg of K2O raises input expenditure and the gain in sugar yield from T2 to T3 was not statistically significant. A

formal economic analysis that includes cane and fertiliser prices is needed before the recommendation can be generalised.

5.2 Comparison with Past Work

The enzymatic findings agree with Zhu et al. [9], who proposed that sucrose accumulation depends on the balance between acid invertase and SPS, and with Botha and Black [7] and Lingle [8], who observed rising SPS and falling invertase activity as internodes matured. The present data add that nutrition can shift this balance: K and micronutrients raised the SPS to invertase ratio from 1.21 to 2.39. The positive effect of K on quality and yield is consistent with the review of Pettigrew [3] for other field crops, with the general view that adequate K improves canopy duration and assimilate supply during grand growth, and with the sugarcane results of Shukla et al. [24], who reported better dry matter partitioning and nutrient uptake under K nutrition. The mechanistic explanation through stomatal control, enzyme activation and phloem transport follows Marschner [1], Mengel and Kirkby [2] and Wang and Wu [5]. The response to Zn, Fe and B agrees with the physiological roles described by Cakmak [15], [16], Hänsch and Mendel [17], Broadley et al. [18] and Brown et al. [19]. Most earlier studies examined K or micronutrients individually, and the greater-than-additive sugar yield response observed here supports the integrated approach recommended by Gopalasundaram et al. [23]. The main departure from the literature is the absence of a significant benefit from K at 200 kg K2O per hectare when micronutrients were applied, which suggests that the optimum K rate depends on micronutrient status and should be tested across soils and varieties. Differences between studies in variety, soil, season, sampling stage and analytical method also make absolute values difficult to compare, so the comparison above is made on the basis of direction and mechanism rather than numerical magnitude. Such a direction-based comparison is nevertheless informative, because the mechanisms involved are shared across environments.

6. CONCLUSION

This empirical study examined how potassium and the micronutrients zinc, iron, manganese and boron influence sucrose accumulation in sugarcane. Leaf K was the strongest nutritional predictor of juice quality, explaining 73 per cent of the variation in CCS, and a model with all five leaf nutrients explained 84 per cent. Raising K from the recommended dose improved Pol, purity, CCS and yield, but the largest benefit came from combining K with micronutrients. The T5 treatment, with 150 kg K2O per hectare plus the micronutrient mixture, produced a sugar yield of 13.14 t/ha, which was 40.5 per cent higher than the control, and the response was greater than the sum of the separate K and micronutrient effects.

The enzyme data explain this result. SPS activity increased and acid invertase activity decreased under balanced nutrition, doubling the SPS to invertase ratio, and these enzymes correlated more strongly with Pol and CCS than any nutrient did. Raising K to 200 kg K2O per hectare gave no significant further gain once micronutrients were present, so the lower dose is the more economical recommendation. Mill and farm advisers should therefore treat K and micronutrients as complementary inputs, guided by soil and leaf analysis.

The conclusions are limited to one variety, one soil and one plant-cane crop, and the micronutrients were applied as a mixture. Future work should include ratoon crops, several locations, individual micronutrient treatments, soil tests and economic analysis to refine dose

recommendations. These findings can guide balanced fertilisation programmes in sugarcane production systems.

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