



Performance Evaluation of Sugarcane (*Saccharum officinarum* L) Cultivars under Varying Nitrogen Fertilization Levels: Implications for Climate Change Mitigation and Sustainable Agriculture.

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Abstract

Nitrogen (N) is a critical nutrient for plant growth and development, regulating cell division, elongation, and biomass buildup. However, poor nitrogen management, particularly excessive and uneven application, results in low nitrate usage efficiency, higher production costs, environmental contamination from nitrate leaching and nitrous oxide emissions, and deterioration of crop product quality. In sugarcane agriculture, uneven nitrogen fertilization exacerbates problems like as lodging, delayed maturity, and diminished juice purity, ultimately reducing the crop's economic viability. Sugarcane (*Saccharum officinarum* L.) is a major cash crop in Pakistan and around the world, but productivity in Pakistan remains suboptimal due to a variety of factors such as delayed planting, poor crop management, pest infestations, insufficient irrigation, and, most notably, an imbalanced use of nitrogen fertilizers. Excess nitrogen has a deleterious impact on sugarcane development by stimulating excessive vegetative growth at the expense of stalk strength and yield quality, resulting in reduced sugar recovery and economic losses. This study assessed the performance of four sugarcane cultivars (SPF 234, HSF 240, CPF 237, and CPF 243) at four nitrogen levels (0, 100, 200, and 300 kg N ha⁻¹) in Bahawalpur during the 2025-2026 season. The results showed that nitrogen treatment and cultivar differences had a substantial impact on germination, tillering, cane length, diameter, millable cane weight, and the number of millable canes per clump. The cultivar CPF 237 consistently outperformed all nitrogen rates, with improved yield-related attributes under increasing nitrogen input. The greatest nitrogen rate (300 kg N ha⁻¹) led to maximum growth and production. However, intermediate nitrogen levels (about 200 kg N ha⁻¹) are recommended to improve yield while avoiding environmental concerns and maintaining juice quality. These findings indicate that combining balanced nitrogen management with the selection of responsive cultivars such as CPF 237 can sustainably increase sugarcane productivity in Pakistan's semi-arid agro-climatic settings.

Keywords Nitrogen, Sugarcane, bioenergy, Nutrients, Juice Purity, Cultivar

Introduction

Sugarcane (*Saccharum officinarum* L.) is a major cash crop grown in over 120 countries. It contributes to sugar production, bioenergy, and industrial byproducts. The crop includes approximately 70-75% carbs, 0.5-1.0% proteins, and 0.1-0.5% lipids, making it a valuable energy source. It generates many by-products, such as molasses used in ethanol and alcohol production, bagasse used as biofuel and in paper industries, press mud used as organic fertilizer, and

bioelectricity created through cogeneration (Iqba *et al.*, 2014). Brazil is the largest producer of sugarcane yield among other countries, and hence in the globe. The next five largest producers in descending order of economic returns experience significant decreases (Abhiram *et al.*, 2025). India, China, Thailand, Pakistan, and Mexico were all in a slight order. Among the world's 105 countries, Pakistan ranks fourth in area, 14th in production, and 16th

in sugar mill underutilization. Brazil and India together account for roughly 60% of global production (Vandenberghe *et al.*, 2022). Sugarcane is Pakistan's second-largest cash crop after cotton, covering over 1.2 million hectares and producing 84.24 million tons per year. (Economic Survey Pakistan 2025). Several factors contribute to low sugarcane production in Pakistan, including delayed planting, poor crop management, insufficient irrigation, pest infestation, sugarcane lodging, and the cultivation of low-yielding varieties (Hemalatha *et al.*, 2015). Excessive and uneven use of chemical fertilizers, particularly nitrogen, is also a big concern. Farmers frequently apply nitrogen at higher rates than recommended, resulting in low nitrogen usage efficiency, increased production costs, and severe environmental consequences (Aslam *et al.*, 2024). Additional nitrogen application does not increase yield beyond the optimum level, but instead promotes nitrate leaching, groundwater contamination, and nitrous oxide emissions (Aslam *et al.*, 2024). Farmers usually continue this method in the hopes of increasing yields, however it has a negative impact on juice quality by lowering sucrose concentration and increasing non-sugary contaminants such as amino acids and reducing sugars (Zeng *et al.*, 2020). These alterations diminish juice purity, sugar recovery, and crystallization efficiency, lowering profitability (William *et al.*, 2018). Moderate nitrogen application (~100 kg N/ha) can improve juice quality parameters like as Brix (total soluble solids) and Pol (sucrose content) without compromising fiber content. Higher nitrogen levels can impair TRS and juice purity, particularly during irrigation (Rhein *et al.*, 2016; Swaminathan *et al.*, 2018). Increased nitrogen delivery promotes vegetative development, resulting in tall, lush, and succulent canes with weak stems. Stalk lignification declines, making the stems fragile and unable to withstand wind or irrigation pressure (Hemalatha *et al.*, 2015). Shoot growth takes precedence over root development, and the root system remains shallow and weak, leaving the plants poorly attached in the soil (Takeda *et al.*, 2022). This imbalance, combined with delayed maturation and the formation of top-heavy plants with big leaf area and high-water content, heightens the risk of lodging. Soft and immature stalks can attract pests and diseases, further eroding crop stands. Lodging causes harvesting issues, decrease of juice quality, less sugar recovery, and economic losses (Abhiraam, G *et al.*, 2025). Excess nitrogen causes nitrate leaching into groundwater and increases nitrous oxide emissions, which accelerate climate change (William *et al.*, 2018). Optimized nitrogen management saves production costs, improves juice quality, boosts sugar recovery, and lessens the danger of groundwater pollution and greenhouse gas emissions. Proper nitrogen utilization promotes soil microbial health and sustainable crop production (William *et al.*, 2018). Nitrogen is essential for sugarcane growth, but poor management can lead to

major difficulties. To ensure long-term production, nitrogen application tactics must be optimized (Okamoto *et al.*, 2021). Sugarcane cultivars range in production potential and nitrogen responsiveness, making cultivar selection equally critical (Dalen *et al.*, 2022). The combination of appropriate nitrogen level and proper cultivar is necessary to provide increased production, enhanced nitrogen usage efficiency, better juice quality, and fewer environmental concerns. Lofton *et al.*, 2015. This study was carried out to assess the performance of various sugarcane cultivars at varied nitrogen levels. The goal was to find the best nitrogen-cultivar combination for high yield, efficient nitrogen utilization, and good juice quality while minimizing environmental impact, so contributing to Pakistan's sustainable sugarcane production.

Materials and methods

Experimental site and plant material

The experiment was carried out during the growing season 2025-2026 at the Field Area of Ashraf Sugar Mill Bahawalpur. The seeds of Four Sugarcane cultivar viz. SPF 234, HSF 240, CPF 237, And HSF 242 were collected from Ashraf Sugar Mill Bahawalpur. This study was conducted to evaluate the performance of different sugarcane cultivars under varying nitrogen levels (0,100,200,300) on the productivity of sugarcane. The plot was 25 m² in size, with five rows of 5 m length and 1 m width. Sugarcane was planted on February 20th in the spring season and harvested 12 months later. The experimental treatments were set up in a factorial arrangement with three replications using a randomized full block design.

Weather data

Climate data

The following information relates to environmental variables (such as temperature, Humidity and rainfall) over the course of this experiment.

Temperature The Mean Minimum temperatures observed during the research period (March 2025 to July 2025) are 16°C, 22°C, 26°C, 24°C, 22°C and Maximum are 36°C, 39°C, 44°C, 46°C, 39°C respectively.

Rainfall (mm)

The rainfall recorded during the research duration (from March 2025 to July 2025) was 0 mm from March to May, and 4 mm in June and 53 mm in July.

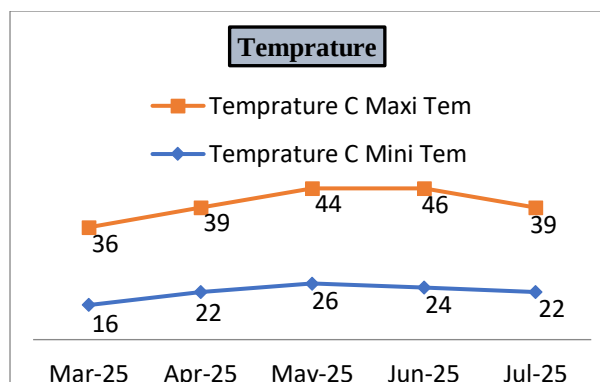


Figure 1. Temperature during crop growth period (Mar 2025- July 2025)

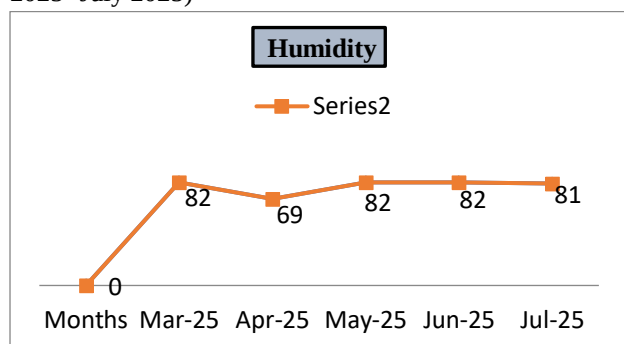


Figure 2. Humidity during crop growth period (Mar 2025- July 2025)

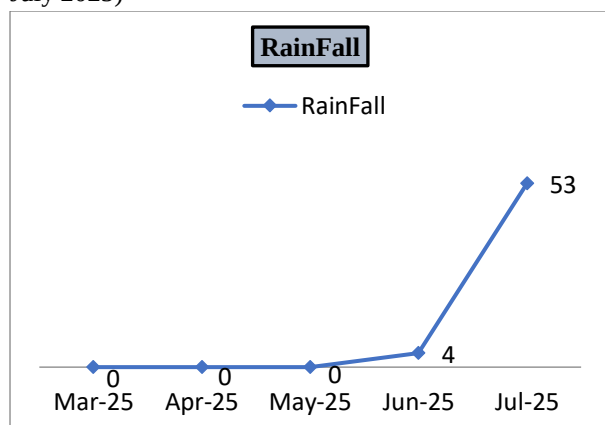


Figure 3. Rainfall during crop growth period (Mar 2025- July 2025)

Crop husbandry

The Sugarcane crop was planted on February 20, 2025, using a planter, with rows spaced 30 cm apart and a seeding rate of 100 Mound ha⁻¹. Before sowing, the experimental soil was ploughed twice using a tractor-mounted cultivator, followed by planking. The experimental soil was characterized as sandy loam with soil organic matter content of 0.56%, pH of 8.2, electrical conductivity of 0.68 dS m⁻¹, soil N content of 0.044%. P and potassium (K) levels were 6 mg kg⁻¹ soil and 149 mg kg⁻¹ soil, respectively, with DTPA extractable Fe at 1.86 mg kg⁻¹ soil. Throughout the cropping season, a eight irrigations of 75 mm were provided during the research phase. After 60 days from planting, the first dose of nitrogen fertilizer was applied (after plant emergence was completed). In Sugarcane crop, the second dose of nitrogen fertilization

was applied 90 days after planting, the third dose was applied 120 days after planting, and the fourth dose was applied 150 days after planting. After emergence to control weeds, a broad-spectrum Herbicide (Scope, Ametryn 40% w/w + Atrazine 40% w/w) was applied. At the vegetative stage to control termites and Shoot Borer, a broad-spectrum insecticide (Ranger, containing fipronil 11.73% w/w) was applied. As a biological control, pheromone traps and trichogama cards were placed in the research area. All other cultural practices were carried out in accordance with the guidelines.

Observations and measurement

Germination

The sugarcane germination count was determined by selecting sample rows from each plot and examining the planted sets 30 days after planting. Each set was checked, and the number of shoots emerging from the soil surface was counted and recorded as germinated sets, while those with no shoots were labeled as non-germinated.

Number of Tillers per Clump.

The number of tillers per clump in sugarcane was calculated by choosing representative clumps from different rows within each plot using a systematic sampling method. To provide trustworthy data, a minimum of 30 clumps were selected at random, 5-10 clumps from 3-5 rows. Each clump was recognized based on its original position, and any living branches greater than 10-15 cm tall with visible leaf sheaths were counted as tillers, while dead or dry shoots were eliminated. Observations were made at critical crop growth stages.

Yield components

At harvest, the following traits were determined:

- 1- Number of millable canes per clump. It was counted on every clump.
- A Sample of ten millable canes from each treatment was randomly taken to determine the following traits:
- 2- Millable cane length (cm): It was measured from land level up to the top visible dewlap.
- 3- Millable cane diameter (cm): It was measured at the middle part of cane stalk.
- 4- Millable cane weight (kg): It was determined by determining the millable cane weight of the sample then dividing it by its number.

Data analysis

The statistical package Statistics 8.1 was used to analyze the experimental data. Various statistical tests were applied to evaluate significant differences and correlations. Analysis of variance (ANOVA) with the Tukey (HSD) test ($p < 0.05$) was used to determine differences among treatments. Graphs were plotted using Origin 2021 software. Principal component analysis (PCA) was conducted to compare these parameters among treatments. Pearson's correlation test was performed to assess relationships between growth, quality, and yield-related parameters.

Results

Germination and Number of Tillers per Clump.

The investigation demonstrated that nitrogen levels and varietal differences had a substantial effect on germination percentage, but their interaction was not significant. The maximum germination rate was reached with N4, followed closely by N3, and the lowest was observed with N1. Among the cultivars, CPF 237 had the highest germination percentage, followed by HSF 240, while SPF 234 and HSF 242 had lower values. Although the nitrogen $\times$ variety association was not statistically significant, CPF 237 performed better under higher nitrogen administration than other varieties. Varietal changes in tiller number per clump were significant, although nitrogen levels and their interaction with varieties were not. CPF 237 generated the most tillers, followed by HSF 240 and SPF 234, while HSF 242 produced the fewest. Tiller productivity varied little across nitrogen treatments, ranging from 7.33 to 9.33 per clump. The findings suggest that tiller production in sugarcane is heavily influenced by genetic potential, with CPF 237 outperforming other varieties regardless of nitrogen.

Yield related traits

The experimental results showed that nitrogen levels and varietal differences had a substantial impact on sugarcane growth and output. The greatest nitrogen level (N4) consistently performed well compare to other treatments in most measures, including millable cane weight, number of millable canes, cane length, and cane diameter. In contrast, the N1 treatment produced the lowest values overall. CPF 237 performed well as compare to other varieties including HSF 240 and SPF 234 in terms of yield-contributing qualities, with higher mean values for millable cane weight, length, diameter, and number of millable canes. However, CPF 243 performed relatively poorly in several aspects. The interaction effects of nitrogen and variety were significant for millable cane weight, diameter, and germination percentage, but not for cane length. Overall, the findings show that increased nitrogen application significantly increased sugarcane productivity, with CPF 237 emerging as the most responsive and high-performing variety under the test conditions

Table 1. Influence of N levels on Mill able cane, Cane Length, Mill able Cane Weight of Sugarcane cultivars

	SP F 23 4	Millable canes Weight				Number of Millable canes					Cane length				
		HSF 240	CPF 237	HSF 242	Mea n (SP)	SPF 234	HSF 240	CPF 237	HSF 242	Mea n (SP)	SPF 234	HSF 240	CPF 237	HSF 242	Mea n (SP)
N1	0.637 hi	0.690 gh	0.723 g	0.623 i	0.668 D	4.667 bc	4.667 bc	5.333 abc	4.333 c	4.750 C	110.67 f	110.33 f	113.00 f	109.33 f	110.83 D
N2	0.790 ef	0.786 f	0.803 def	0.730 g	0.775 C	6.000 abc	6.333 abc	6.000 abc	6.333 abc	6.167 B	125.67 de	124.67 e	124.33 e	125.67 e	125.08 C
N3	0.863 bc	0.857 bcd	0.893 abc	0.843 cde	0.864 B	6.333 abc	7.000 ab	6.333 abc	6.667 abc	6.583 AB	134.33 bc	133.67 c	137.00 ab	133.33 cd	134.58 B
N4	0.910 ab	0.900 ab	0.933 a	0.923 a	0.917 A	7.667 a	7.667 a	7.333 a	6.667 abc	7.333 A	142.67 a	141.67 ab	141.00 ab	143.33 a	142.17 A
Me an (C) C	0.800 B	0.808 B	0.838 A	0.780 C		6.167 A	6.417 A	6.250 A	6.000 A		128.33 A	127.58 A	128.83 A	127.92 A	

P < 0.05 Var = ***; Trt = ***; Var $\times$ Trt = ***

Var = ns; Trt = ***; Var $\times$ Trt = ns

Var = ns; Trt = ***; Var $\times$

Trt = ns

Means sharing the same letters in the column do not differ significantly at p < 0.05; ** = p < 0.01; *** = p < 0.001

Correlation Analysis

Pearson correlation analysis was performed to determine the strength and direction of the relationships among the six measured sugarcane traits, namely germination percentage (GER), number of tillers per clump (NTC), cane length (CL), number of millable canes (MC), cane diameter (CD), and millable cane weight (MCW). The results revealed positive and statistically significant correlations among all evaluated traits, although the magnitude of association varied considerably. The strongest relationship was recorded between cane diameter and millable cane weight ($r = 0.969$, $p < 0.001$), indicating that thicker canes were closely associated with greater millable cane weight. Cane length also exhibited very strong positive correlations with cane diameter ($r = 0.961$, $p < 0.001$) and millable cane weight ($r = 0.935$, $p < 0.001$), demonstrating the close association of cane size attributes with final cane productivity. Germination percentage showed strong positive relationships with cane diameter ($r = 0.857$, $p < 0.001$), millable cane weight ($r = 0.850$, $p < 0.001$), and cane length ($r = 0.846$, $p < 0.001$). Likewise, the number of millable canes was strongly and positively correlated with cane diameter ($r = 0.791$, $p < 0.001$), millable cane weight ($r = 0.776$, $p < 0.001$), and cane length ($r = 0.774$, $p < 0.001$). A moderate positive association was observed between germination percentage and the number of millable canes ($r = 0.641$, $p < 0.001$). In contrast, the number of tillers per clump exhibited relatively weaker, although significant, positive correlations with the other traits, with its strongest association being with the number of millable canes ($r = 0.506$, $p < 0.001$). Overall, the correlation pattern indicates that cane diameter, cane length, and millable cane weight are closely interrelated productivity traits, while improved germination and establishment are also positively associated with subsequent cane growth and yield components. These relationships provide useful evidence for interpreting trait associations in the present sugarcane study; however, the observed correlations should be interpreted as statistical associations rather than direct causal effects.

CORRELATION ANALYSIS OF SUGARCANE RESEARCH DATA

1. Variables Included

Code	Variable	Unit/description
GER	Germination (%)	Percentage
NTC	Number of tillers per clump	Count per clump
CL	Cane length (cm)	cm

Code	Variable	Unit/description
MC	Number of millable canes	Count
CD	Cane diameter (cm)	cm
MCW	Millable cane weight (kg)	kg

Correlation Heatmap

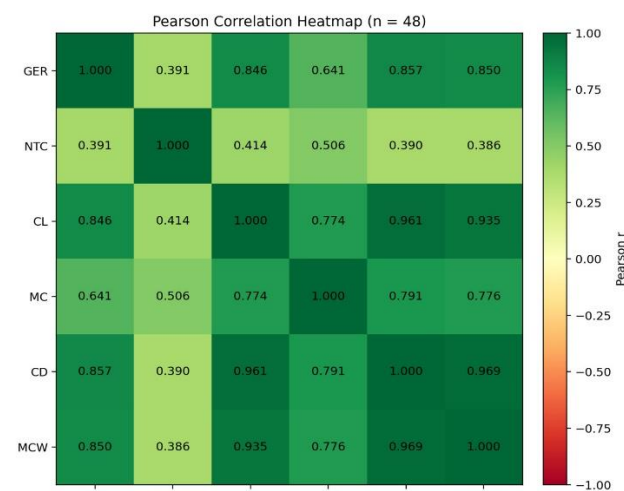


Figure 1. Pearson correlation heatmap for the six measured sugarcane traits (n = 48).

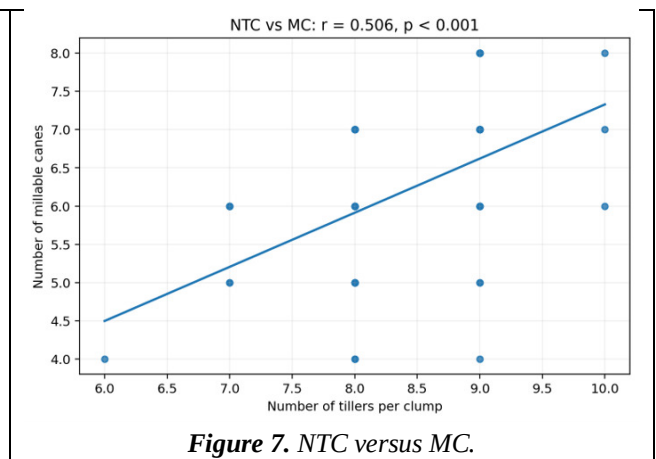
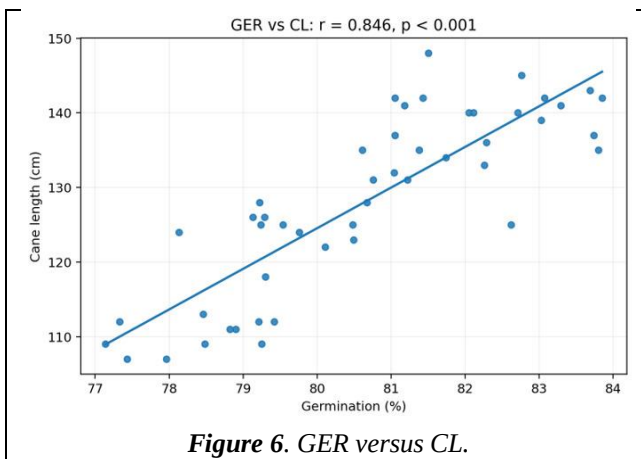
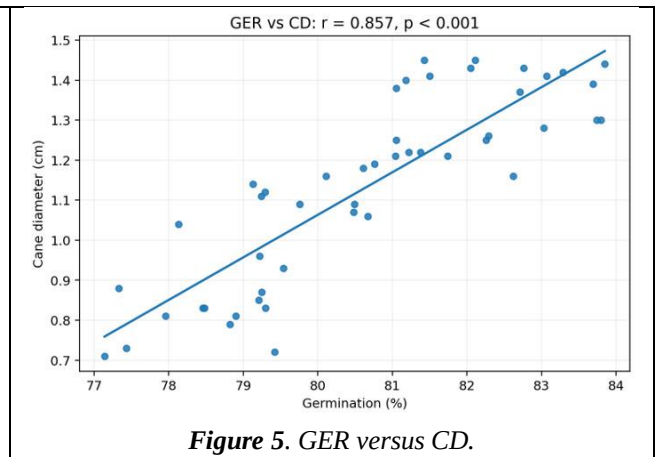
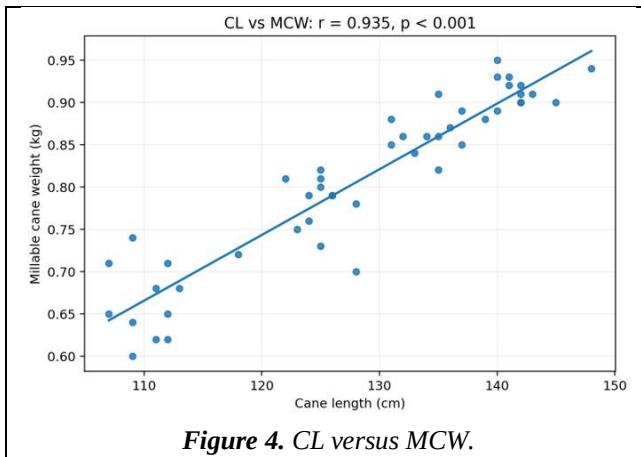
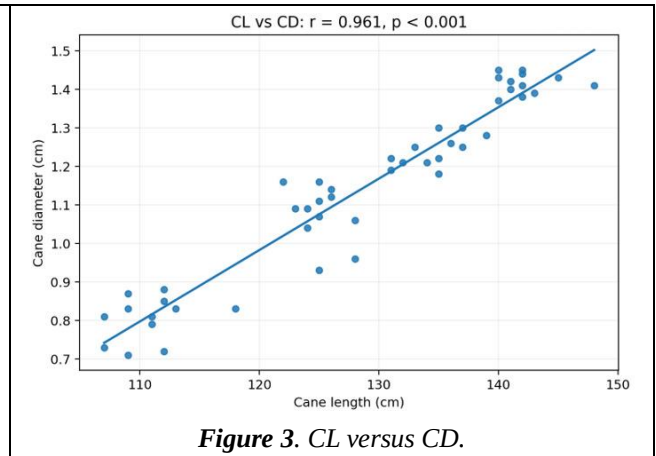
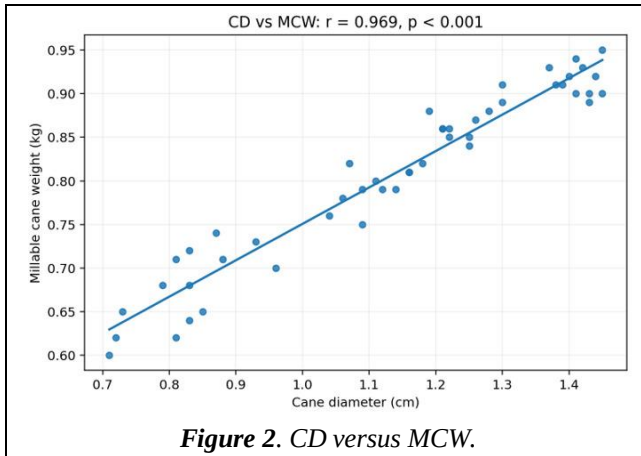
3. Pearson Correlation Matrix

Trait	GER	NTC	CL	MC	CD	MCW
GER	1.000	0.391 **	0.846 ***	0.641 ***	0.857 ***	0.850 ***
NTC	0.391 **	1.000	0.414 **	0.506 ***	0.390 **	0.386 **
CL	0.846 ***	0.414 **	1.000	0.774 ***	0.961 ***	0.935 ***
MC	0.641 ***	0.506 ***	0.774 ***	1.000	0.791 ***	0.776 ***
CD	0.857 ***	0.390 **	0.961 ***	0.791 ***	1.000	0.969 ***
MCW	0.850 ***	0.386 **	0.935 ***	0.776 ***	0.969 ***	1.000

Note. Pearson r values are shown. *** $p < .001$, ** $p < .01$, * $p < .05$ (two-tailed). Diagonal values equal 1.000.

Correlation Scatter Graphs

The following scatter graphs display selected relationships, including the strongest correlations and the tiller–millable cane relationship. A fitted linear trend line is shown in each graph.



Discussion

Among cultivars, CPF 237 exhibited the highest germination, followed by HSF 240, while SPF 234 and HSF 242 recorded lower values. These findings suggest that nitrogen enhances the physiological potential of sets, but genetic differences among varieties play a dominant role in germination. Similar observations were reported by Lofton et al. (2015), who highlighted varietal differences in establishment ability under varying nitrogen levels. Tiller production was significantly affected by varietal differences but not by nitrogen levels or their interaction (Skocaj et al., 2013). CPF 237 produced the maximum tillers per clump, followed by HSF 240 and SPF 234, while HSF 242 showed the lowest. This indicates that tillering is largely governed by genetic potential rather than nitrogen fertilization. Although nitrogen is important for vegetative growth, excessive application often promotes shoot elongation at the expense of tiller formation (Hemalatha et al., 2015). The relatively stable tiller numbers across nitrogen treatments confirm that cultivar selection is the main driver of tillering capacity in sugarcane. Nitrogen levels significantly enhanced cane length, with maximum height observed at N4, followed by N3, while unfertilized plots (N1) produced the shortest stalks. Nitrogen accelerates cell division and elongation, thereby increasing internodal length and overall stalk height. Among cultivars, CPF 237 attained the greatest cane length, demonstrating superior responsiveness to nitrogen. HSF 242, however, remained shorter, indicating poor adaptability. These findings agree with Swaminathan et al. (2018), who noted that moderate nitrogen application improves stalk elongation, but excessive nitrogen delays maturity and weakens structural strength. Cane diameter was strongly influenced by both nitrogen and varietal differences, with significant interaction effects. CPF 237 under N4 achieved the largest stalk diameter, while HSF 242 under N1 recorded the smallest. Nitrogen contributes to enhanced assimilate partitioning toward stalk thickening, improving photosynthetic efficiency and biomass accumulation. However, higher nitrogen levels beyond the optimum can sometimes lead to softer and more succulent stalks, making them prone to lodging (Takeda et al., 2022). The strong varietal effect indicates that stalk diameter is also genetically regulated, with CPF 237 showing superior adaptability. Millable cane weight increased significantly with higher nitrogen doses, with N4 producing the heaviest stalks. This reflects the combined effects of improved cane length and diameter under nitrogen fertilization. Among the cultivars, CPF 237 again exhibited the highest values, while HSF 242 lagged. The nitrogen $\times$ cultivar interaction was significant, indicating that some varieties, particularly CPF 237, are more efficient at converting applied nitrogen into biomass. Similar responses were documented by Rhein et al. (2016), who reported increased stalk weight under higher nitrogen application, although excessive

fertilization reduces juice quality. Both nitrogen levels and cultivars influenced the number of millable canes, with N4 plots outperforming others (Skocaj et al., 2015). CPF 237 recorded the highest number of millable canes per clump, showing its superior potential for ratoon sustainability and productivity. In contrast, HSF 242 produced the lowest, reflecting poor adaptability. The increase in millable canes under higher nitrogen can be attributed to better vegetative vigor and tiller survival, but excessive nitrogen is known to cause lodging and poor cane maturity (Abhiram et al., 2025).

Conclusion

The present study investigated the performance of four sugarcane cultivars under varying nitrogen fertilization levels to identify the optimum nitrogen–cultivar combination for yield enhancement, juice quality improvement, and climate-smart agriculture. Sugarcane is a high-energy crop that plays a vital role in sugar production, biofuel generation, and multiple industrial applications (Iqbal et al., 2014). However, its productivity in Pakistan remains suboptimal due to delayed planting, poor crop management, irrigation limitations, pest infestations, and particularly the imbalanced use of nitrogen fertilizers (Aslam et al., 2024). Excess nitrogen not only reduces nitrogen-use efficiency but also degrades juice quality and contributes to environmental problems such as nitrate leaching and nitrous oxide emissions, which exacerbate climate change (William et al., 2018). Thus, balancing nitrogen inputs with variable selection is central to sustainable sugarcane production. The crop husbandry practices followed in this study ensured proper soil preparation, fertilization, irrigation, and pest control, minimizing management-related variability and enabling an accurate evaluation of cultivar and nitrogen responses. The experimental site was characterized by sandy loam soil with low organic matter and nitrogen availability, conditions typical of many sugarcane-growing regions in Pakistan. Such soils often exhibit nitrogen deficiency, which explains the strong crop response to nitrogen application observed in this experiment. Climate conditions during the growing season also shaped crop growth: temperatures ranged between 16°C (minimum) and 46°C (maximum), with negligible rainfall from March to May, followed by limited precipitation in June (4 mm) and July (53 mm). These conditions reflect the semi-arid climate of Bahawalpur, where water and nutrient management play a decisive role in determining crop performance (Pan *et al.*, 2022). The combined results highlight CPF 237 as the most responsive cultivar across all nitrogen levels, producing higher germination, tiller numbers, cane length, diameter, millable cane weight, and millable canes per clump. Nitrogen application significantly enhanced yield-related parameters, with N4 (300 kg N ha⁻¹) providing maximum values. However, considering environmental sustainability, intermediate

levels such as N3 (200 kg N ha⁻¹) may be more appropriate, as excessive nitrogen use contributes to nitrate leaching, nitrous oxide emissions, and reduced juice purity (Zeng et al., 2020; William et al., 2018). Thus, a balanced nitrogen

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