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Precise macronutrient application can improve cane yield and nutrient uptake in widely spaced plant-ratoon cycles in the Indo-Gangetic plains of India

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Introduction: Sugarcane is a long-duration and nutrient-exhaustive crop. To improve nutrient use efficiency, the 4R nutrient stewardship approach comprises applying nutrients at the right time and place with the right method and at the right proportion. Improper nutrient management in such a nutrient-exhaustive crop will result in various nutrient losses and environmental pollution.

Methods: Concerning this, a field study was performed on calcareous soils of the lower Indo-Gangetic plains of India during two subsequent years at the Sugarcane Research Institute, RPCAU, India, to explore the effect of precise application of macronutrients (N and K) in different methods of applications. The application methods (broadcasting and band application) were maintained in the main plot, and split N and K applications were put in the subplots.

Results and Discussion: A highly significant difference was observed in the numbers of millable cane, cane, and sugar yield under the split applications of fertilizer. The decline in millable cane numbers, cane, and sugar yield due to the broadcasting method was to the tune of 17.5 and 17.6%, 14.8 and 17.1%, and 14.7 and 15.8% in plant and ratoon crops, respectively as compared to band placement of the fertilizers. Yield increased by 16.0 and 15.1% under plant and ratoon crops, respectively, with seven split applications of N and K compared to the control (two split of N and no split application of K). Band placement of N and K fertilizers markedly improved the nitrogen uptake (284.1 and 287.3$kgha^{-1}$, in plant and ratoon, respectively) and phosphorus uptake (34.9 and 28.3$kgha^{-1}$ in plant and ratoon, respectively) when compared to broadcasting. Application of N and K in seven splits resulted in better availability of nutrients in the soil, thereby facilitating the higher NPK uptake by the plants and ratoon both comparing two split applications of N and no splitting of K. From this study, it was observed that the band placement coupled with seven splitting of N and K is the best fertilizer application protocol, ensuring higher growth, yield, quality, and nutrient uptake of sugarcane in the calcareous soils of the Indo-Gangetic plains.

KEYWORDS

band placement, cane yield, crop quality, NPK uptake, sugarcane, split application of fertilizer

1. Introduction

Sugarcane is an important agro-industrial crop of tropical and subtropical climates and plays a significant role in the Indian economy. As a long-duration crop, sugarcane has a high demand for nutrients, especially nitrogen (N) and potassium (K) (Dotaniya et al., 2016). Among the macronutrients, N is more prone to leaching and volatilization losses. Fertilizer utilization is more prevalent in intensive sugarcane farming, which needs a lot of nitrogen since it generates an abundance of biomass (Otto et al., 2022). Sugarcane has a high water and nitrogen demand, which increases the risk of ground-or surface-water contamination (Dotaniya et al., 2016). N uptake by the crop has been affected by various factors such as the amount and quality of N fertilizer used, timing and frequency of its application, the kind and length of the crop, the ability of the crop to use N, the depth of the root system, rainfall, the hydraulic properties of the soil, and overall crop management techniques (Kumar et al., 2019b). A better fertilizer application strategy considering suitable method and time of application is crucial to maximizing the growth and yield of the crops with the least nutrient leaching (Pramanick et al., 2018; Lakshmi et al., 2021; Singh et al., 2021).

Strategies entail altering fertilizer application rates and frequencies to enhance the N efficiency and reduce the N leaching from the rooting zone (Pramanick et al., 2022). In most sugarcane growing areas, synthetic fertilizers are typically applied using the broadcasting method, which reduces nutrient use-efficiency to a considerable extent (Abdel Wahab, 2014). The health of the soil can be ensured by the judicious use of chemical fertilizers and by systematically implementing the 4R (correct rate, right time, right source, and proper technique) concept of nutrient management (Johnston and Bruulsema, 2014). This will help to develop a balanced relationship between soil quality and agronomic management of field soil. The fertilizer application method and rate must be changed concurrently for high crop yield and high nutrient use efficiency (Laik et al., 2021; Pramanick et al., 2023). The N, P, and K fertilizers, which are primarily imported, are significantly more expensive and are not utilized effectively by farmers in sufficient quantities, which causes stagnation or a fall in sugarcane productivity over time (Singh et al., 2019). All of these indicate a better potential for using more balanced fertilizers to increase cane output, improve quality, maintain system sustainability, and improve nutrient use efficiencies. Sugarcane seldom recovers more than 40% of its nitrogen fertilizer (Skocaj et al., 2013). Therefore, a well-balanced fertilizer application, which includes a significant amount of N and K, might be a first step toward attaining these critical objectives. However, phosphorus is also vital for cane production. Split applications describe adjusting fertilizer supply to a predetermined target yield and a specific soil moisture level (Pramanick et al., 2022). Fertilizers for sugarcane plants should have an appropriate quantity of nitrogen (N), as well as the proper ratios of phosphorus (P) and potassium (K).

The current focus should be on factors that limit sugarcane output and that are within farmers' control, as these appear to be more pressing and resolvable. Numerous studies have examined the effects of applying nitrogen split throughout two or three applications (Lakshmi et al., 2020). Sugarcane growers in India have been successfully persuaded to use balanced N and P fertilizing techniques. Potassium, a crucial component for cane productivity as well as for other quality indicators, is regrettably commonly ignored by farmers. Farmers regularly lose this costly nutrient, which is strongly linked to environmental degradation, climate change, and soil health, due to excessive amounts of nitrogen fertilizer. Due to the vulnerability of fertilizer N to leaching and de-nitrification losses, split N fertilizer applications seem advantageous. Nutrient loss is more significant in the calcareous soil in Bihar, India, and nitrogen and potassium in splits might result in less loss of nutrients and greater fertilizer use efficacy. A suitable fertilizer application method coupled with proper split applications of macronutrients in sugarcane is yet to be developed in the vast calcareous soil regions of the lower Indo-Gangetic plains. Considering the significance of splitting nitrogen and potassium fertilizers in sugarcane, the present study was conducted to determine the effective macronutrient application protocol for achieving better growth attributes, yield, juice quality, and nutrient uptake in sugarcane under plant-ratoon cycles. This study will provide important information on the macronutrient management strategy for sugarcane, ensuring better yield and lower nutrient loss in the calcareous soils of the Indo-Gangetic regions.

2. Materials and methods

2.1. Experimental site

The current study was carried out in the lower Indo-Gangetic plains of Bihar between 2019 and 2021 in a plant-ratoon system of sugarcane on calcareous soils. The available nitrogen, phosphorus, and potassium in the soil of the experimental field were 230.5, 20.3, and 130.1 kg ha^{-1}, respectively. The soil had a pH value of 8.2 and was a sandy loam texture. Rainfall was 1,590 and 1,881 mm during the growing seasons of the plant and ratoon crops, respectively. The detailed climatic scenario during the study period is included in Supplementary Figure S1.

2.2. Experimental design and sampling

The experiment was conducted using a split-plot design with two main plot factors (B1: Band placement and B2: Broadcasting) and four sub-plot factors with a split application of the recommended dose of nitrogen (RDN) and recommended dose of potassium (RDK) as follows: S1: Basal 10% remaining at 45, 75, 90, and 120 days after planting or DAP in equal splits (RDN + RDK in 5 splits); S2: Basal 10% remaining at 45, 75, 90, 120, and 150 DAP in equal splits (RDN + RDK in 6 splits); S3: Basal 10% remaining at 45, 75, 90, 120, 150, and 180

DAP in similar splits (RDN + RDK in 7 splits); and S4: Half of total N and a full dose of P and K at planting and rest of N at 45 and 120 DAP in equal quantity. There were three replications of the treatment combinations. In the case of band placement, the fertilizers were applied 20 cm below the surface, while in the broadcasting method, the fertilizers were broadcasted over the surface of the soil. Figure 1 represents the schematic depiction of the treatment details. The area of each plot was 56 m^2 (8 m × 7 m). Evaluation of plant growth, yield, and nutrient uptake was carried out on randomly selected plant samples. At harvest time, whole cane samples were collected, and cane juice was extracted using a power crusher. The juice quality was assessed using the Spencer and Meade method (Spencer and Meade, 1995).

2.3. Crop management

The recommended dose of fertilizer (RDF) was 150 kg ha^{-1} N, 85 kg ha^{-1} P, and 60 kg ha^{-1} K for the plant crop, and 170 kg ha^{-1} N, 50 kg ha^{-1} P, and 60 kg ha^{-1} K for the ratoon crop. The variety of sugarcane used in this study was Rajendra Ganna-1, which is a very popular variety of sugarcane with the farmers in the study area. The plant crop of sugarcane was planted on 20 March 2020 and the ratoon crop was initiated on 12 February 2021 in the same field. The planting was done in furrow using three budded setts in 120 cm row spacing. Four irrigations and one hand-weeding and hoeing were performed at appropriate stages.

2.4. Soil and plant analysis

In the current experiment, soil parameters such as electrical conductivity (EC), organic carbon (OC), available nitrogen (alkaline KMnO4 method), phosphorus (NaHCO3 extracted), and available potassium (NH4OAC extracted) were determined after harvesting of the ratoon crop. For determination of EC, the soil suspension (Soil: Water 10 g:50 mL) in the beaker was allowed to settle for a maximum of half an hour. Then, the standard KCl solution was prepared and the conductivity meter was calibrated with the standard KCl solution. Afterward, the EC was determined using an EC meter. The ground air-dried soil samples were passed through a 0.2 mm sieve to analyze soil organic carbon (SOC). SOC was determined through the modified Walkley and Black method (Jackson, 1973) using 1 N K2Cr2O7, conc. H2SO4, orthophosphoric acid, sodium fluoride, and ferrous ammonium sulphate solution. Available (mineralizable) nitrogen (N) in the soil was determined by using the alkaline permanganate (KMnO4-N) method (Subbiah and Asija, 1956). Phosphorus estimation was done by using sodium bicarbonate as an extractant (Olsen et al., 1954). Color development was measured using a spectrophotometer [Double Beam Spectrophotometer AU2703, Systronics (India) Ltd., India] at 720 nm wavelength with known standards. Available potassium (exchangeable + water-soluble K) in soil was determined by using a neutral normal ammonium acetate solution using a flame photometer [Systronics (India) Ltd., India] (Jackson, 1973). The total nitrogen content (%) by the crop was determined by a modified macro-Kjeldahl method (Jackson, 1973), while phosphorus content was determined by a vanado-molybdo-phosphoric acid yellow color method in an HNO_3 system with a colorimeter (Jackson, 1973). Potassium content was evaluated by a wet digestion method and a flame photometer (Jackson, 1973). Nutrient uptake was determined by multiplying the nutrient content in the crop with respective biomass production (Pramanick et al., 2017).

2.5. Statistical analysis

Analysis of variance method (ANOVA) method for split-plot design was followed to statistically analyze all the data. Fisher's LSD method (least significant difference) was adopted to differentiate the treatment means at 5% probability ($p \leq 0.05$), as stated in Gomez and Gomez (1976). All the statistical computations were done using SPSS software version 25 (IBM Corp. 2017).

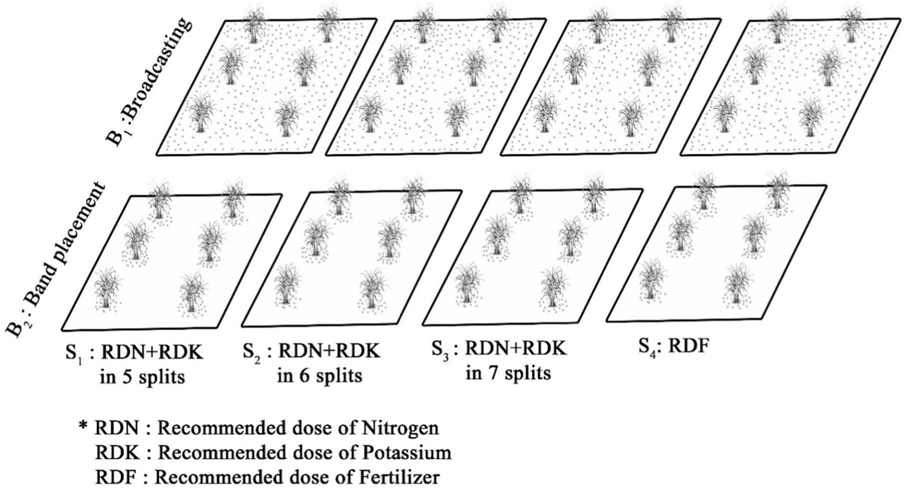

FIGURE 1
Schematic diagram of the treatment details.

3. Results

3.1. Growth

The tiller population was found to be increasing with advanced growth stages 2–4 months after planting. The study results showed a higher tiller population 4 months after planting (MAP) in the band placement method, accounting for an increase of 24.7% and 23.2% in plant and ratoon crops, respectively when compared to the broadcasting method (Figure 2). The tiller population of sugarcane was significantly ($p \leq 0.05$) influenced by the application of nitrogen and potassium in seven splits (S3), and it was found that S3 resulted in the increment of tiller number to the tune of 23.0% and 21.3% at 4 months after planting (MAP) as compared to the recommended dose of fertilizer (S4), in plant and ratoon cycles of sugarcane, respectively. Plant height under plant and ratoon systems was significantly ($p \leq 0.05$) influenced by splits application of macronutrients (nitrogen and potassium) and method of establishments. Splitting N and K seven times (RDN + RDK in 7 splits) resulted in the tallest plants, accounting for 7.7 and 6.2% increases in plant height for plant and ratoon crops, respectively, at 5 MAP, 8.3% and 7.9% increases in plant height for plant and ratoon crops, respectively, at 6 MAP, and 3.9% and 3.7% increases in plant height for plant and ratoon crops, respectively, at 7 MAP, as compared to the RDF application. Band

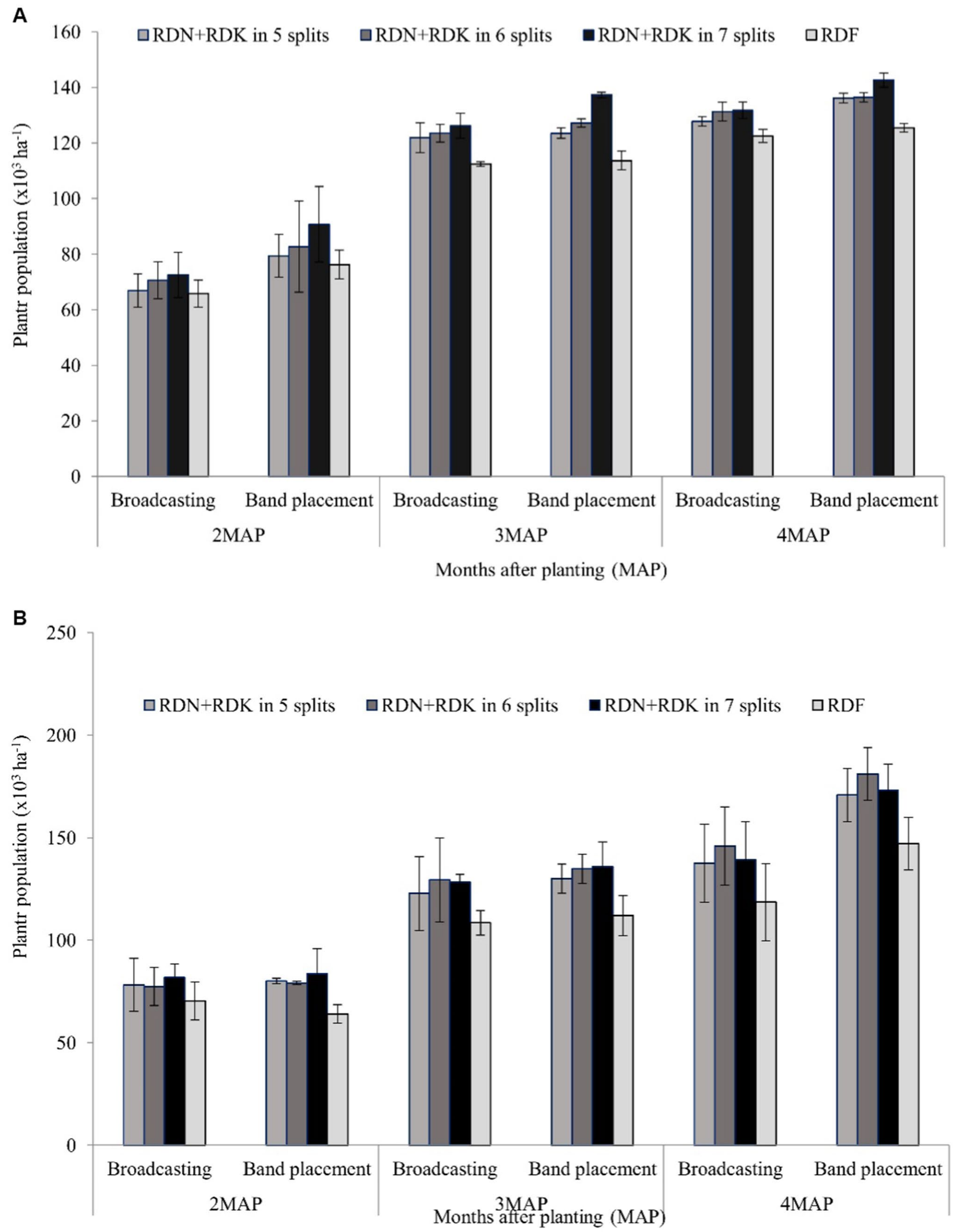

FIGURE 2
Effect of different treatments on plant populations in **(A)** sugarcane plant crop and **(B)** sugarcane ratoon crop. Lines above the bars denote the standard deviation ($n = 3$). RDN, RDK, and RDF denote recommended dose of N, recommended dose of K, and recommended dose of fertilizers.

placement also showed higher plant height as compared to broadcasting during the growth period of the crop. However, the application methods and split dose did not significantly affect plant height at harvest in plant and ratoon crops (Figure 3).

Dry matter accumulation (DMA) increased with the advancement of crop age. Moreover, the method of fertilizer application had a significant ($p \leq 0.05$) influence on the DMA of sugarcane (Figure 4). The maximum dry matter accumulation was recorded under the band placement method of fertilizer application compared to broadcasting at 6, 7 MAP, and harvest. The DMA was also found significantly ($p \leq 0.05$) higher in the plots receiving nitrogen in combination with potassium in seven splits as compared to the recommended dose of fertilizer, whereas DMA was found to be statistically at par with the treatment 6 and 5 split applications of N and K under plant and ratoon crops.

3.2. Yield parameters

Results showed that the millable canes were significantly ($p \leq 0.05$) affected by the method of planting and split application in plant and ratoon crops. The maximum number of millable canes (117.9 and $119.2 \times 10^3\,ha^{-1}$ in plant and ratoon crops, respectively) was recorded in band placement. This method of planting exhibited about 21.2% and 21.0% increments in millable cane numbers in plant and ratoon crops, respectively, as compared to the millable cane numbers under the broadcasting method. It was also revealed that seven times the splitting of nitrogen and potassium (RDN + RDK in 7 splits) in sugarcane produced more millable cane (114.9 and $116.3 \times 10^3\,ha^{-1}$ in plant and ratoon crops, respectively). However, this treatment was ($p \leq 0.05$) found at par with the six times splitting of N and K (RDN + RDK in 6 splits). The minimum number of millable cane (92.7

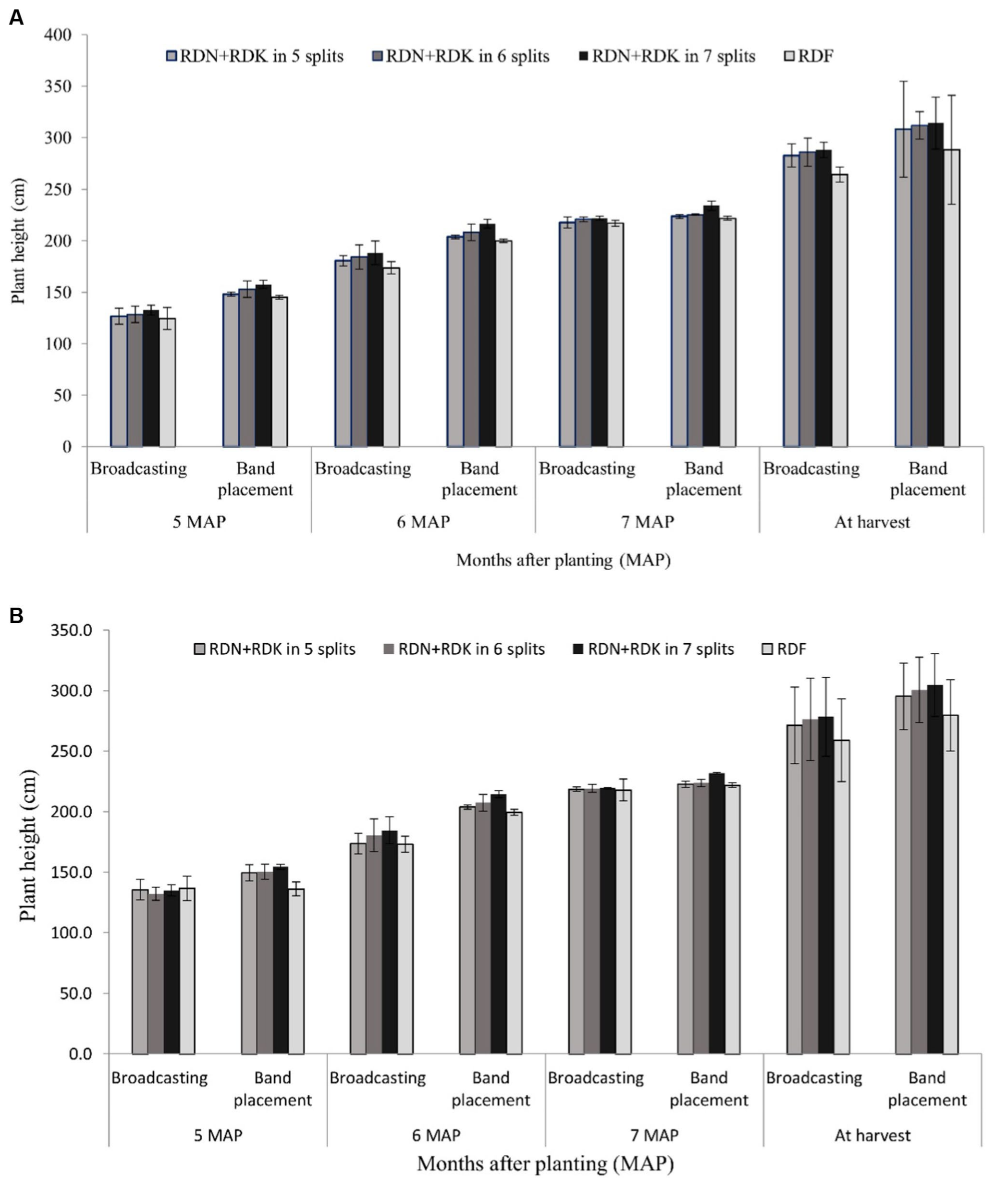

FIGURE 3
Effect of different treatments on plant height in **(A)** sugarcane plant crop and **(B)** sugarcane ratoon crop. Lines above the bars denote the standard deviation ($n = 3$). RDN, RDK, and RDF denote recommended dose of N, recommended dose of K, and recommended dose of fertilizers.

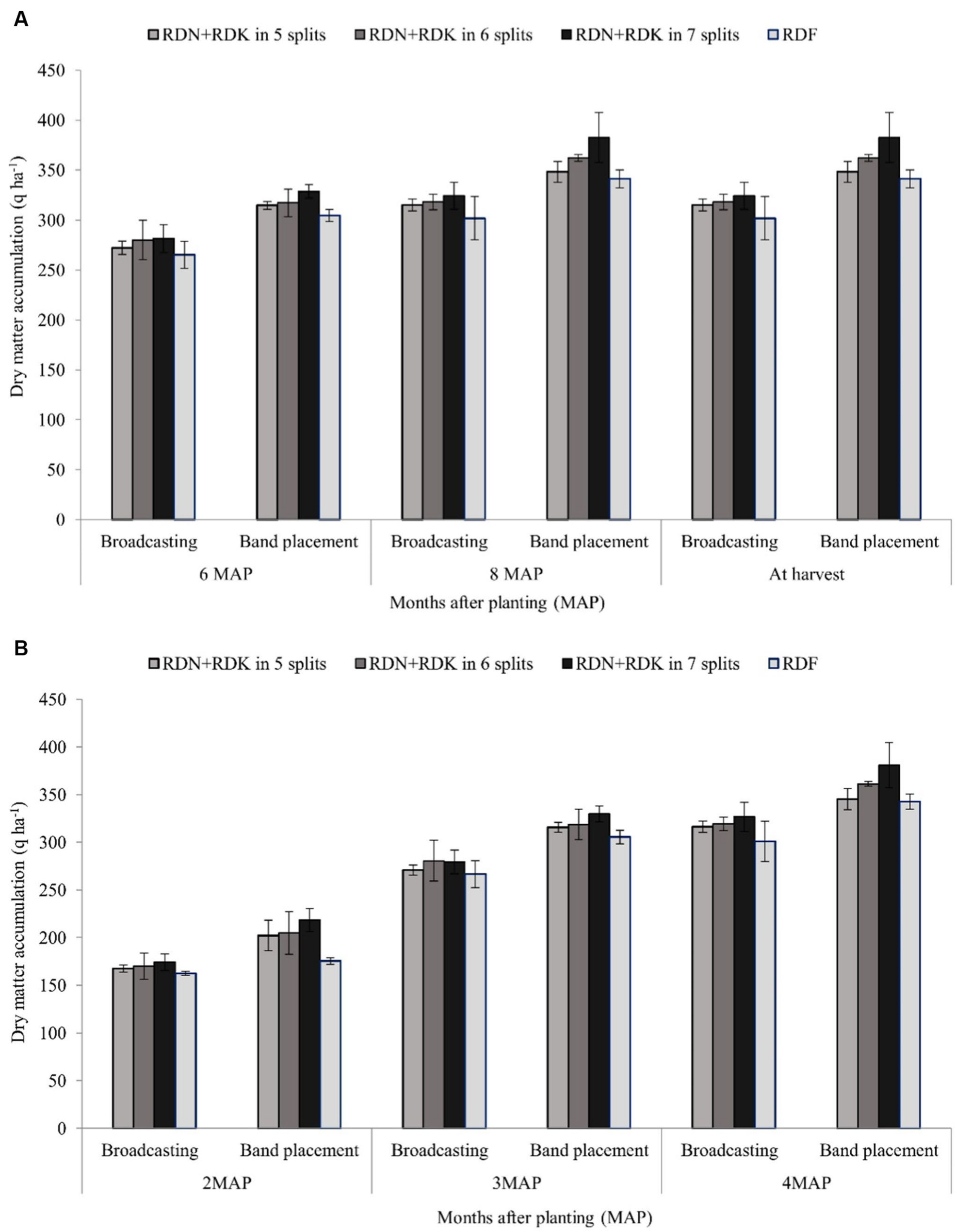

FIGURE 4
Effect of different treatments on dry matter accumulation in **(A)** sugarcane plant crop and **(B)** sugarcane ratoon crop. Lines above the bars denote the standard deviation (n = 3). RDN, RDK, and RDF denote recommended dose of N, recommended dose of K, and recommended dose of fertilizers.

and 92.4 × 103 ha^{-1}) was observed in the RDF for plant and ratoon crops, respectively (Table 1).

Sugarcane growers must consider cane yield, which is majorly influenced by genotype, management techniques, and the environment. Harvesting at the right stage of crop maturity is critical for maximizing tonnage while minimizing losses in a growing environment. Harvesting of immature or over-mature canes results in significant losses in cane yield and sugar recovery. The present study indicated that the fertilizer application method, *viz.*, band placement and broadcasting, significantly ($p \leq 0.05$) influenced the cane yield in both the plant and ratoon crops, while different split applications of N and K did not influence the cane yield of ratoon crops. In the ratoon crop, cane yield was observed at the maximum (78.3 t ha^{-1}) in 7 splits application and it was the minimum (66.5 t ha^{-1}) in the recommended dose of fertilizer. The maximum cane yield (86.7 and 80.6 t ha^{-1} in plant and ratoon crops, respectively) was observed in band placement, and the minimum cane yield (73.9 and 66.8 t ha^{-1} in plant and ratoon crops, respectively) in the plant and ratoon crops was recorded in the broadcasting method. Cane yield was found to be increased by 19% with the split application of N and K for 7 times (RDN + RDK in 7 splits) as compared to the RDF (S4) where N was applied in 2 splits with no split application of K (Table 1). Sugar yield was not significantly ($p \geq 0.05$) influenced by the application methods of fertilizer (N and K) in both plant and ratoon crops. However, the splitting of nitrogen and

TABLE 1 Yield attributes, yield, and quality of plant-ratoon cycles of sugarcane (Rajendra Ganna-1) as influenced by method and split doses of nitrogen and potassium application.

Treatment	Millable canes (×10^3 ha^{-1})s		Cane yield (t ha^{-1})		Brix (%)		Pol (%)		Purity (%)		Juice recovery (%)		Commercial cane sugar (%)		Sugar yield (t ha^{-1})	
	Plant	Ratoon	Plant	Ratoon	Plant	Ratoon	Plant	Ratoon	Plant	Ratoon	Plant	Ratoon	Plant	Ratoon	Plant	Ratoon
Fertilizer application methods																
B1	97.3	98.5	73.9	66.8	20.6	18.3	18.2	17.7	88.4	86.1	60.8	61.9	12.5	12.7	9.3	8.5
B2	117.9	119.2	86.7	80.6	20.8	18.2	18.3	17.7	88.7	87.2	62.7	63.8	12.6	12.5	10.9	10.1
SEm (±)	3.4	2.9	2.1	2.1	0.2	0.3	0.2	0.3	0.3	0.5	0.8	1.0	0.2	0.2	0.3	0.3
CD ($p \le 0.05$)	20.5	17.9	12.6	12.7	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Splitting of N and K fertilizer																
S1	109.3	111.7	80.6	73.2	20.7	18.6	18.2	17.5	88.5	86.0	60.7	61.6	12.6	12.7	10.1	9.3
S2	113.7	115.2	83.8	76.7	20.8	18.3	18.3	17.6	88.6	86.3	61.9	63.2	12.6	12.6	10.6	9.7
S3	114.9	116.3	85.2	78.3	20.9	18.2	18.4	17.7	88.9	86.9	64.3	65.7	12.7	12.6	10.9	9.9
S4	92.7	92.4	71.6	66.5	20.4	18.1	18.0	17.8	88.2	87.4	59.9	61.2	12.5	12.5	8.9	8.3
SEm (±)	4.72	3.58	2.8	2.6	0.2	0.3	0.2	0.3	0.4	0.7	0.6	1.1	0.2	0.20	0.4	0.3
CD ($p \le 0.05$)	14.5	11.1	8.71	NS	NS	NS	NS	NS	NS	NS	1.8	3.4	NS	NS	1.2	1.1

B1 and B2 denote broadcasting and band placement, respectively. S1, S2, S3, and S4 denote RDN + RDK in 5 splits, RDN + RDK in 6 splits, RDN + RDK in 7 splits, and RDF, respectively.

potassium exerts a significant effect on sugar yield under plant and ratoon crops, and plots receiving nitrogen and potassium in 7 splits (RDN + RDK in 7 splits) resulted in the highest sugar yield, accounting for an increase of approximately 23% and 19% over the recommended dose of fertilizer in plant and ratoon crops, respectively (Table 1).

3.3. Quality

Quality parameters such as brix, pol, and purity percentage were not significantly influenced by the methods and split application of nitrogen and potassium under plant and ratoon crops. It was also observed that juice recovery was not greatly affected by the method of fertilizer application. However, split fertilizer application (N and K) significantly affected the juice recovery in plant and ratoon crops. Higher juice recovery was achieved in the cane plant receiving nitrogen and potassium in 7 splits (64.3% and 65.7% in plant and ratoon crops, respectively) compared to the recommended dose of fertilizer (59.9% and 61.2% in plant and ratoon crops, respectively). Table 1 shows that commercial cane sugar percentage was not significantly influenced by the method and split application of nitrogen and potassium in both plant and ratoon crops.

3.4. Soil physicochemical parameters

Data presented in Table 2 show that the electrical conductivity of soil was not significantly ($p \ge 0.05$) influenced by the method of fertilizer application in plant and ratoon crops. The electrical conductivity (EC) of soil differed significantly ($p \le 0.05$) among the split application of N and K.

The maximum value of EC was found in S4, i.e., RDF (0.28, 0.28 dS m^{-1} in plant and ratoon crops, respectively). The method of fertilizer application and split application of N and K fertilizer did not exert significant ($p \ge 0.05$) influence on soil organic carbon (OC) in plant and ratoon crops. Available soil N was found to be significantly ($p \le 0.05$) affected by the method of fertilizer application under both plant and ratoon systems. Soil available N was found higher under the band placement method compared to that under the broadcasting method, accounting for a 4.6% and 3.4% increase in available N in the plant and ratoon-cropped soils, respectively. The split application of N and K significantly influenced the available N in plant crops. The higher values were observed in 7 splits application of N and K (RDN + RDK in 7 splits) over the RDF. Olson-P was not significantly influenced by the method and split applications of N and K fertilizer in plant and ratoon crops. The method of fertilizer applications (broadcasting and band placement) did not exert a significant effect on available K in both the years of study in plant-ratoon cycles. However, the splits application of N and K significantly influenced the available K in plant crops. Split application of N and K for 7 times (RDN + RDK in 7 splits) recorded the highest value of available K, which increased by 18.8% as compared to the available K under no splitting of K (S4).

3.5. Nutrient uptake

Band placement method of fertilizer application influenced the uptake of NPK in plant and ratoon crops, except for K uptake in

TABLE 2 Physicochemical properties of soil and uptake of NPK in plant-ratoon cycles of sugarcane (Rajendra Ganna-1) as influenced by method and split doses of nitrogen and potassium application.

Treatment	Electrical conductivity (dS/m)		Organic carbon (%)		Available N (kg ha^{-1})		Olson P (kg ha^{-1})		Available K (kg ha^{-1})		N uptake (kg ha^{-1})		P uptake (kg ha^{-1})		K uptake (kg ha^{-1})	
	Plant	Ratoon	Plant	Ratoon	Plant	Ratoon	Plant	Ratoon	Plant	Ratoon	Plant	Ratoon	Plant	Ratoon	Plant	Ratoon
Fertilizer application methods																
B1	0.24	0.23	0.45	0.46	195.5	197.7	10.2	10.1	112.7	110.3	248.9	249.9	25.7	25.6	250.1	240.8
B2	0.25	0.27	0.44	0.47	204.4	204.4	11.1	11.2	120.5	118.6	284.1	287.3	34.9	28.3	292.9	252.4
SEm (±)	0.02	0.01	0.02	0.01	1.1	0.4	0.6	0.4	2.2	2.6	5.2	4.9	1.1	0.3	6.5	10.2
CD ($p \leq 0.05$)	NS	NS	NS	NS	6.56	2.3	NS	NS	NS	NS	31.9	24.6	6.2	1.6	39.7	NS
Splitting of N and K fertilizer																
S1	0.23	0.23	0.40	0.43	200.4	198.8	10.0	9.9	113.7	112.6	258.8	260.5	26.6	23.4	263.4	242.1
S2	0.23	0.23	0.43	0.48	202.4	201.2	10.8	10.8	123.7	114.6	272.5	273.8	31.1	26.6	286.5	242.9
S3	0.27	0.26	0.47	0.46	204.1	202.0	12.4	10.9	124.3	116.5	297.9	302.9	33.7	28.7	306.5	249.8
S4	0.28	0.28	0.47	0.49	192.9	202.2	9.4	11.0	104.6	118.9	236.6	237.3	29.7	29.0	229.8	251.5
SEm (±)	0.02	0.01	0.01	0.02	0.9	1.70	0.7	0.5	3.1	2.9	4.5	3.9	1.1	1.7	5.4	11.9
CD ($p \leq 0.05$)	0.06	0.02	NS	NS	2.9	NS	NS	NS	9.7	NS	13.7	12.1	3.3	NS	16.5	NS

B1 and B2 denote broadcasting and band placement, respectively. S1, S2, S3, and S4 denote RDN + RDK in 5 splits, RDN + RDK in 6 splits, RDN + RDK in 7 splits, and RDF, respectively.

ratoon crops. N, P, and K uptakes under band placement of fertilizers increased to the tune of 14.1%, 15.0%, and 35.8%, respectively, over the broadcasting method in the plant crop, and 10.5%, 17.1%, and 4.8%, respectively, over the broadcasting method in the ratoon crop. N uptake was significantly influenced by split application in plant and ratoon cycles. Higher N uptake was observed in plots that received 7 times splitting of N and K. Lower nitrogen uptake (236 and 237.3 kg ha^{-1} in plant and ratoon crops, respectively) was noticed with a recommended dose of fertilizer (S4). The treatments comprising S3 (RDN + RDK in 7 splits) and S2 (RDN + RDK in 6 splits) were the ones that most improved P and K uptakes, compared to other split application protocols in plant crops. Significant differences were not observed in P and K uptake in ratoon crops (Table 2).

4. Discussion

Growth of sugarcane was found to improve under 7 split applications of N and K in both plants and ratoon crops. This might be the result of optimal sugarcane metabolism (Cakmak, 2005; Wang et al., 2013), enzyme activation (Hawkesford et al., 2012), transport of carbohydrates, photosynthesis, hormone balance, auxin levels (Rubio et al., 2009), and cane root growth (Bhatt and Singh, 2021) upon the S3 treatment (split application of N and K for 7 times) compared to the other treatments. It is widely believed that factors such as the number of millable canes and the weight of a single cane can contribute to cane productivity (Singh et al., 2019). The findings of this study showed that the plant crop cane production was much higher than the ratoon crop one. The main factors that contribute to this low yield in the ratoon crop are cultivars with low and variable ratooning potential, inadequate crop management practices, the accumulation of toxic substances in the rhizosphere zone, inability to absorb nutrients by the ratoon, the loss of soil fertility, shallow ratooning, soil compaction, and an increase in the prevalence of pests and diseases (Xu et al., 2021). The cane yield and biomass could be greatly improved by applying nitrogen and potassium fertilizer using a band placement technique. This investigation found that adding bands to both plant and ratoon crops increased crop productivity. According to Bashagaluke et al. (2018), surface application without band placement of fertilizers resulted in significant plant nutrient loss due to fixation, erosion, and other losses, which may have led to an unbalanced soil nutrient environment and a decline in production. Higher cane yield (85.2 t ha^{-1}) was achieved with 7 times split nitrogen and potassium application in plant crops alone. Singh et al. (2008) and Lakshmi et al. (2020) also demonstrated the advantages of K split application regarding cane yield. In the research trial, split application of nitrogen and potassium in plant and ratoon crops significantly enhanced sugar yield, which might be due to the better availability of these macronutrients to the crop as split application facilitated the minimum loss of nutrients beyond the root zone.

Regarding sugar yield, the plant crop showed about 10% more yield compared to the ratoon crop. The lower cane yield and a smaller number of millable stalks in the ratoon crop might be responsible for the lesser increase in sugar yield. According to this research, split applications of nitrogen and potassium resulted in a higher number of millable canes than the standard approach. Early plant population has a significant impact on the millable stalks per hectare, whereas later nutrient competitiveness has an impact on individual growth (Kapur et al., 2011). Therefore, N application primarily influenced the millable stalks ha^{-1} by impacting the emergence and tillering rate and then jointly determining the cane yield by affecting the stalk length, diameter, and weight of sugarcane at a later stage. Potassium application primarily affects sugarcane juice quality (Kumar et al., 2019a). In this study, it was observed that split applications of N might be helpful to prevent the loss of nutrients such as nitrogen, which is vulnerable to leaching and volatilization losses. At the same time, K split application also might ensure better K availability soil and uptake by the plants. This was ultimately reflected in the better quality of the sugarcane. Sugarcane quality parameters, *viz.*, brix, pol, purity, and CCS percent, were all higher in the 7 splits application (S3) and band placement, although these differences were insignificant (Table 1). In this study, we have found that the higher juice recovery (65.7%) observed in ratoon crop over plant crop (64.3%) might be due to the early harvesting of the ratoon crop, resulting in better quality and better sugar recovery (Viator et al., 2010).

The findings of the current investigation showed that the NPK uptake by sugarcane under various split applications of nitrogen and potassium differed significantly. In increasing the number of splitting of macronutrients, N and K might have facilitated their even availability in soil throughout the development of cane, which ultimately led to a quicker rate of crop growth (Junejo et al., 2010). These results also confirm the findings recorded by Sandeep et al. (2013). The highest N, P, and K uptakes in sugarcane crops at harvest in plant and ratoon crops were found in 7 split-application of N and K. Many previous studies also reported similar results. The application of increasing N rates resulted in increased N accumulation in leaves, stalks, and crowns (Costa et al., 2016; Pramanick et al., 2022). Additionally, the results demonstrated that applying fertilizer with bands was the most effective compared with the broadcasting method. Soil available N, P, and K were significantly influenced by the band placement method. This might be because the band placement method reduced the loss of nutrients as compared to the broadcasting method (Nkebiwe et al., 2016), ultimately facilitating the better uptake of nutrients by both plants and ratoon crops.

5. Conclusion

In the present study, it was found that the band placement of fertilizers increases the availability of nutrients in both the sugarcane main crop and next-year ratoon crop, thereby, facilitating better nutrient uptake by the plant, which was ultimately reflected in better crop growth, yield, and quality of the crop. Concerning splitting of the macronutrients, it was found that more splitting of the soil mobile macronutrients such as N and K for long-duration crops such as sugarcane was always beneficial in terms of sugarcane growth, yield, and juice quality. From this two-year-long study on sugarcane to quantify the fertilizer application methods and number of split applications of N and K, it was found that the band placement of fertilizers was the most suitable method of fertilizer application ensuring yield and quality of the crop. Application of full dose of recommended P and 10% of recommended N and K at basal followed by splitting of remaining N and K fertilizers at equal rates at 45, 75, 90, 120, 150, and 180 days after planting was the best split application protocol for the macronutrients for sugarcane in the Indo-Gangetic plains.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

NK, LR, and AS led the research work, planned, supervised, and conducted field experiments, and read and edited the manuscript. NK, LR, and BP collected soil/plant samples, performed chemical analysis, wrote the initial draft of the manuscript, and prepared figures and tables. AS, NK, LR, AG, AA, MS, AH, and BP performed project supervision, reviewed, read, and edited the manuscript with significant contributions. NK, LR, AH, MS, AA, AG, and BP performed the statistical analysis. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1223881/full#supplementary-material

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