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Modeling relationship between soil potassium, plant potassium, yield and juice quality of sugarcane

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Abstract
Potassium plays a crucial role in sugarcane growth, yield formation, and sugar accumulation. A field experiment was conducted to model the relationship between soil potassium, plant potassium uptake, yield, and juice quality of sugarcane under different potassium split application schedules. The experiment was carried out for two plant crops and one ratoon crop on black cotton soil at Vasantdada Sugar Institute farm using a randomized block design with three replications. Nine potassium management treatments, including recommended dose of fertilizers, farmers' practice, and soil test–based fertilizer (STBF) approaches with varied split applications, were evaluated. Pooled results revealed that application of 100% recommended dose of potassium (RDK) based on soil testing, applied in four equal splits at planting, 45, 180, and 240 days after planting, significantly increased cane yield (124.2 t ha^{-1}), commercial cane sugar (CCS) yield (19.6 t ha^{-1}), plant population, cane height, cane girth, and benefit–cost ratio (4.5) compared to RDF. Juice quality parameters such as brix, pol, purity, and CCS percentage were not significantly influenced by potassium split application. The study concluded that soil test–based potassium application in appropriate splits improves productivity and profitability of sugarcane without adversely affecting juice quality.

Keywords: Sugarcane, potassium management, soil test–based fertilizer, cane yield, CCS yield, juice quality

Introduction
Sugarcane (*Saccharum officinarum* L.) is a major commercial crop cultivated extensively in tropical and subtropical regions of the world and serves as the principal source of sugar, ethanol, and several agro-industrial by-products. In India, sugarcane occupies a pivotal position in the agricultural economy due to its high productivity, long duration, and significant contribution to rural employment and industrial development. Owing to its high biomass production and prolonged growth period, sugarcane removes large quantities of nutrients from the soil, necessitating balanced and efficient nutrient management for sustaining yield and sugar recovery (Singh *et al*., 2018) [10].

Among the essential macronutrients, potassium (K) plays a vital role in sugarcane growth and development. Potassium is involved in enzyme activation, regulation of stomatal conductance, photosynthesis, carbohydrate metabolism, and translocation of assimilates from leaves to stalks. It also contributes to osmotic regulation, water-use efficiency, stress tolerance, stalk strength, and resistance to pests and diseases (Orlando Filho, 2014; Havlin *et al.*, 2017) [6, 3]. In sugarcane, potassium nutrition is closely associated with cane elongation, juice extraction efficiency, and sucrose accumulation in the stalk, thereby directly influencing cane yield and commercial cane sugar (CCS) yield.

Traditionally, many Indian soils, particularly black cotton soils, were considered rich in potassium due to the presence of K-bearing minerals. However, continuous intensive cultivation of sugarcane, adoption of high-yielding varieties, limited recycling of crop residues, and imbalanced fertilizer use have resulted in gradual depletion of available potassium and reduced potassium-supplying capacity of soils (Tiwari, 2017) [14]. Despite this, potassium fertilization in many sugarcane-growing regions remains either neglected or applied indiscriminately without reference to soil test values, leading to low nutrient use efficiency and inconsistent yield responses.

An important practical issue observed in farmers' fields is the application of potash fertilizer at later stages of crop growth, including maturity, even though general fertilizer recommendations suggest potassium application only up to about 120 days after planting. Farmers often apply potassium at advanced growth stages based on visual crop response or traditional experience, believing that late application improves cane weight and juice quality. This practice raises a critical scientific question: whether potassium application during the maturity phase is beneficial or necessary, particularly when soils already contain appreciable levels of available potassium.

Sugarcane often shows a response to potassium fertilization even in soils testing medium to high in available K. This phenomenon has been attributed to factors such as limited diffusion of potassium in heavy textured soils, fixation of potassium in non-exchangeable forms, high crop demand during peak growth phases, and restricted root activity at later stages of crop growth (Sparks & Huang, 1985; Römheld & Kirkby, 2010) [13, 8]. Moreover, the temporal mismatch between soil potassium availability and crop demand may result in transient potassium deficiency during critical stages, thereby justifying split application strategies rather than a single basal dose.

Soil test–based fertilizer (STBF) recommendations and judicious split application of potassium synchronized with crop growth stages have been suggested as effective approaches to improve potassium uptake efficiency and crop performance (Tiwari, 2017) [14]. However, systematic field-based studies evaluating the effect of potassium application beyond the traditionally recommended stages, and quantifying its impact on yield, juice quality, and economics, are limited. Furthermore, integrated modeling studies linking soil potassium status, plant potassium uptake, yield, and juice quality under different split application schedules are scarce, particularly under black cotton soils of Maharashtra.

Therefore, the present investigation was undertaken to evaluate and model the relationship between soil potassium, plant potassium uptake, yield, juice quality, and economic returns of sugarcane under different potassium split application strategies, with special emphasis on assessing the beneficial or non-beneficial effects of potassium application during later growth and maturity phases. The study aims to generate scientific evidence to rationalize farmers' practices and refine potassium fertilizer recommendations for sustainable and profitable sugarcane production.

Materials and Methods

Experimental site and soil

The study was conducted at the Vasantdada Sugar Institute farm, Maharashtra, India, on medium to deep black cotton soil during 2018–19 to 2021–22. The experiment was laid out in a Randomized Block Design (RBD**)** with three replications. Sugarcane variety VSI 08005was planted during the suru season at 4.5 ft spacing, with plot size of 9.59 × 8.0 m².Nine potassium application strategies were evaluated: an absolute control (T_1), recommended dose of fertilizer (RDF; T_2), farmers' practice with additional K at 240 DAP (T_3), and six treatments receiving 100% recommended dose of potassium (RDK) applied in various split schedules (T_4–T_9), including 4 or 6 splits and application with or without sugarcane trash-based fertilizer (STBF).The experiment included two plant crops and one ratoon crop**.** Data were collected on cane yield, commercial cane sugar (CCS) yield, plant population, millable cane height, internode number, cane girth, juice quality parameters (brix, pol, purity, CCS%), and economics. Pooled analysis was performed over the plant and ratoon crops. Data were subjected to ANOVA following RBD, and treatment means were compared using critical difference (CD)at 5% probability. The data collected was statistically analyzed as per the procedures given by Panse and Sukhatme (1978) [7].

Cane and CCS yield

Pooled analysis of two plant crops and one ratoon crop clearly indicated that potassium management significantly influenced both cane yield and commercial cane sugar (CCS) yield of sugarcane. Treatments receiving soil test–based potassium in split doses consistently recorded higher cane yield, which was directly reflected in increased CCS yield. Application of 100% recommended dose of potassium (RDK) based on soil test–based fertilizer (STBF) in four equal splits (T_7) resulted in superior cane yield, while the highest CCS yield (20.2 t ha^{-1}) was observed in T_9, closely followed by T_7 (19.6 t ha^{-1}), both being significantly superior to the recommended dose of fertilizers (RDF; 17.5 t ha^{-1}). The enhancement in CCS yield was primarily attributed to increased cane yield rather than significant alterations in juice quality parameters, indicating that higher biomass production per unit area was the major contributor to sugar output. Potassium plays a pivotal role in photosynthesis, carbohydrate metabolism, enzyme activation, and phloem transport, thereby ensuring efficient translocation of assimilates from source leaves to developing stalks, which enhances both cane growth and sugar accumulation (Römheld & Kirkby, 2010; Orlando Filho, 2014; Marschner, 2012) [8, 6, 5]. Split application of potassium ensures continuous availability throughout the long crop duration of sugarcane, particularly during critical stages such as tillering, grand growth, and stalk elongation, preventing transient deficiencies and improving nutrient use efficiency (Tiwari, 2017; Shukla *et al.*, 2020) [14, 9]. Several studies have also reported that soil test–based and split potassium application significantly improves cane yield and CCS yield under black and alluvial soils, mainly through enhanced dry matter accumulation, improved photosynthetic efficiency, and sustained assimilate transport rather than drastic changes in juice quality traits (Singh *et al*., 2018; Bhatt *et al*., 2022) [10, 1]. Thus, optimized potassium management through appropriate rate, timing, and soil test–based application emerges as a key strategy for maximizing sugarcane productivity and sugar yield per unit area.

Plant population and growth parameters

Plant population was numerically higher under soil test–based potassium treatments, with the maximum population (89.1 thousand ha^{-1}) recorded in treatment T_7, indicating a positive influence of balanced potassium nutrition on early crop establishment and tiller survival. Although the number of millable canes did not differ significantly among treatments, potassium application significantly influenced important growth parameters such as millable cane height and cane girth. Treatments receiving potassium in multiple splits up to later growth stages produced significantly taller canes, highlighting the importance of sustained potassium availability during the elongation and grand growth phases of sugarcane. Adequate potassium nutrition enhances cell elongation and expansion by maintaining cellular turgor, regulating osmotic balance, and improving stomatal conductance, which together promote higher photosynthetic efficiency and assimilate production (Marschner, 2012; Havlin *et al*., 2017) [5, 3]. Increased cane girth observed under T_7 compared to RDF may be attributed to improved carbohydrate translocation and efficient dry matter partitioning to the stalk under optimal potassium supply. The number of internodes, however, remained largely unaffected across treatments, suggesting that potassium mainly influenced internode elongation and thickening rather than internode initiation. Similar improvements in stalk height, diameter, and overall physical quality of sugarcane with adequate and well-timed potassium fertilization have been reported under diverse agro-ecological conditions, emphasizing potassium's role in enhancing individual cane weight and yield potential (Srivastava & Rai, 2014; Kingston, 2016; Singh *et al*., 2019) [12, 4, 11].

Juice quality parameters

Juice quality parameters such as brix, pol, purity, and CCS percentage were not significantly influenced by different potassium application schedules. This indicates that potassium application mainly affected biomass production and sugar yield through increased cane yield rather than altering juice composition. Similar observations have been reported by several researchers, noted that potassium improves sugar yield indirectly by enhancing cane growth, while juice quality parameters remain relatively stable (Orlando Filho, 2014; Tiwari, 2017) [6, 14].

Economic evaluation

Economic analysis revealed that soil test–based potassium application in four equal splits (T_7) resulted in the highest benefit–cost ratio (4.5), indicating superior profitability over RDF and farmers' practice. The higher economic returns were attributed to increased cane and CCS yields without a proportionate increase in cost of cultivation. These findings emphasize the economic advantage of adopting soil test–based and split potassium fertilization strategies in sugarcane cultivation (Singh *et al*., 2018) [10].

Modeling relationship between potassium and yield

Regression analysis showed a strong and positive relationship between plant potassium uptake and cane yield ($R^2 = 0.78$) as well as CCS yield ($R^2 = 0.74$), indicating that improved potassium uptake significantly enhanced productivity. Soil available potassium also exhibited a positive association with cane yield, though the relationship was relatively weaker. The absence of a significant relationship between potassium levels and juice quality parameters further supports the conclusion that potassium primarily influences yield attributes rather than juice quality composition (Sparks & Huang, 1985; Römheld & Kirkby, 2010) [13, 8].

Table 1: Effect of soil potassium and plant potassium on cane, CCS yield and economic evaluation

Treatment	Cane yield (t ha^{-1})	CCS yield (t ha^{-1})	B:C ratio	No. of milliable cane ('000') ha
T_1- Absolute control	109.6	17.6	6.0	82.3
T_2 - RDF (340:170:170 NPK kg/ha) – (50% RDK at planting + 50% RDK at earthing up)	113.4	17.5	4.0	85.2
T_3 –Farmers practice (Kolhapur region- 400:200:200 NPK kg/ha) – (50% RDK at planting + 50% RDK at earthing up + additional 30Kg potash at 240DAP)	121.2	19.3	4.0	87.5
T_4 – 100% RDK (12.5% RDK at planting + 12.5% RDK at earthing up + 25% RDK at 180 DAP + 50% RDK at 240 DAP)	118.1	19.2	4.1	85.5
T_5 – 100% RDK on STBF (12.5% RDK at planting + 12.5% RDK at earthing up + 25% RDK at 180 DAP + 50% RDK at 240 DAP)	122.0	19.6	4.5	86.5
T_6 - 100% RDK 25% RDK at planting + 25% RDK at 45DAP + 25% RDK at 180 DAP + 25% RDK at 240 DAP	120.8	19.0	4.2	86.7
T_7 - 100% RDK on STBF 25% RDK at planting + 25% RDK at 45DAP + 25% RDK at 180 DAP + 25% RDK at 240 DAP	124.2	19.6	4.5	89.1
T_8- 100% RDK (12.5% RDK at planting + 12.5% RDK 60 DAP + 25% RDK at earthing up + 12.5% RDK at 180 DAP + 25% RDK at 240 DAP+ 12.5% RDK at 300DAP)	121.7	19.1	4.3	87.7
T_9 - 100% RDK on STBF (12.5% RDK at planting + 12.5% RDK 60 DAP + 25% RDK at earthing up + 12.5% RDK at 180 DAP + 25% RDK at 240 DAP+ 12.5% RDK at 300DAP	123.5	20.2	4.5	86.5
S.E.±	2.93	0.43		1.57
CD%	8.80	1.30		NS
CV	4.73	4.39		

Table 2: Effect of potassium and plant potassium on growth observation

Treatment	Milliable cane height (cm)	Internode	Girth (cm)	CCS %
T_1- Absolute control	245.1	18.6	8.8	16.0
T_2 - RDF (340:170:170 NPK kg/ha) – (50% RDK at planting + 50% RDK at earthing up)	251.6	20.0	9.2	15.5
T_3 –Farmers practice (Kolhapur region- 400:200:200 NPK kg/ha) – (50% RDK at planting + 50% RDK at earthing up + additional 30Kg potash at 240DAP)	260.1	21.2	9.5	15.5
T_4 – 100% RDK (12.5% RDK at planting + 12.5% RDK at earthing up + 25% RDK at 180 DAP + 50% RDK at 240 DAP)	264.7	21.0	9.7	16.2
T_5 – 100% RDK on STBF (12.5% RDK at planting + 12.5% RDK at earthing up + 25% RDK at 180 DAP + 50% RDK at 240 DAP)	271.1	22.7	9.8	15.8
T_6 - 100% RDK 25% RDK at planting + 25% RDK at 45DAP + 25% RDK at 180 DAP + 25% RDK at 240 DAP	261.0	22.4	9.8	15.7
T_7 - 100% RDK on STBF 25% RDK at planting + 25% RDK at 45DAP + 25% RDK at 180 DAP + 25% RDK at 240 DAP	270.1	20.4	10.0	15.8
T_8- 100% RDK (12.5% RDK at planting + 12.5% RDK 60 DAP + 25% RDK at earthing up + 12.5% RDK at 180 DAP + 25% RDK at 240 DAP+ 12.5% RDK at 300DAP)	272.8	20.9	9.8	15.7
T_9 - 100% RDK on STBF (12.5% RDK at planting + 12.5% RDK 60 DAP + 25% RDK at earthing up + 12.5% RDK at 180 DAP + 25% RDK at 240 DAP+ 12.5% RDK at 300DAP	279.1	22.1	9.9	16.4
S.E.±	6.06	0.98	0.20	0.37
CD%	18.2	NS	0.62	NS
CV	4.42		4.15	

Conclusion

The present study clearly demonstrated that soil test–based application of 100% recommended dose of potassium (RDK) in four equal splits at planting, 45, 180, and 240 days after planting significantly enhanced cane yield, commercial cane sugar (CCS) yield, and economic returns of sugarcane grown on black cotton soils. The superiority of this potassium management strategy was attributed to sustained potassium availability throughout the crop growth period, which improved plant growth attributes, potassium uptake, and efficient translocation of assimilates to the stalk. Regression analysis further established a strong and positive relationship between potassium uptake and cane yield, confirming the critical role of potassium in determining productivity. Importantly, juice quality parameters such as brix, sucrose, and purity remained largely unaffected by potassium treatments, indicating that improvements in CCS yield were primarily driven by higher cane yield rather than changes in juice quality. The findings highlight that soil test–based and split potassium application enhances nutrient use efficiency, prevents both potassium deficiency and excess application, and supports balanced crop nutrition. Therefore, adoption of soil test–based potassium management with split application is recommended as a sustainable and economically viable practice for improving sugarcane productivity in black cotton soils, contributing to long-term soil fertility, higher farmer profitability, and sustainable sugarcane production systems.

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