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RESEARCH ARTICLE

Photosynthetic Parameters, Productivity and Plant Macronutrient Acquisition in Sugarcane as Affected by Potassium Salt of Active Phosphorus (PSAP) Under North Central and Eastern Zones of India

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Abstract

Among the macronutrients, potassium (K) and phosphorus (P) are also very important nutrients that improved the cane productivity and nutrient acquisition in sugarcane plants. The research experiment was carried out at RPCAU-Kalyanpur farm, Samastipur, Bihar, India, to know the effect of potassium salt of active phosphorus (PSAP) on photosynthetic parameters, productivity and plant macronutrient acquisition in sugarcane during the spring season under North Central and Eastern zones of India during 2021–22 and 2022–23. The results of the findings revealed that leaf surface temperature, transpiration and photosynthetic rate was significantly affected by the application of recommended dose of fertilizer + sett soaking with 0.80% PSAP solution along with PSAP at the rate of 0.40, 0.65, 1.10 and 1.10% in 4 times foliar spray (60, 80, 100 and 120 DAP). It was increased by 7.9, 38.6 and 36.9% over the recommended dose of fertilizer. Growth attributes such as tillers, cane length and millable canes did not significantly influenced by the different treatments. Significantly maximum single cane weight (1340 g) was found in the plots receiving RDF along with sett soaking at the rate of 0.8% PSAP solution and PSAP in 3 times foliar spray at the rate of 0.4, 0.65 and 1.10% (60, 90 and 120 DAP). While highest cane yield (106.8 t ha^{-1}), gross (336.4×10^3 Rs ha^{-1}) and net returns (146.1×10^3 Rs ha^{-1}) were recorded in the plots applied with recommended dose of fertilizer + sett soaking with 0.80% PSAP solution along with PSAP at the rate of 0.40, 0.65, 1.10 and 1.10% in 4 times foliar spray (60, 80, 100 and 120 DAP). Although maximum value of benefit: cost ratio (1.91) was observed in recommended dose of fertilizer + sett soaking with 0.8% PSAP solution. Significant improvement in plant macronutrient (NPK) acquisition was registered under the application of recommended dose of fertilizer + sett soaking with 0.80% PSAP solution along with PSAP at the rate of 0.40, 0.65, 1.10 and 1.10% in 4 times foliar spray (60, 80, 100 and 120 DAP) and it was increased by 27.6, 37.9 and 29.2% in N, P and K compared to recommended dose of NPK (recommended dose of fertilizer). However, soil macronutrient availability and juice quality did not significantly influence by the different treatments except sugar yield. Results of the study suggests that recommended fertilizer dose + sett soaking with 0.80% PSAP solution along with PSAP at the rate of 0.40, 0.65, 1.10 and 1.10% in 4 times foliar spray (60, 80, 100 and 120 DAP) may be recommended for increasing growth, photosynthetic parameters, cane productivity, juice quality and macronutrient acquisition in sugarcane.

Keywords Sugarcane · Photosynthetic parameters · Cane yield · Macronutrient acquisition

Introduction

Sugarcane (*Saccharum* spp. hybrid complex) productivity is continuously depleting day by day and it must be significantly boosted by using available resources. Increasing agricultural production and enhancing agricultural produce quality are the foremost objectives of all agricultural developmental institutions and financing agencies, and they are working hard to achieve them. Plant nutrients have a critical role in crop growth, development, and yield. Kumar et al. (2023a) also stated that nutrient source for sugarcane plants

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should also have an appropriate quantity and proper ratios of phosphorus (P) and potassium (K). The importance of phosphorus (P) in metabolic activities and potassium (K) in inducing capabilities in plants to withstand severe abiotic and biotic stressors cannot be overstated. These key agricultural nutrients have traditionally been given by irrigation with synthetic fertilizers, which results in just 10–20% absorption by crop plants. Phosphorus is fixed in calcareous soil at a rate of 80–90%, rendering it unavailable to plants (Nandargikar et al. 2023). To address these issues, catalytic technology was used to create the potassium salt of active phosphorus (PSAP). It is also recently known as potassium metaphosphate dimer. It is a salt that doesn't include any nitrogen, sodium, or chloride. The development of potassium salt of active phosphorus (PSAP) is significant because it rapidly penetrates plant cells, controlling a range of physiological functions and lowering the incidence of insect pests (Hartt 1969; Bhatt et al. 2022; Verma et al. 2021) and ultimately increase cane juice yields and quality. In PSAP, phosphorus is catalytically activated, and the split method is used to link potassium to this highly water soluble activated phosphorus. Potassium from PSAP is very active and chloride-free. With regard to the active phosphorus in PSAP, phosphate bonds between ATP and ADP in cane helps to create more energy. PSAP's molecule is water soluble and P and K nutrients are readily available to agricultural plants in a spray and easily absorbed by plant roots and leaves. Phosphorus is one of the most significant main nutrients and is directly linked to the crucial growth process of the sugarcane plant. During the early stages of growth, the sugarcane plant has its greatest need for P (Kumar and Sinha 2008). The availability of nutrients, such as potassium (K) and phosphorus (P), to sugarcane plants can be greatly impacted by their immobilization, fixation, and leaching. Indeed, there are a number of variables that can affect how quickly sugarcane absorbs P and K from the soil, such as soil properties, water management practices, and climatic circumstances (Kumar et al. 2023a). In poor soils, deficiencies in potassium and phosphorus can also result in a large yield loss, even if their foliar application might increase cane productivity and quality (Bhatt et al. 2022). Potassium is an essential component for sugarcane, and its use can boost cane output without reducing sucrose content. Potassium significantly influences both cane productivity and various quality indicators in the crop (Bhilala et al. 2023). Proper potassium management is essential for achieving high sugarcane yields with good sugar content. It is important to adapt these guidelines to your specific region, soil conditions, and sugarcane variety, as recommendations can vary. Here are some key aspects of potassium management in sugarcane: Acquisition of nutrients is essential for plant growth as well as for maintaining osmotic pressure and water status, boosting nitrate reductase activity, and increasing transpiration and photosynthesis. Therefore, it is crucial to understand the crop response to these resources for sustainable sugarcane yield. When the PSAP is activated, minerals in the soil get ionized. It does not fix in any way. It also plays an important function in plant metabolism by generating tolerance. When various syntheses are advanced in the presence of active potassium from PSAP, more cane and sugar yield is generated. PSAP application boosts plant production by 30–50% while boosting product quality and saving cultivation costs (Nandargikar et al. 2023). It's vital to note that the efficiency of PSAP treatment might vary based on factors including soil type, climate, and the types of microorganisms utilized. Local factors and crop requirements should be used to identify the best application techniques and timing. Frequent soil testing and plant monitoring can assist guarantee that PSAP or comparable practices are employed in the most beneficial method for sugarcane production. The use of PSAP in farming will undoubtedly increase farmers' revenue by generating significant additional profits. To the best of our knowledge, there hasn't been any research done to determine that up to what extent, PSAP affects yield, quality and nutrient acquisition in sugarcane. Keeping this under consideration, experiment was planned and conducted to assess the impact of PSAP on photosynthetic parameters, productivity, nutrient acquisition and cane quality under North Central and Eastern Zones of India.

Materials and Methods

Experimental Site

An experiment was carried out during 2021–22 and 2022–23 at Kalyanpur Farm, Sugarcane Research Institute, Dr. Rajendra Prasad Central Agricultural University, Pusa, Samastipur, Bihar, India to evaluate the responses of Potassium Salt of Active Phosphorus (PSAP) on photosynthetic parameters, productivity and acquisition of macronutrient in sugarcane.

Weather Parameters

The maximum and minimum temperature ranges from 17.4–37.1 and 7.6–26.6 °C and maximum and minimum relative humidity was 75–98 and 33–87% in 2021–22, respectively. Total rainfall, evaporation and sunshine hours were 1910 mm, 121 mm and 220.1 h during spring 2021–22. While in the year 2022–23, the maximum and minimum temperature ranges from 14.3–37.9 and 6.3–26.6 °C and maximum and minimum relative humidity was 79–100 and 39–83.7%. Total rainfall, evaporation and sunshine hours were 801.2 mm and 198.1 mm, and 166.9 h, respectively, as shown in Fig. 1a and b. However 30 years average annual

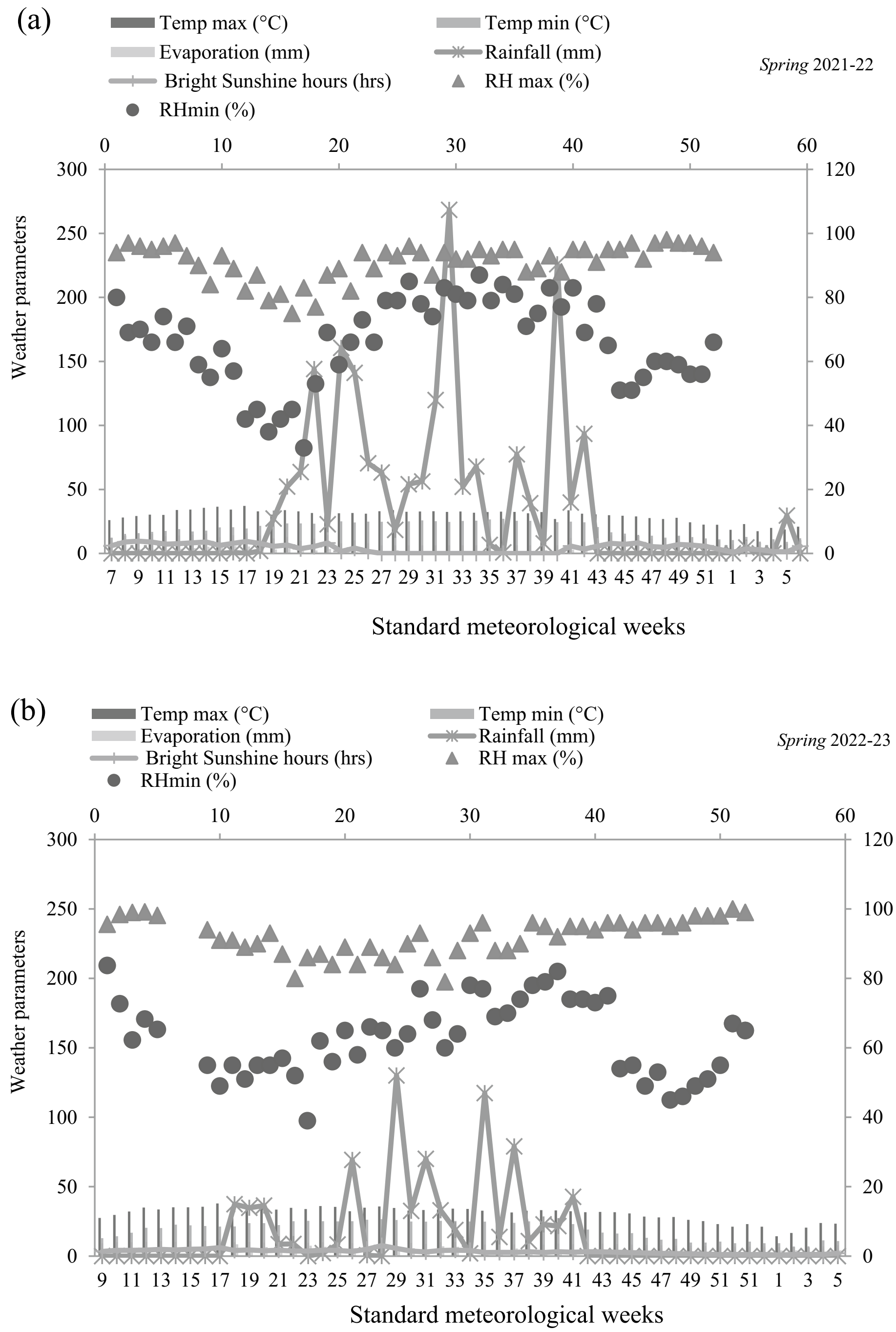

Fig. 1 **a** and **b** Meteorological parameters during experimental years 2021–22 and 2022–23

rainfall of experimental site was 1210 mm. In experimental period greater variability in rainfall pattern was experienced. During these times, variations in temperature, relative humidity, and rainfall can have a big impact on plant development and agricultural practices.

Experimental Details

The experiment was designed in randomized block with 10 treatments replicated thrice viz. T_1—Recommend dose of NPK (RDF); T_2—RDF + sett soaking with 0.8% PSAP solution; T_3—Recommended N, 50% P and 50% K; T_4—T_3 + sett soaking with 0.8% PSAP solution; T_5—T_2 + PSAP in 3 times foliar spray at the rate of 0.4, 0.65 and 0.80% (60, 90 and 120 DAP); T_6—T_2 + PSAP in 3 times foliar spray at the rate of 0.4, 0.65 and 1.10% (60, 90 and 120 DAP); T_7—T_2 + PSAP in 4 times foliar spray at the rate of 0.4, 0.65, 1.10 and 1.10% (60, 80, 100 and 120 DAP); T_8—T_4 + PSAP in 3 times foliar spray at the rate of 0.4, 0.65 and 0.80% (60, 90 and 120 DAP); T_9—T_4 + PSAP in 3 times foliar spray at the rate of 0.4, 0.65 and 1.10% (60, 90 and 120 DAP); T_{10}—T_4 + PSAP in 4 times foliar spray at the rate of 0.4, 0.65,1.10 and 1.10% (60, 80, 100 and 120 DAP). The net plot size was 8.0×4.8 m^2.

Soil Properties

The soil of the experimental plot was sandy loam in texture and alkaline in reaction (pH 8.2). The value of available N, P and K ha^{-1} were 243.0, 10.2 and 112.5 kg, respectively.

Cultural Operations

The sugarcane variety CoP 16437 planted in furrow at 120 cm row spacing with 3 bud setts under different treatments. After the field preparation, layout and sugarcane planting was done on 18 February, 2021 and 15 February, 2022 and harvesting was done on 31 January, 2022 and 28 January, 2023 in first and second year cropping season of plant crop, respectively. The recommended dose of fertilizer was 150: 37.1: 49.8 kg N, P and K ha^{-1}, respectively, which was applied in the form of urea, single super phosphate and muriate of potash. All agronomic practices were employed in the experimental fields. Irrigation was given four (04) times during different growth stages and subsequently weeding (02) and one hand hoeing was also done for good management of sugarcane crop. All packages and practices were followed for effective control of sugarcane borers during both the years of the study.

Procedures for Data Collection

Data on growth, physiological and yield parameters was taken at different growth stages of the crop. Yield and quality of juice was also taken and analysed. In both years of the experiment, five representative healthy canes were taken from each plot following the 12th month of the plant production, i.e. on 11 November 2021 and 20 November 2022. A cane crusher was used to extract juice from harvested canes for quality examination using conventional procedures (Sundara and Tripathi 1999), and the juice was also determined using the method specified by Meade and Chen (1977).

The cane yield per plot was measured during harvest by weighing the cane product and converting the weight to a cane yield. Sugar yield was calculated as;

Sugar yield (t ha^{-1}) = [S − 0.4 (B − S) × 0.73] × cane yield (t ha^{-1})/100; where S and B are sucrose and brix percent in cane juice, respectively.

B/C ratio was calculated to assess if the crop investment is economically sustainable (Kumar et al. 2023b).

Photosynthetic Parameters

Photosynthetic parameters such as the net photosynthetic rate, stomatal conductance of water and transpiration rate were observed on 120 days after foliar application of PSAP in sugarcane plants using a Li-6800 portable photosynthesis system (Li-COR Biosciences, Lincoln, NE, US). For each treatment, leaf photosynthetic parameters were recorded between 09:00 and 12:00 h on both treated and non-treated plants (three replicates). In each treatment, position-wise leaves (+ 1 to + 4 from the top to middle part of the leaf) were used for photosynthetic responses without changing the leaf angle (Verma et al. 2020). Leaf surface and leaf chamber temperature was measured by using thermocouples (Hall et al. 2014).

Soil Properties

Soil samples were collected after harvesting of sugarcane from different treatments for analysing the physico-chemical properties of post-harvest soil. All standard procedures were followed during laboratory analysis for available nitrogen, phosphorus and potassium. To assess available nitrogen, alkaline permagnate ($KMnO_4$) method were used which involves oxidizing of soil organic matter with a hot alkaline $KMnO_4$ solution. In a boric acid mixed indicator solution, the ammonia (NH_3) produced during the oxidation is distilled and trapped. By titrating with standard acid, the amount of NH_3 trapped was calculated and expressed as kg ha^{-1} (Subbiah and Asija 1956). Spectrophotometer used to extract the soil with 0.5 N $NaHCO_3$ was used to measure the amount of available phosphorus in the soil (Olsen et al. 1954) and estimated by utilizing ascorbic acid to produce a blue colour and given as kg ha^{-1}. Available soil potassium content was measured according to Hanway and Heidel's (1952) description, by extracting the potassium from the soil with a 1 N neutral ammonium acetate solution and taking a reading on a flame photometer.

Plant Nutrient Analysis

Plant samples were collected from tagged sugarcane at harvest. After being rinsed in demineralized water, they were dried in the sun to a constant weight. Standard procedures were used to estimate the concentration of N, P, and K. Nitrogen was assessed using the micro-kjeldahl method after plant samples were digested in sulphuric acid at a temperature between 360 and 410 °C. The amount of phosphorus and potassium was determined in plant samples after digestion of mixture in tri-acid solution (HNO_3, $HClO_4$, and H_2SO_4 in a ratio of 10:4:1) using the vanadomolybdo phosphoric yellow colour and flame photometeric method (Piper 1966), respectively.

Statistical Analysis

All data of this study were statistically analysed according to the technique of variance (ANOVA) for Randomized block design (RBD) using statistical tools (Gomez and Gomez 1984).

Results

Plant Growth and Physiological Characteristics

Pooled year data (Table 1) showed that germination percentage at 30 DAS and tiller at 120 DAS did not significantly affected by the different treatments. However, maximum germination (33.3%) and tillers (127.3×10^3 ha^{-1}) was observed by the foliar application of PSAP in 4 times @ 0.40, 0.65, 1.10 and 1.10% (60, 80, 100 and 120 DAP) along with RDF and sett soaking with 0.8% PSAP solution. Different treatments did not exert significant influence on cane length and millable canes at harvest. However, maximum cane length (305 cm) and millable canes (84.7×10^3 ha^{-1}) were observed in the plots supplied with T_2 + PSAP in 4 times foliar spray at the rate of 0.40, 0.65, 1.10 and 1.10% (60, 80, 100 and 120 DAP). It was increased by 8.92 and 15.4% in cane length and millable canes over the recommended dose of NPK. Single cane weight was significantly influenced by the different treatments as shown in Table 1. Maximum cane weight (1340 g) was found in the T_6 treatments, i.e. T_2 + PSAP application at the rate of 0.40, 0.65 and 1.10% in 3 times (60, 90 and 120 DAP) and it was significantly at par with sett soaking in solution of PSAP 0.80% and PSAP in 4 times foliar spray at the rate of 0.40, 0.65, 1.10 and 1.10% (60, 80, 100 and 120 DAP), respectively, with RDF. Similar effect observed in the treatments T_8, T_9, T_{10} and treatment T_1, T_3, T_4 also did not differ significantly with each other. Weight of cane under RDF treatments decreased by 21.8% compared to treatments in which recommended dose of fertilizer was applied with soaking of sett in the solution of 0.80% PSAP along with spray of PSAP at 60, 80, 100 and 120 DAP at the rate of 0.40, 0.65, 1.10 and 1.10% (Table 1). Our results indicated that leaf chamber and surface temperature did not differ among the treatments. However, significant effect on photosynthetic parameters such as transpiration (8.72 mol m^{-2} s^{-1}) photosynthetic rate (29.5 µmol m^{-2} s^{-1}) and stomatal conductance of water (0.18 mol m^{-2} s^{-1}) were observed under application of T_2 + foliar spray of PSAP at 60, 80, 100 and 120 DAP (0.40, 0.65, 1.10 and 1.10%) as presented in Fig. 2.

Yield Characteristics and Cane Yield

Yield of cane was significantly influenced by the treatments. Significantly highest cane yield (106.8 t ha^{-1}) was registered under the foliar application of PSAP at the rate of 0.40, 0.65, 1.10 and 1.10% in 4 times with RDF and sett soaking in 0.80% PSAP solution which is accounting to the extent of 35.4% compared to T_1—Recommend dose of NPK (RDF) and it was significantly similar with the T_6—T_2 + PSAP at the rate of 0.40, 0.65 and 1.10% in 3 times (60, 90 and 120 DAP). There were no significant differences in the treatments T_5, T_2 and T_{10}. Lowest cane yield was observed under application of recommended N and 50% PK. However, there were similar effect among the treatments and T_1, T_4 and T_3 as indicated in Table 1.

Table 1 Growth, yield parameters, yield and Profitability as affected by different treatments (Mean data of 2 years)

Treatments	Germination %	Tiller population ($\times10^3$ ha^{-1}) at 120 DAP	CL (cm)	MC ($\times10^3$ ha^{-1})	SCW (g)	CY (t ha^{-1})	GR ($\times10^3$ ha^{-1})	NR ($\times10^3$ ha^{-1})	BCR
T_1	27.3	105.9	280	73.4	1100	78.9	248.5	106.4	1.75
T_2	29.1	111.3	288	75.2	1235	90.9	286.3	136.6	1.91
T_3	30.3	102.4	283	72.6	1076	76.6	241.3	102.9	1.74
T_4	28.0	105.6	281	73.1	1089	78.6	247.6	101.6	1.70
T_5	28.9	116.3	296	76.9	1310	98.0	308.7	135.3	1.78
T_6	28.9	118.5	300	77.7	1340	102.4	322.6	145.7	1.82
T_7	33.3	127.3	305	84.7	1307	106.8	336.4	146.1	1.77
T_8	29.1	109.3	290	74.3	1129	82.9	261.1	91.3	1.54
T_9	29.7	108.3	287	74.6	1143	83.9	264.3	91.1	1.53
T_{10}	31.8	110.7	291	75.2	1217	90.0	283.5	96.9	1.52
SEm (±)	1.48	5.87	13.7	3.84	62.5	4.12	13.73	5.47	0.078
CD	4.41	NS	NS	NS	186	12.3	40.8	16.2	0.23

CL—cane length; MC—millable canes; SCW—single cane weight (g); CY—cane yield; GR—gross returns, NR—net returns, BCR—benefit cost ratio, CD—critical difference at 0.05% level of significance

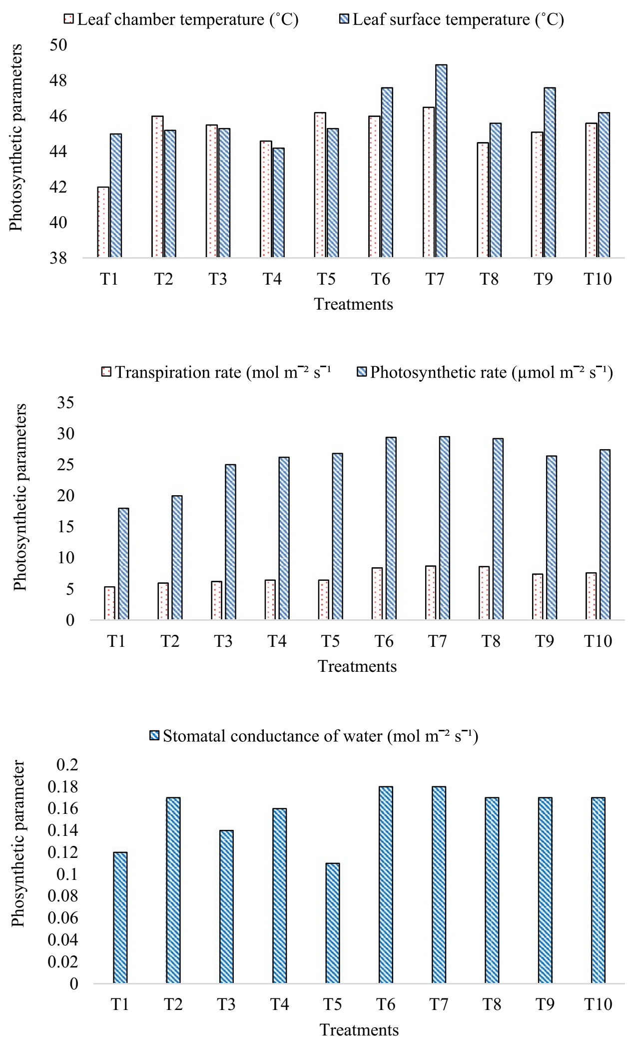

Fig. 2 Photosynthetic parameters as affected by different treatments (Mean data of 2 years)

Economics and Quality Parameters

The database obtained from Table 1 revealed that gross returns and net returns significantly showed differences among the treatments. Maximum gross returns (336.4×10^3 Rs ha^{-1}) and net returns (146.1×10^3 Rs ha^{-1}) were found in the treatments in the plots receiving RDF along with sett soaking of PSAP at the rate of 0.80% solution and spray of PSAP as foliar at the rate of 0.40, 0.65, 1.10 and 1.10% in 4 times (60, 80, 100 and 120 DAP) and it was increased by 26.1 and 27.2% over the treatments T_1-Recommend dose of NPK (RDF). Data presented in Table 1 showed that gross returns were significantly similar with the treatments T_6—PSAP application in 3 times at the rate of 0.40, 0.65 and 1.10% (60, 90 and 120 DAP) along with recommended dose of fertilizer and sett soaking in 0.8% PSAP solution. While net returns in the treatments T_6, T_2, T_5 did not significantly differ. Similarly, B:'C ratio did not affect by the different treatments. However, higher B: C ratio was found in the treatments T_2. All juice quality parameters did not differ by the treatments except sugar yield. Brix, pol, purity and commercial cane sugar percentage at 12 month was not influenced significantly by the different treatments. However, maximum brix (21.5%), pol (18.7%) in the plots receiving recommended dose of fertilizer while highest purity (88.4%) was observed in the treatments T_7 in which RDF + sett soaking with 0.80% PSAP along with foliar spray in 4 times (60, 80,100 and 120 DAP) at the rate of 0.40, 0.65, 1.10 and 1.10% of PSAP was applied (Table 2). Sugar yield was significantly higher (13.7 t ha^{-1}) in treatments T_7 and it was statistically similar with T_6 treatment. Lowest sugar yield (9.8 t ha^{-1}) was observed in treatments with reduced P and K (T_3).

Plant NPK Acquisition and Availability in Soil

Table 2 showed that different treatments exert significant influence on acquisition of nitrogen (N), phosphorus (P) and potassium (K) at harvest. Plots receiving recommended dose of fertilizer + sett soaking with 0.8% PSAP along with 0.40, 0.65, 1.10 and 1.10% of PSAP in 4 times foliar spray (60, 80,100 and 120 DAP) recorded maximum uptake of nitrogen (294.1 kg ha^{-1}), phosphorus (28.4 kg ha^{-1}) and potassium (325.7 kg ha^{-1}) compared to recommended N and 50% PK (206.7, 19.7 and 223.9, 294.1 kg ha^{-1}, respectively) and it was statistically at par with treatments T_6 –recommended dose of fertilizer along with sett soaking in PSAP solution at the rate of 0.8% and PSAP at the rate of 0.40, 0.65 and 1.10% as foliar spray in 3 times (60, 90 and 120 DAP). Availability of nutrients (NPK) did not showed any differences among the treatments. However, N availability was maximum (249 kg ha^{-1}) under the treatments T_8. While available P and K was highest in the plots receiving recommended N, 50% P and 50% K + sett soaking with 0.80% PSAP solution.

Discussion

Growth and Photosynthetic Parameters as Affected by Potassium Salt of Active Phosphorus (PSAP)

Our findings as shown in Table 1 revealed that the growth attributes such as germination and tillers at 120 DAS, did not differs by different PSAP sprays treatments. However, increase in germination of cane (33.3%) and tillers (127.3×10^3 ha^{-1}) was observed in the plots applied with recommended dose of fertilizer + sett soaking with 0.8 PSAP solution along with PSAP in 4 times spray at the rate of 0.40, 0.65, 1.10 and 1.10% (60, 80, 100 and 120 DAP) which was accounting to the extent

Table 2 Juice quality, sugar yield, plant macronutrient (NPK) acquisition and availability as affected by different treatments (Mean data of 2 years)

Treatments	Brix (%)	Pol (%)	Purity (%)	CCS (%) 12 months	SY (t ha^{-1})	Nu (kg ha^{-1})	Pu (kg ha^{-1})	Ku (kg ha^{-1})	AN (kg ha^{-1})	AP (kg ha^{-1})	AK (kg ha^{-1})
T_1	21.5	18.7	87.4	12.9	10.10	212.9	20.6	230.7	256.0	12.5	116.0
T_2	21.3	18.6	87.5	12.8	11.60	245.5	24.3	273.0	242.0	11.7	115.0
T_3	21.0	18.5	87.8	12.8	9.80	206.7	19	223.9	254.0	12.1	120.0
T_4	21.3	18.5	87.4	12.7	10.00	213.5	20.5	232.8	257.0	12.6	124.0
T_5	21.1	18.4	87.4	12.7	12.40	271.9	20.1	296.0	238.0	11.4	113.0
T_6	21.2	18.5	87.1	12.7	13.00	282.2	27.3	311.0	237.0	11.6	111.0
T_7	21.1	18.6	88.4	12.8	13.70	294.1	28.4	325.7	234.0	11.3	107.0
T_8	21.1	18.5	87.8	12.8	10.60	222.3	21.8	244.0	249.0	11.4	118.0
T_9	21.2	18.7	88.1	12.9	10.80	228.0	22.1	246.8	248.0	12.0	120.0
T_{10}	21.0	18.4	87.7	12.7	11.40	243.0	23.3	265.1	247.0	12.0	117.0
SEm (±)	0.22	0.18	0.99	0.125	0.56	11.9	1.04	13.8	12.1	0.55	5.5
CD	NS	NS	NS	NS	1.7	35.4	3.1	41.0	NS	NS	NS

CCS%—commercial cane sugar percentage, SY—sugar yield; Nu: nitrogen uptake, Pu—phosphorus uptake, Ku—potassium uptake, AN—soil available nitrogen, AP—soil available phosphorus, AK—soil available potassium CD—critical difference at 0.05% level of significance

of 18.0 and 19.6% as compared to T_1 and $T_{3,}$, respectively. This suggested that, in addition to tiller formation, P nutrition encouraged in tiller retention. Phosphorus is vital for the growth and production of sugarcane and other plants. It is essential for plant development and, in the case of sugarcane, sugar production due to its function in photosynthesis, energy transmission, and tiller formation. Appropriate phosphorus management, including fertilization, is critical for optimizing sugarcane productivity and crop health. Our results of the investigation revealed that photosynthetic rate increased with the application of PSAP in the treatments T_7 (Fig. 2). This might be due to the fact that the main physiological process for crop growth and productivity is photosynthesis (Chaves et al. 2009; Bhatt 2020). Further, Verma et al. (2021) revealed that PSAP promoted photosynthetic activity by maintaining the photosynthetic machinery in water-stressed conditions. One of the key physiological mechanisms underlying crop growth and yield is photosynthetic capability. This procedure has a significant influence on plant growth and production (Chaves et al. 2009). Plant leaves are indeed the primary sites for photosynthetic activities, and their structure and arrangement play a crucial role in the efficiency of photosynthesis (Verma et al. 2020). To maximize plant output, maintain healthy leaves and make sure they get enough light, nutrients, and water. Leaf health, leaf orientation, and the number and arrangement of leaves on a plant can all have an influence on its overall photosynthetic efficiency. Proper leaf care and management are essential for plant growth and development, especially crops such as sugarcane, where high sugar production is based on effective photosynthesis. In our research, findings revealed that leaf chamber and leaf surface temperature did not influence by the different treatments (Fig. 2). Significant highest values of transpiration, photosynthetic rate and stomatal conductance of water (mol m^{-2} s^{-1}) were observed under application of PSAP at the rate of 0.40, 0.65, 1.10 and 1.10% (60, 80, 100 and 120 DAP) in 4 times with recommended dose of fertilizer and soaking of setts at the rate of 0.80% solution which is accounting to the tune of 7.9, 38.6 and 33.3%, respectively (Fig. 2). This might be due to the reason that the foliar application of nutrients is a common practice in agriculture and horticulture. It involves applying nutrient solutions directly to the leaves of plants, allowing for the rapid absorption of essential mineral elements. Foliar application of PSAP offers several advantages, including the ability to supplement plant nutrition during critical growth phases without concerns about nutrient interactions with soil particles (Fernandez and Brown 2013).

Yield Attributes and Yield as Affected by Potassium Salt of Active Phosphorus (PSAP)

The results of the field study showed that millable canes did not affected by the different treatments (Table 1). However, higher number of millable canes registered under the T_7

treatments in which combined use of fertilizer and PSAP @ 0.40, 0.65, 1.10 and 1.10% at 60, 80, 100 and 120 DAP was applied with sett soaking. It eventually resulted in a greater number of mature stalks, most likely due to the formation of additional meristems and an increase in total metabolic activity in the plants. Kumar and Sinha (2008) found that P fertilization had a substantial impact on tillers and millable canes. The analysis of data highlights that single cane weight and yield of sugarcane was significantly higher by the application of PSAP as foliar spray at different growth periods of crop. Maximum cane weight and cane yield was achieved in the plots receiving RDF + sett soaking with 0.8% PSAP solution in combination with foliar spray of PSAP in 4 times at the rate of 0.40, 0.65, 1.10 and 1.10% (60, 80, 100 and 120 DAP) as presented in Table 1. This might be due to the fact that application of PSAP is an agricultural practice aiming at increasing the availability and absorption of phosphorus (P) and potassium (K) by plants such as sugarcane. PSAP can have a number of beneficial impacts on sugarcane development, production, and quality through altering physiological and metabolic processes (Singh and Tilak 2001; Singh et al. 2018). An increase in cane weight resulted by the functional relationship between length and diameter. Application of PSAP improved cane growth, physiological and yield parameters under PSAP spray which reflected in the cane yield. Faster phosphorus and potassium absorption in cane leaves further modulates physiological and metabolic processes, improving cane growth, yield and quality metrics (Singh et al. 2018). As shown in our studied results (Table 1) that significantly higher yield was found in T_7, T_6 treatments to the tune of 28.3 and 29.1%,, respectively, as compared to the reduced recommended dose of fertilizer, which might be due to the more attack of insect pests. Singh et al. (2012) indicated that the function of cane yield in sugarcane cultivation is indeed closely related to several key factors, including the length, diameter, and number of millable canes. These factors play a critical role in determining the overall sugarcane yield and quality.

Profitability and Quality Parameters as Affected by Potassium Salt of Active Phosphorus (PSAP)

Our study showed that gross and net returns of sugarcane significantly increased in the plots applied with RDF with sett soaking in 0.80% solution + foliar spray of PSAP at the rate of 0.40, 0.65, 1.10 and 1.10% at 60, 80, 100 and 120 DAP (Table 1). These results supported in Bhatt et al. (2022) study. Present investigations also revealed that a non-significant variation was observed in brix, pol, purity, and CCS (%) except sugar yield under different PSAP spray treatments as indicated in Table 2. Sugar yield under the treatments T_7 (T_2 + PSAP at the rate of 0.40, 0.65, 1.10 and 1.10% in 4 times) as foliar spray (60, 80, 100 and 120 DAP) was increased by 28.5% as compared to treatments with recommended N with 50% NK and it was significantly similar with the application of RDF with sett soaking of 0.80% PSAP solution along with foliar spray of PSAP at the rate of 0.40, 0.65 and 1.10% in 3 times at 60, 90 and 120 DAP. These findings might be explained by the active phosphorus of PSAP, which aids in the production of extra energy in the form of P-bound ATP/ADP in sugarcane. This extra energy accelerates all paths to the next competitor far faster than control plots. Furthermore, the development of diverse syntheses in the presence of PSAP active potassium would result in additional sugar in the canes (Kumar et al. 2018). Active potassium of PSAP converts reducing sugar, finally into sucrose which reflects as CCS (%) and CCS (t ha^{-1}).

Plant Macronutrients Acquisition and Availability in Soil as Affected by Potassium Salt of Active Phosphorus (PSAP)

In the 2-year field experiments, findings revealed that macronutrients (NPK) acquisition had significant differences by the different treatments as depicted in Table 2. Plant received recommended dose of fertilizer along with sett soaking (0.8% PSAP solution) and spray of PSAP in 3 times at the rate of 0.40, 0.65, 1.10 and 1.10% (60, 80, 100 and 120 DAP) as foliar form, accumulated higher amount of nitrogen, phosphorus and potassium. Proper nutrition with these essential nutrients can significantly impact the metabolic and physiological activities of the plant, leading to increased yields. To obtain the benefits from high P and K content in plant tissues, correct nutrition management practices must be followed. This comprises soil testing, targeted fertilization, and changing nutrient inputs depending on the sugarcane crop's individual demands at various development phases. They are not only important for the yield but also help to explain their combined effect on root growth. Regular nutrient and plant health monitoring is required to guarantee that the plant's P and K requirements are satisfied, encouraging excellent yields and quality in sugarcane production. These findings support those of Kumar et al. (2004). There is also markedly increase in the N-uptake in the same treatments. This was attributable to increase in cane yield with simultaneous increase in P concentration in the plants, which increased the P and K uptake. Synergistic interactions are well known for N × K and N × P interactions (Aulakh and Malhi 2005). Study also showed that when the highest K rate was used, vegetative growth (yield) and N and K uptake were improved with the NH_4^+-N fed plants. It is clear that K interacts with N and is important in its utilization throughout the crop growth and yield production cycle (Better Crops 1998). Crops respond to higher K levels when N is sufficient, and greater yield response to N fertilizer occurs when K is sufficient. Availability of macronutrients did not significantly influence by the PSAP sprays at different intervals (Table 2). However, maximum nitrogen, phosphorus and potassium availability (257, 12.6 and 124 kg ha^{-1}) was observed in the treatments T_4—T_3 + sett soaking with 0.80% PSAP solution and T_5—T_2 + PSAP at the rate of 0.40, 0.65 and 0.80% in 3 times at 60, 90 and 120 DAP, respectively. Research has shown that K interacts with phosphorus (P) and that together they may interact with other nutrients. A simpler P-K interaction, but perhaps of more widespread importance, is their synergistic effect on yield (Better Crops 1998).

Conclusions

From the experimental findings, it was observed that the application of RDF + sett soaking with 0.80% PSAP solution in combination with PSAP at the rate of 0.40, 0.65, 1.10 and 1.10% (60, 80, 100 and 120 DAP) as foliar spray in 4 times improved the availability of nutrients in sugarcane crop thereby, facilitating better acquisition of macronutrients by the plant, which was ultimately reflected in better growth, photosynthetic activities, cane productivity and quality of juice. Concerning application of PSAP as foliar spray with sett soaking and RDF, it was found that foliar application of P and K in the form of PSAP for long-duration crops such as sugarcane was always beneficial in terms of cane growth, yield and nutrient acquisition. From this 2-year-long study on sugarcane to quantify the application of PSAP, it was revealed that the foliar spray of Potassium Salt of Active Phosphorus (PSAP) was the most appropriate and effective growth enhancing product for application ensuring yield and quality of sugarcane. Further investigation and field experiments are needed to confirm the particular effects of PSAP and to discover the most effective application techniques and rates for optimizing nutrient availability in sugarcane farming. Nutrient management, including PSAP application, should be customized to the crop's and soil's individual circumstances and demands. Application of full dose of recommended NPK and sett soaking with 0.80% PSAP solution in combination with PSAP at the rate of 0.40, 0.65, 1.10 and 1.10% in 4 times as foliar spray (60, 80, 100 and 120 days after planting) was the best foliar application for the P and K for sugarcane in the North Central and Eastern Zones of India.

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Author Contributions NK conducted the experiments and collected the data. LR compiled and drafted the manuscript. JK analysed the data. AKS supervised the research.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Human and Animal Rights The present research did not involve human participants and/or animals.

Consent for Publication All authors included in this study consent for publication.

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