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RESEARCH ARTICLE

Integrated management of genotype, row spacing and fertiliser application can lead to sustainable sugarcane production in the Indo-Gangetic Plains of India

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Abstract

A poor nutrient management strategy leads to an imbalance in the soil nutrient status, which could have a long-term negative influence on crop output. Keeping this in view, a field experiment was conducted at Sugarcane Research Institute, Dr. Rajendra Prasad Central Agriculture University, Pusa, Samastipur Bihar, to assess performance of early maturing sugarcane genotypes with two row configurations (90 and 120 cm) under two levels of macronutrients (NPK) i.e. N_{150}+ $P_{37.1}$ + $K_{49.8}$ and $N_{187.5}$+ $P_{46.4}$ + $K_{62.3}$kg/ha on soil nutrient equilibrium sugarcane crop during 2018–19. Genotype CoP 13437 recorded a significantly higher tiller population and number of millable canes (169.7 and 114.9 × 10^3/ha) while genotype CoSe 95422 showed the highest B:C ratio (2.33). Maximum cane yield was observed in 90 cm row spacing with the increased NPK level and the increase in cane yield under $N_{187.5}$ + $P_{46.4}$+ $K_{62.3}$ kg/ha was to the tune of 27.5 %. Genotype CoSe 95422 produces a higher cane yield (102.6 t/ha) of sugarcane, followed by CoP 13437 (101.5 t/ha). The uptake of macronutrients increased when more fertiliser was applied (280, 27.3 and 318.2 NPK kg/ha). With increasing fertility levels ($N_{187.5}$+ $P_{46.4}$+ $K_{62.3}$ kg/ha), a net gain of NPK was observed. Therefore, balanced nutrient management combined with appropriate genotype selection and row spacing significantly enhanced sugarcane productivity and improved soil nutrient status for sustainable cultivation.

Keywords: cane yield; fertility level; genotype; nutrient uptake; row spacing

Introduction

An adequate initial plant development and improved sugarcane yield depend on optimal planting density. The most significant planting architectural component for sugarcane is considered to be row spacing. Sugarcane production cannot be improved unless promising cultivars and technologies are widely embraced (1). Similarly, research has demonstrated that a varietys' better genetic potential results in a higher cane yield (2). High-yielding cultivars and enhanced crop production methods are adopted in an effort to increase cane production (3). Planting low-yielding cultivars is one of the factors that contribute to poor cane yield. Variety plays a key role in both increasing and decreasing per unit area sugar yield, while the use of unapproved, inferior quality cane varieties affects sugarcane production negatively, as the situation prevails today (4). Planting improved cane varieties is the solution to the low cane yield and sugar recovery issues (5). The success of a variety depends on how well it can adapt to the local agro-climatic conditions. Due to several problems, including inadequate crop management, poor soil quality, abiotic and biotic stressors and others, sugarcane productivity in India is quite low. By increasing resilience to biotic and abiotic stressors and careful use of all necessary nutrients, cane output can be increased and sugar recovery can be accelerated. Balanced use of plant nutrients is essential for sustaining the productivity of crops and soil. Research indicates that among various inputs in sugarcane production, fertilisers contribute the maximum to the crop yield (6). The role of nitrogen in plants is of prime importance due to its presence as an integrated structural constituent of the protein molecule (7).

Phosphorus is essential for cell division, which accounts for stalk and root elongation, resulting in the growth of the plant. It is also involved in the regulation of sugar synthesis and storage (8). The sugarcane genotypes show variable performance under different agronomic practices. Row spacing enables more uniform plant distribution and increases the effectiveness of plant canopy radiation absorption (9). Most of the farmers used conventional planting methods like 60 to 75 cm apart furrows, which are helpful in a higher plant population per unit area to some extent, but it results in problems in management operations like intercultural, air circulation and light interception, which are very important factors for good crop yield (10). Variety is essential for boosting cane yield and to fully utilise a varietys' genetic potential, the right environment, with the help of the best inputs, is needed. Conventionally grown crops are unable to fully absorb solar radiation despite being one of the best converters of solar energy to chemical energy. Hence, increasing crop geometry by proper plant spacing is crucial for increasing yield. Different genotypes may require variable row spacing for the best absorption of solar radiation and/or the extraction of soil water and minerals. Sugarcane is considered mature when its sucrose concentration exceeds 16 %. Early cultivars mature in less than nine months. Sugarcane requires a lot of N, P and K to be used properly because it is an input-intensive crop, especially during the formative and grand growth stages for greater yield. The minerals N, P and K are crucial for improving productivity and how well they work relies on how well each variety can absorb and use the nutrients for the creation of dry matter. Because various genotypes have varied genetic potentialities, they respond to increasing levels of nutrients differentially (11, 12). The right management solutions are needed to maximise the yield potential of the cultivars. The ability of genotypes to effectively absorb the supplied nutrients, particularly NPK, is the most crucial component. The genotypes also have varied features and the potential to increase sugarcane productivity. Keeping these facts in mind, the current study was conducted to determine how different rates of macronutrients and row configurations affected the balance of soil nutrients and to quantify changes in the status of soil nutrients, depletion and buildup under the Indo-Gangetic Plains of India.

Materials and Methods

Site description

A field experiment was conducted in the 2018–19 cropping season on sugarcane at Pusa farm, SRI, Dr. Rajendra Prasad Central Agriculture University, Pusa, Samastipur, Bihar. The size of each plot was 8.0 m in length and 7.2 m in width, having an area of 57.6 m^2. The soil was sandy loam with having pH of 8.25. It was low in organic carbon (0.45 %), available N (205 kg/ha), available P (8.9 kg/ha) and K (101.7 kg/ha). Maximum temperature ranged between 22.8–33.7 °C and minimum temperature between 8.1–26.5 °C. Relative humidity ranged from 79–90 % (7 h) and 55–74 % (14 h) during the crop growing season. The total rainfall received during the experimental period was 871 mm and the number of rainy days (60) (Fig. 1).

Experimental details and crop management

The experiment was laid out in a factorial randomised block design having two levels of macronutrient fertilisers and two levels of row spacing (90 and 120 cm) were applied as per treatments and six genotypes (CoP 13437, CoSe 13451, CoSe 13452, CoLk 94184, CoSe 95422, CoSe 01421) were tested, which were replicated three times. Crop was planted in the spring season on 26 February 2018. Full dose of P and K and half dose of nitrogen was applied in respective treatments and the remaining ¼th was applied at tillering stage and the rest at the grand growth stage. Nitrogen, phosphorus and potassium sources were urea, single super phosphate and muriate of potash, respectively. All agronomic practices were followed throughout the growth period according to the recommendations (13). Crop was harvested on 18 February 2019.

Plant sampling and analysis

From each plot, five plants were randomly selected and marked for observations to assess the impact of the different treatments on the growth and development of the experimental crop. Germination percentage was recorded at 45 days after planting (DAP). Similarly, the number of tillers was counted at 120 DAP. Other biometric observations, like millable canes and single cane weight, were recorded at harvesting. Whole cane plant at harvest was taken for data recording during experimentation and juice samples were collected for quality analysis in the laboratory as per standard procedures (14).

The uptake of nitrogen, phosphorus and potassium was calculated by using a formula by multiplied the concentration by their respective dry matter accumulation (t/ha) (15, 16). The nitrogen, phosphorus and potassium of soil (0–15 cm) were analysed as per the standard procedure (17–19). Nutrient balance was also calculated, in which we have taken the initial soil nutrient status, nutrient uptake by plant and available N, P and K of post-harvest soil of the experimental field.

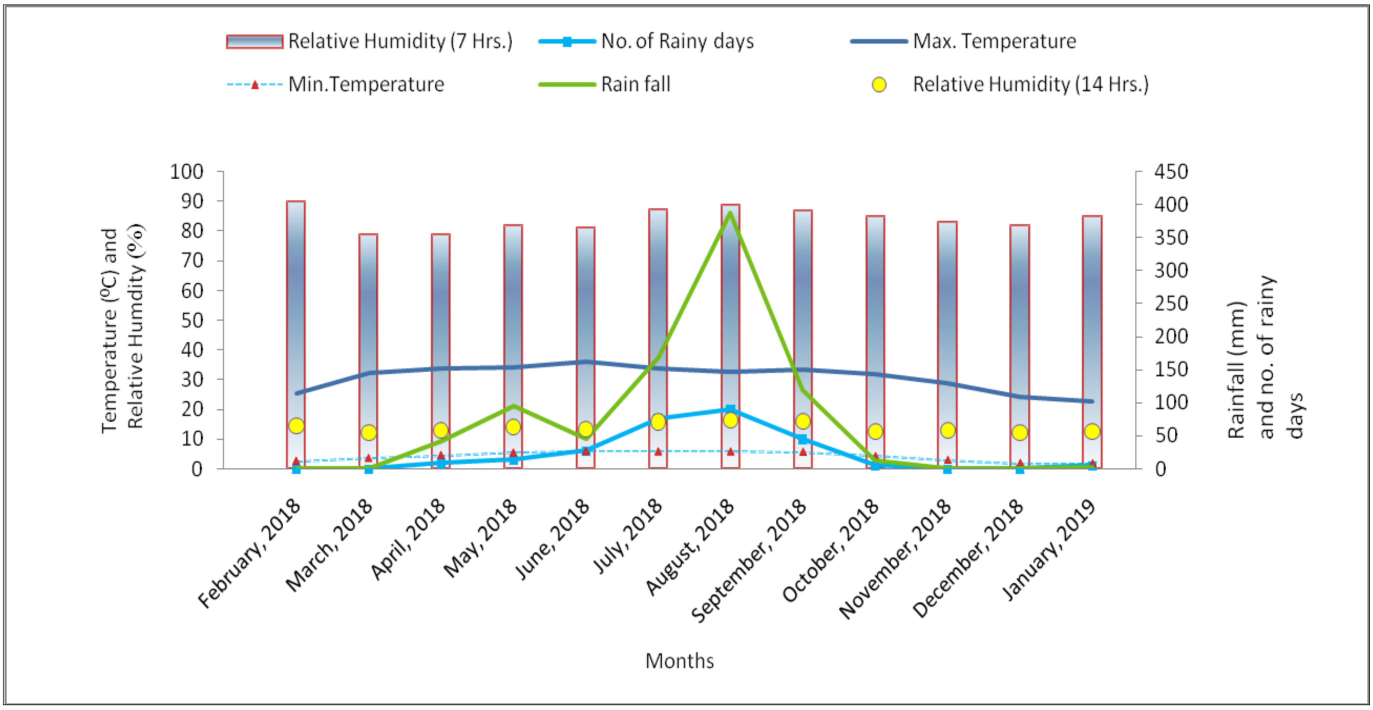

Fig. 1. Climatological data of the experimental site obtained at a local agro-meteorological station during the experimental period.

Economic analysis

Various economic parameters were computed based on the prevailing market prices of both inputs and outputs. The total cost of cultivation was determined by incorporating variable costs (except for land rent), encompassing expenditures on seed cane, fertiliser, human labour, machinery used for land preparation, fertiliser application, irrigation, weeding, plant protection, harvesting, threshing etc. Labour costs associated with diverse field operations were quantified on a per-hectare basis, following the person-days/ha (where 8 hours equate to 1 person-day, adhering to the labour law of the Indian government). The cost of labour was estimated by multiplying the labour input in all operations by the minimum wage rate prescribed by the Government of Indias' labour law. Gross returns were computed by multiplying the cane yield by the current market price of cane (2019). Net returns for each treatment were subsequently calculated as per Eqn. 1 formula:

$$\text{Net returns} = \text{Gross returns} - \text{Cost of cultivation} \quad \text{(Eqn. 1)}$$

Benefit: Cost invested was calculated by dividing net returns by the cost of cultivation. For the economic analysis of this study, the exchange rate of 1 USD equivalent to ₹72.15 for the year 2019 was considered.

Statistical analysis

All data were statistically analysed using analysis of variance (ANOVA) for factorial randomised block design, using SAS v9.4 software (SAS, Inc., North Carolina, USA) (20). Treatment means were evaluated using the F-test, with a critical difference (CD) at 5 % probability level used to assess differences between mean treatment data.

Results

Growth, yield attributes and cane yield

Results of the study indicated that row configuration, macronutrient fertiliser level and genotypes did not significantly influence germination as depicted in Table 1. Tillers at 120 days after planting, single cane weight and millable canes (×10^3/ha) were significantly affected by all the factors (Table 1). Sugarcane planted at a row configuration of 90 cm increased the tillers and millable canes by 36.1 and 25.2 % to a 120 cm configuration. However, the tillers increased by 23.0 and 18.0 % with increasing fertility level, i.e. $N_{187.5}$ + $P_{46.4}$+ K $_{62.3}$ kg/ha. Among different genotypes, CoP13437 recorded significantly higher tiller population and millable canes, followed by CoP 13451 and CoLk 94184. It was found to the tune of 26.2 and 20.1 % higher than the genotype CoSe 95422. Significant variation in dry matter accumulation was observed due to the 90 cm configuration, which accounted for the magnitude of 31.3 % over the 120 cm configuration (Fig. 2). Increasing the fertility level from N_{150} + $P_{37.1}$+ $K_{49.8}$ to $N_{187.5}$+ $P_{46.4}$+ $K_{62.3}$ increased dry matter accumulation by 2.68 %. Dry matter accumulation observed was significantly higher in genotype CoSe 95422, followed by CoSe 13451. While the minimum dry matter accumulated by genotype CoLk 94184, which decreased by 69.2 and 63.3 % over dry matter accumulated by CoSe 95422 and CoP 13437, respectively (Table 1). While the single cane weight (g) was observed to be higher when sugarcane was planted at 120 cm configuration and it was 5.9 % higher than 90 cm spacing. With increasing fertility level ($N_{187.5}$ + $P_{46.4}$+ $K_{62.3}$) kg/ha, maximum single cane weight was observed and it increased by 6.32 % as compared to the recommended fertility level. However, genotype CoSe 95422 gained maximum cane weight (1063.3 g), followed by CoP 13437 (930.8 g). Appreciable variation in cane yield was observed with planting at 90 cm row configuration (Fig. 3). The magnitude of increase was 31.1 % over the planting at 120 cm row configuration. Significant increase in cane yield was obtained with the increased NPK level and the increase in cane yield by N $_{187.5}$ + $P_{46.4}$+ $K_{62.3}$ kg/ha was to the tune of 27.5 %. Significantly higher (105.6 t/ha) cane yield was obtained in genotype CoSe 95422 followed by CoP 13437 (102.7 t/ha), due to more number of millable cane per unit area. Furthermore, the sucrose % was not influenced significantly by all the factors (Table 1).

Economics

Significant effect was observed on net return and benefit: cost by row configuration, macronutrient level and genotype factor (Table 1). The maximum net returns of ₹160800 with a benefit-to-cost ratio of 2.21 was recorded with closer planting (90 cm) in sugarcane crop than wider planting (120 cm). Successive increases in fertility levels increased the net returns and benefit: cost (Table 1). Application of $N_{187.5}$+ $P_{46.4}$+ $K_{62.3}$ kg/ha gave 62.01 % more net returns than N_{150}+ $P_{37.1}$+ $K_{49.8}$ kg/ha fertility levels. Progressive increase in benefit: cost was observed with an increase in doses of fertilisers. Genotype CoSe 95422 fetched the maximum net returns (174.9 × 10^3), followed by CoP 13437 (166.4 ×10^3/ha) with the highest

Table 1. Growth, yield attributes, sucrose content and economics of sugarcane genotypes as influenced by row configuration, macronutrient levels

Treatment	Germination (%)	Tillers (× 10^3/ha) at 120 DAP	Single cane weight (g)	Millable Canes (× 10^3/ha)	Sucrose (%)	Cost of cultivation (× 10^3/ha)	Gross returns (× 10^3 /ha)	Net returns (× 10^3 /ha)	Benefit: cost
Row spacing (cm)									
90 cm	33.3	178.8	847.6	123.7	18.37	133.0	293.8	160.8	2.21
120 cm	34.0	131.4	897.7	91.5	18.38	129.9	224.2	94.3	1.73
SEm(±)	0.66	2.30	12.3	1.48	0.066	-	4.38	1.81	0.028
CD (P = 0.05)	NS	6.4	34.1	4.1	NS	-	12.1	5.0	0.08
Fertility level (kg N + P + K /ha)									
N_{150} + $P_{37.1}$ + $K_{49.8}$	33.0	139.1	845.9	98.7	18.48	130.3	227.6	97.4	1.75
$N_{187.5}$ + $P_{46.4}$ + $K_{62.3}$	34.3	171.1	899.4	116.5	18.27	132.7	290.4	157.8	2.19
SEm(±)	0.66	2.30	12.3	1.48	0.066	-	4.38	1.81	0.028
CD (P = 0.05)	NS	6.4	34.1	4.1	NS	-	12.1	5.0	0.08
Genotypes									
CoP 13437	32.2	169.7	930.8	114.9	18.29	131.5	297.9	166.4	2.27
CoSe 13451	32.6	161.6	910.0	109.4	18.38	131.5	278.7	147.3	2.12
CoSe 13452	33.9	134.5	805.0	102.6	18.27	131.5	226.6	95.1	1.72
CoLk 94184	33.2	161.0	610.3	106.9	18.63	131.5	180.8	49.3	1.38
CoSe 95422	34.0	155.5	1063.3	105.2	18.27	131.5	306.3	174.9	2.33
CoSe 01421	36.2	148.1	916.5	106.4	18.40	131.5	264.0	132.5	2.01
SEm(±)	1.13	3.99	21.3	2.57	0.110	-	7.60	3.13	0.048
CD (P = 0.05)	NS	11.1	59.1	7.1	NS	-	21.0	8.7	0.13

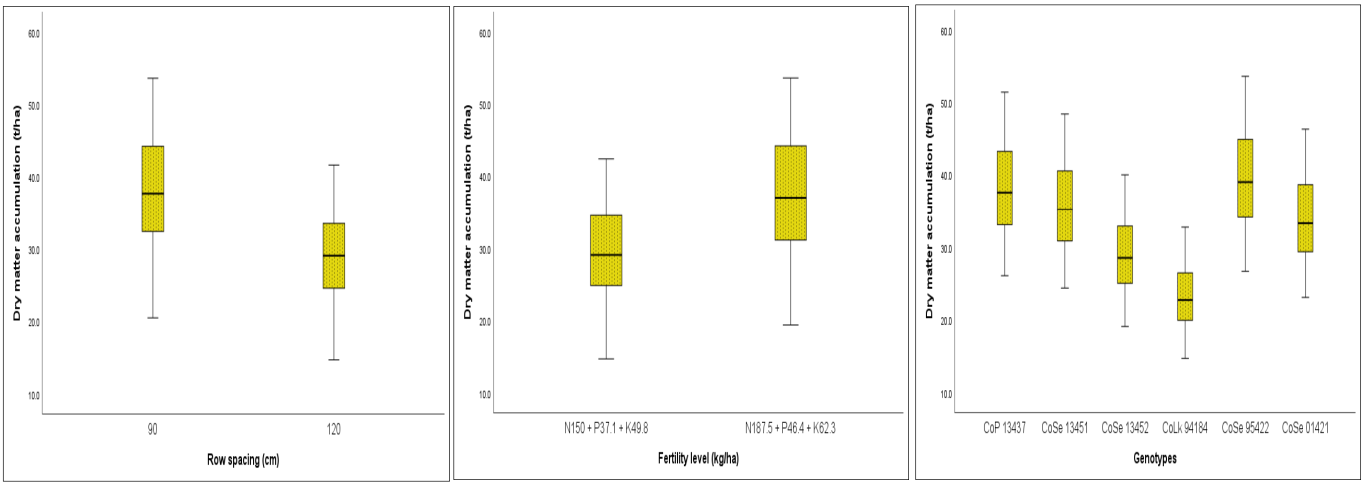

Fig. 2. Dry matter accumulation (t/ha) as influenced by different row configurations, macronutrient levels and genotypes.

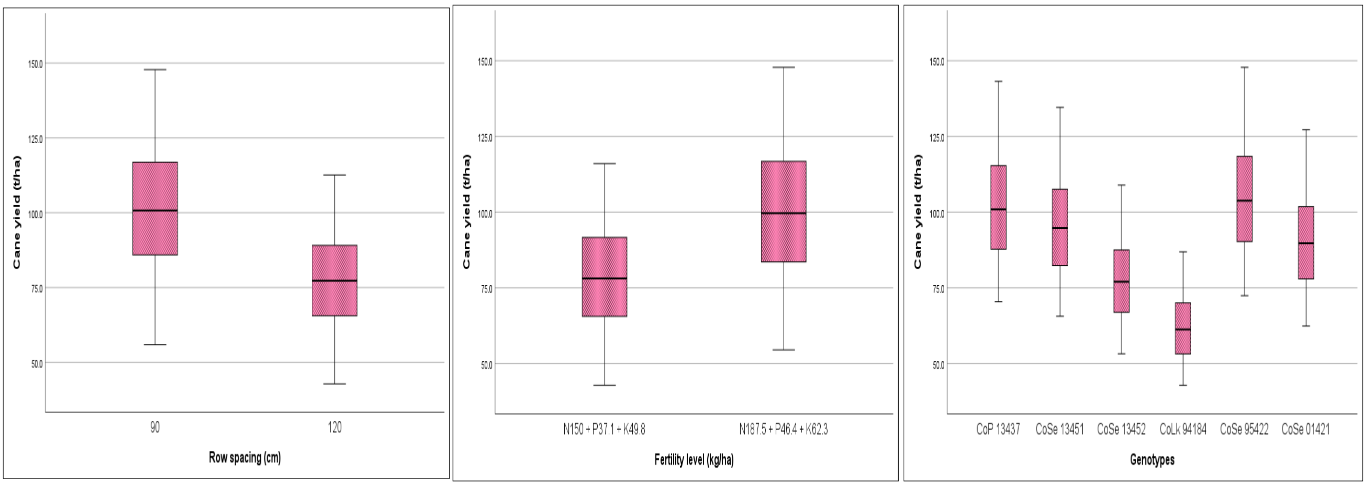

Fig. 3. Cane yield (t/ha) as influenced by different row configurations, macronutrient levels and genotypes.

benefit: cost ratio of 2.33.

Post-harvest soil nutrient status

Available soil N was significantly affected by row configuration, fertility and genotype factors (Fig. 4). The highest available nitrogen was observed at 120 cm row configuration and it decreased by 2.5 % when planted in rows having 90 cm configuration. While the availability of soil nitrogen was the highest (251 kg/ha) at 87.5 + 46.4 + 62.3 kg N P K /ha, as compared to 150 + 37.1 + 49.8 kg N P K /ha. It increased by 6.81 % with increasing macronutrient fertility level. The post-harvest available soil nitrogen content indicated significant differences among the genotypes. Significantly higher soil nitrogen availability (256 kg/ha) was observed by genotype CoLk 94184 followed by CoSe 13452 (251 kg/ha). Appreciable variation was observed in available soil phosphorus as affected by fertility level and genotype factors. While there were no significant effects on soil phosphorus availability by row configuration; however, available soil phosphorus increased by 3.41 % at wider row spacing (120 cm) over narrow spacing (90 cm). With increasing levels of nitrogen, phosphorus and potassium application (187.5 + 46.4 + 62.3 kg/ha), available phosphorus increased by 12.5 %. Genotype CoSe 95422 showed the lowest available soil phosphorus and it decreased by 1.3 % over the genotype CoLk 94184. Available soil potassium was recorded as highest under the 120 cm row configuration (119 kg/ha) as compared to the 90 cm configuration (115 kg/ha). Maximum K status in post-harvest soil was observed under high fertility level (187.5+ 46.4 + 62.3 kg N + P + K /ha). It increased by 7.1 % over the low fertility level (150 + 37.1 + 49.8 kg N + P + K /ha). The available K status

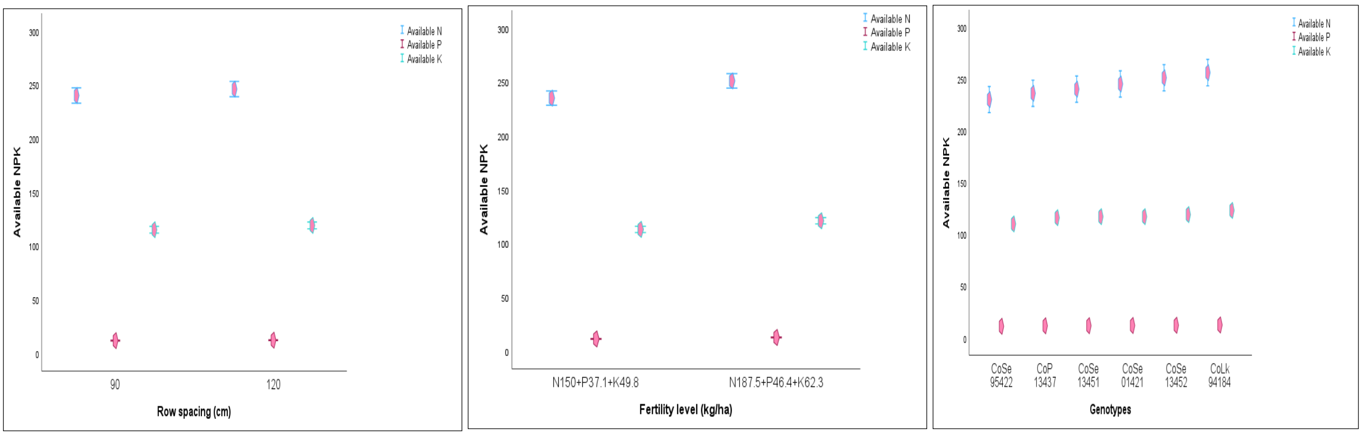

Fig. 4. Available NPK (kg/ha) as influenced by different row configurations, macronutrient levels and genotypes.

decreased by 10.6 % in genotype CoSe 95422 planted plots over CoLk 94184.

Nutrient uptake

Nitrogen, phosphorus and potassium uptake were significantly influenced by all the factors (Fig. 5). NPK uptake was observed to be highest at a row configuration of 90 cm. It increased by 27.7, 27.1 and 25.2 % over the 120 cm row configuration. With an increase in macronutrient level, there was a significant increase in NPK uptake. Higher uptake of nitrogen (280 kg/ha), phosphorus (27.3 kg/ha) and potassium (318.2 kg/ha) was recorded under 187.5 + 46.4 + 62.3 kg N + P + K /ha macronutrient fertility level. Genotype CoSe 95422 resulted in the highest nitrogen, phosphorus and potassium uptake (264.3, 29.8 and 352.4 kg/ha), respectively. However, genotype CoLk 94184 absorbed the minimum NPK, which decreased by 44.9, 46.6 and 48.9 % over NPK absorbed by the genotype CoSe 95422.

Nutrient balance

Net gain of nitrogen was observed in 120 cm row configuration plots (Table 2). There was a marked increase in nitrogen balance and it was to the tune of 17.1 % over the 90 cm row configuration. Improvement in nitrogen was recorded in the plots receiving higher amounts of nitrogen, phosphorus and potassium. Maximum nitrogen gains (46 kg/ha) were observed in 187.5 + 46.4 + 62.3 kg N P K/ha fertility level. The gain in availability of nitrogen was recorded by genotype CoLk 94184 (51 kg/ha), followed by CoSe 13452 (46 kg/ha). However, minimum gain in nitrogen was observed by genotype CoSe 95422 (25 kg/ha). Data depicted in Table 3 revealed that soil phosphorus gain over initial P status was quite lower (3.2 kg/ha) at wider row configuration (120 cm). Higher magnitude of net P gain was observed at 187.5 + 46.4 + 62.3 kg N P K /ha as compared to 150 + 37.1 + 49.8 kg N P K /ha fertility level. Genotype CoLk 94184 (3.6 kg/ha) followed by CoSe 13452 (3.3 kg/ha) followed by CoSe 13451 (2.9 kg/ha). However, minimum gain in phosphorus was observed by genotype CoSe 95422 (2.3 kg/ha). Net gain of potassium was found to be positive in all treatments (Table 4). The expected balance had negative values in all the treatments. However, positive gain in potassium status in post-harvest soil was found and it was higher (17.3 kg/ha) in the row configuration (120 cm) as compared to 90 cm. Higher levels of fertiliser application result in higher net gain of potassium. It must be

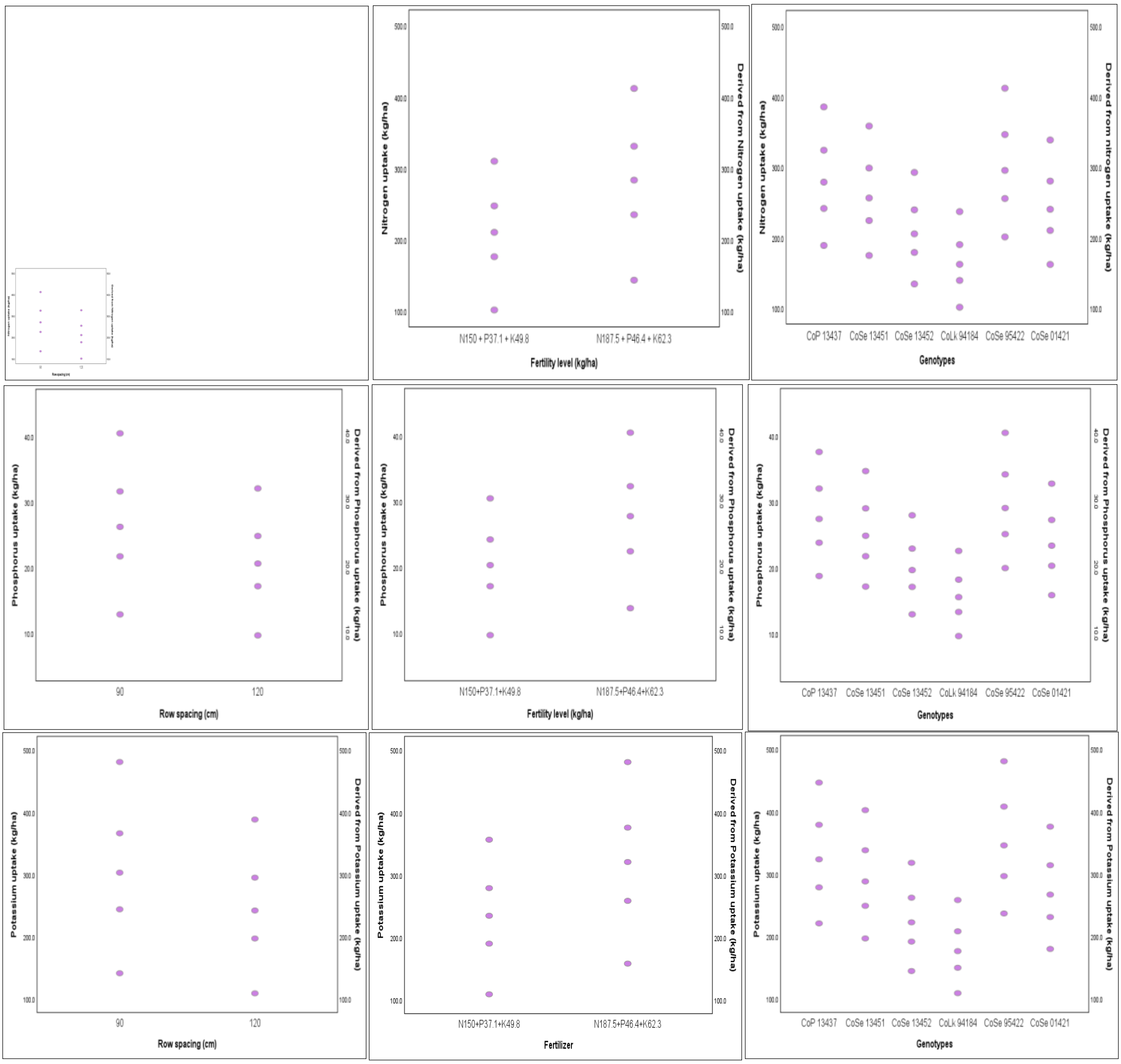

Fig. 5. Nitrogen, phosphorus and potassium uptake (kg/ha) as influenced by different row spacing, fertility level and genotypes.

Table 2. Balance sheet of N as influenced by row configuration, macronutrient levels and sugarcane genotypes

Treatment	Initial soil N status (kg/ha)	Added N (kg/ha)	N-uptake (kg/ha)	Expected balance in soil {(A + B) – C}	Available soil N after harvest (kg/ha)	Apparent gain (E-D) or loss (D-E)	Net gain (E-A) or Loss (A-E)
	(A)	(B)	(C)	(D)	(E)	(F)	(G)
Row spacing (cm)							
90 cm	205	168.8	274.1	99.7	240	140.3	35
120 cm	205	168.8	214.7	159.1	246	86.9	41
SEm(±)	-	-	3.56	-	3.2	-	-
CD (*P* = 0.05)	-	-	9.9	-	NS	-	-
Fertility level (kg N + P + K /ha)							
$N_{150} + P_{37.1} + K_{49.8}$	205	150.0	208.8	146.2	235	88.8	30
$N_{187.5} + P_{46.4} + K_{62.3}$	205	187.5	280.0	112.6	251	138.4	46
SEm (±)	-	-	3.56	-	3.2	-	-
CD (*P* = 0.05)	-	-	9.9	-	8.9	-	-
Genotypes							
CoP 13437	205	168.8	249.1	90.9	236	145.2	31
CoSe 13451	205	168.8	230.1	112.3	240	127.8	35
CoSe 13452	205	168.8	183.8	164.3	251	86.7	46
CoLk 94184	205	168.8	145.6	207.9	256	48.1	51
CoSe 95422	205	168.8	264.3	72.7	230	157.3	25
CoSe 01421	205	168.8	215.3	128.4	245	116.6	40
SEm(±)	-	-	6.16	-	5.6	-	-
CD (*P* = 0.05)	-	-	17.1	-	15.4	-	-

Table 3. Balance sheet of P as influenced by row configuration, macronutrient levels and sugarcane genotypes

Treatment	Initial soil P status (kg/ha)	Added P (kg/ha)	P-uptake (kg/ha)	Expected balance in soil {(A + B) – C}	Available soil P after harvest (kg/ha)	Apparent gain (E-D) or loss (D-E)	Net gain (E-A) Or Loss(A-E)
	(A)	(B)	(C)	(D)	(E)	(F)	(G)
Row spacing (cm)							
90 cm	8.9	41.8	26.7	24.0	11.7	-12.3	2.8
120 cm	8.9	41.8	21.0	29.7	12.1	-17.6	3.2
SEm (±)	-	-	0.32	-	0.16	-	-
CD (*P* = 0.05)	-	-	0.9	-	NS	-	-
Fertility level (kg N + P + K /ha)							
$N_{150} + P_{37.1} + K_{49.8}$	8.9	37.1	20.3	25.7	11.2	-14.5	2.3
$N_{187.5} + P_{46.4} + K_{62.3}$	8.9	46.4	27.3	28.0	12.6	-15.4	3.7
SEm(±)	-	-	0.32	-	0.16	-	-
CD (*P* = 0.05)	-	-	0.9	-	0.4	-	-
Genotypes							
CoP 13437	8.9	41.8	27.9	22.8	11.7	-11.1	2.8
CoSe 13451	8.9	41.8	25.5	25.2	11.8	-13.4	2.9
CoSe 13452	8.9	41.8	20.1	30.6	12.2	-18.4	3.3
CoLk 94184	8.9	41.8	15.9	34.8	12.5	-22.3	3.6
CoSe 95422	8.9	41.8	29.8	21.0	11.2	-9.8	2.3
CoSe 01421	8.9	41.8	23.9	26.8	12.0	-14.8	3.1
SEm(±)	-	-	0.56	-	0.27	-	-
CD (*P* = 0.05)	-	-	1.6	-	0.8	-	-

Table 4. Balance sheet of K as influenced by row configuration, macronutrient levels and sugarcane genotypes

Treatment	Initial soil K status (kg/ha)	Added K (kg/ha)	K-uptake (kg/ha)	Expected balance in soil {(A + B) – C}	Available soil K after harvest (kg/ha)	Apparent gain (E-D) or loss (D-E)	Net gain (E-A) or Loss (A-E)
	(A)	(B)	(C)	(D)	(E)	(F)	(G)
Row spacing (cm)							
90 cm	101.7	56.1	306.3	-148.5	115	263.5	13.3
120 cm	101.7	56.1	245.0	-87.3	119	206.3	17.3
SEm ±	-	-	4.07	-	1.4	-	-
CD (*P* = 0.05)	-	-	11.3	-	4	-	-
Fertility level (kg N + P + K /ha)							
$N_{150} + P_{37.1} + K_{49.8}$	101.7	49.8	233.1	-81.6	113	194.6	11.3
$N_{187.5} + P_{46.4} + K_{62.3}$	101.7	62.3	318.2	-154.2	121	275.2	19.3
SEm ±	-	-	4.07	-	1.4	-	-
CD (*P* = 0.05)	-	-	11.3	-	4	-	-
Genotypes							
CoP 13437	101.7	56.1	328.7	-170.9	116	286.9	14.3
CoSe 13451	101.7	56.1	293.7	-135.9	117	252.9	15.3
CoSe 13452	101.7	56.1	226.9	-69.1	119	188.1	17.3
CoLk 94184	101.7	56.1	179.9	-22.1	123	145.1	21.3
CoSe 95422	101.7	56.1	352.4	-194.7	110	304.7	8.3
CoSe 01421	101.7	56.1	272.5	-114.7	117	231.7	15.3
SEm ±	-	-	7.05	-	2.4	-	-
CD (*P* = 0.05)	-	-	19.5	-	7	-	-

assumed that either K was released from the reserves held in the inner layer or some other form of K (presumably non-exchangeable K) has been taken up by sugarcane.

Discussion

The findings of this study highlight the synergistic influence of genotype selection, row configuration and fertiliser management on sustainable sugarcane production. The interaction among these factors appears to play a crucial role in optimising both agronomic and economic outcomes in the Indo-Gangetic Plains. Closer row spacing (90 cm) facilitated greater plant population density, leading to significantly improved cane yield and nutrient uptake. Research has demonstrated that narrower row spacing enhances resource use efficiency by minimising inter-row competition and maximising radiation interception (21). However, this configuration did lead to comparatively lower post-harvest soil nutrient status, possibly due to greater biomass extraction and nutrient uptake by denser plant stands. The impact of macronutrient levels on yield and nutrient dynamics observed in the present study corroborates the results that higher NPK inputs improve cane growth parameters and nutrient accumulation (22). Nevertheless, the increased uptake also influenced soil nutrient depletion, especially when high-yielding genotypes were combined with closer spacing. Thus, while increased fertiliser application improves productivity, it necessitates careful nutrient budgeting to avoid long-term soil degradation (23). Genotypic variability in performance was evident in terms of yield components, nutrient uptake and post-harvest soil fertility. CoSe 95422 demonstrated remarkable nutrient uptake efficiency and higher productivity, but this was also associated with reduced residual soil nutrient levels, indicating a potential trade-off between yield and soil health. Similar genotypic differences in nutrient assimilation efficiency were reported, highlighting the need for genotype-specific nutrient management strategies (24). Although both fertility levels showed high, the observed 70 kg/ha difference in crop uptake exceeded the 37.5 kg/ha difference in measured total available nutrient. This apparent discrepancy likely reflects several complementary factors. Sugarcane plants under the higher fertility treatment developed greater root systems and higher biomass, improving uptake efficiency and synchronising nutrient demand with periods of supply; this amplifies the effect of a relatively modest increase in available pool (25).

Furthermore, higher fertility may have reduced nutrient losses (leaching, fixation, volatilisation) and enhanced microbial mineralisation, thereby increasing the fraction of nutrients actually taken up (26). The observed nutrient balance trends, especially for nitrogen and potassium, indicate that wider spacing (120 cm) is beneficial for nutrient conservation in soil, possibly due to reduced plant population pressure (27). Row configuration influenced not only crop productivity but also the nutrient cycling and retention in the soil-plant system in sugarcane (28, 29, 30). Furthermore, the economic analysis reinforces the agronomic findings by demonstrating that optimal spacing and nutrient levels, coupled with high-performing genotypes like CoSe 95422 and CoP 13437, can lead to substantial increases in net returns and benefit-cost ratios. Research has demonstrated that integrated agronomic management with improved profitability in sugarcane systems (31).

The strong interrelationships among nutrient uptake and yield traits highlight the coordinated role of macronutrient assimilation in sugarcane productivity. Potassium uptake showed an almost perfect correlation with nitrogen uptake (r = 0.996), indicating that these nutrients are absorbed and utilised in a closely synchronised manner during crop growth (Table 5). Similarly, cane yield exhibited strong positive correlations with N (r = 0.899), P (r = 0.904) and K (r = 0.891) uptake, suggesting that enhanced nutrient absorption directly contributes to higher biomass accumulation and yield. In contrast, available soil N, P and K showed weak and non-significant relationships with yield and uptake traits, implying that nutrient abundance in soil alone does not ensure improved productivity. This is likely due to nutrient losses through leaching or volatilisation, especially under high rainfall or irrigated conditions. The observed positive associations among available N, P and K and between available P and K (r ≈ 0.95), reflect inherent soil fertility linkages, yet their limited influence on uptake emphasises that nutrient availability must coincide with plant demand for efficient utilisation. Overall, these correlations reinforce that balanced nutrient uptake, rather than mere soil nutrient status, determines yield outcomes (32, 33). Therefore, an integrated management approach combining optimal row spacing, fertility level and genotype selection is essential to achieve sustainable and profitable sugarcane production, particularly in the Indo-Gangetic region.

Conclusion

On the basis of the findings of this study, it can be concluded that the 90 cm row configuration was still doing well under sub-tropical conditions. In this investigation, we found that all treatments had positive nutrient equilibrium, meaning that the amount of nutrients provided to the soil was more than the amount of nutrients removed. It is a sign that the addition of fertiliser was adequate to make up for crop N, P and K depletion for conserving sustainability. However, these

Table 5. Correlation study among different traits

Parameters	Dry matter accumulation (t/ha)	Cane yield (t/ha)	N uptake (kg/ha)	P uptake (kg/ha)	K uptake (kg/ha)	Available N (kg/ha)	Available P (kg/ha)	Available K (kg/ha)
Dry matter accumulation (t/ha)	1.000	0.901^{**}	0.992^{**}	0.990^{**}	0.980^{**}	0.075	0.177	0.072
Cane yield (t/ha)		1.000	0.899^{**}	0.904^{**}	0.891^{**}	-0.171	-0.034	-0.159
N uptake (kg/ha)			1.000	0.999^{**}	0.996^{**}	0.086	0.206	0.092
P uptake (kg/ha)				1.000	0.998^{**}	0.056	0.180	0.065
K uptake (kg/ha)					1.000	0.060	0.187	0.074
Available N (kg/ha)						1.000	0.967^{**}	0.985^{**}
Available P (kg/ha)							1.000	0.976^{**}
Available K (kg/ha)								1.000

**Correlation is significant at the 0.01 level (2-tailed).

gains must be balanced with soil nutrient conservation for long-term sustainability. Application of 187.5:46.4:62.3 kg N:P:K /ha was found optimum for maximising productivity and profitability of sugarcane, while genotype CoSe 95422, being statistically similar to CoP 13437, showed higher net returns and benefit: cost may be recommended for commercial cultivation.

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Authors' contributions

NK conceived and designed the study, carried out the methodology, performed formal analysis and investigation and provided resources. NK, LR and SS curated the data. LR and SS drafted the original manuscript. NK and SK reviewed and edited the manuscript. NK, LR and SK supervised the work. NK, LR and SS validated the study. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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