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Seasonal Effects on the Genetic Relationships among Agronomic and Quality Traits in Sugarcane (*Saccharum officinarum* L.) in the North Coastal Zone of Andhra Pradesh

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The current study aims to evaluate the seasonal impact on the response of genetic variability, trait associations, and selection potential for cane yield and quality traits in eleven sugarcane clones over crop seasons. The total of twelve cane yield and quality traits was recorded for observations. The analysis of variance revealed that significant variation was observed for all cane yield and juice quality traits across the three crop cycles. Cane yield and yield attributes exhibited a moderate to high degree of genotypic and phenotypic coefficients of variation, while quality traits,*viz.*, sucrose (%), Brix (%), and CCS (%), exhibited a low degree of variability. Both cane yield and juice quality traits show a high degree of heritability across crop seasons. Cane yield and yield-related traits exhibit high heritability coupled with a high genetic advance as a percentage of the mean. In contrast, juice quality traits such as sucrose (%), Brix (%), and CCS (%) exhibit high heritability coupled with moderate genetic advance as a percentage of the mean across the crop seasons. Genotypic correlation demonstrates that the cane yield was positively and significantly associated with the number of shoots at 120DAP, millable canes, and CCS yield across the seasons. Additionally, traits such as the number of shoots at 240DAP, stalk length, and jaggery yield exhibited significant positive correlations in the first and second plant crops. Path analysis indicated that CCS yield, jaggery yield, and brix percentage showed positive direct effects as well as significant positive correlations to cane yield, confirming a true genetic relationship among these traits.

(***Key words:*** *Correlation, Path analysis, Ratoon crop, Sugarcane, Variability*)

Sugarcane is a globally important commodity crop and plays a significant role in the agricultural industry. It serves as the primary source of sugar and jaggery production worldwide (Alarmelu and Kurup, 2023). Sugarcane accounts for 80% of the world's sugar production and 20-25% of bioethanol production. Sugarcane is a highly polyploid and C_4 plant widely cultivated in tropical and subtropical regions (Mekonnen, *et al.,* 2024). Brazil is the largest sugarcane-producing country (1.92 billion tonnes), which accounts for 38% of global sugarcane production. Following Brazil, India produces 376.90 million tonnes of sugarcane from 4.73 million hectares. In India, Andhra Pradesh produces 7.95 million tonnes of sugarcane from 0.10 million hectares, with the major sugarcane growing districts located in the north coastal zone of the state (Tyagi *et al.,* 2023).

The development of high-yielding sugarcane clones is challenging due to the limited selection methods available for asexually propagated crops (Yadawad *et al.,* 2022). Major strategy in breeding populations within test environments relies on a clear understanding of the genetic relationships among the various agronomic traits of the crop (Shanmuganathan *et al.,* 2015). In sugarcane, both yield and quality traits are relevant and exhibit complex interactions. Therefore, knowledge of the genetic and phenotypic relationships among these traits is beneficial for plant breeders during the selection process (Tolera *et al.,* 2024). To tackle the

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challenges in developing high-yielding and high-quality varieties, it is essential to exploit the genetic variability present in sugarcane clones (Barreto *et al.,* 2021; Tyagi and Sharma, 2025). This genetic variability is crucial for crop improvement, as it provides valuable insights into trait heritability and informs the application of effective selection methods for producing high-yielding lines (Abu-Ellail *et al.,* 2024; Venkatarayappa *et al.,* 2025). Yield is inherently complex because the expression of yield traits depends on various environmental and soil factors (Reddy *et al.,* 2024; Zhang *et al.,* 2025; Abu-Ellail *et al.,* 2025). Consequently, relying solely on direct heritability for these traits may not be effective. A combined approach using correlation and path coefficient analysis can help identify significant traits that influence yield, thereby enhancing the selection process. In sugarcane cultivation, farmers prefer cultivars that are suitable for multiple ratoonings. The plant and ratooning ability of different clones affects genetic variance, heritability, and the potential for genetic improvement in various sugarcane yield components. However, the effects of crop age on the genetic relationships among these yield components have not yet been explored. Therefore, the present study was conducted on eleven clones to characterize and assess variability and trait associations in two plant crops and one ratoon cycle for cane yield and quality traits.

MATERIALS AND METHODS

This study was conducted on eleven sugarcane clones (Table 1) over three seasons under the Main Yield Trials. The first plant and ratoon crop investigation were conducted during the years 2020-22, while the second plant crop was carried out during 2021-22 at north coastal zone in the Regional Agricultural Research Station, Anakapalle, under Acharya N.G. Ranga Agricultural University, Guntur, India. Entries from three seasons were assessed by applying RBD with three replications. Each clone was planted in six rows, measuring six meters in length and 90 centimeters apart in each row. All the agronomic packages of practices recommended for the crop growth season were uniformly followed throughout the three seasons. These three eksali crops are harvested at 300-320 days old to ensure uniformity in data collection and analysis.

The study focused on twelve quantitative and qualitative traits of sugarcane, selected based on the descriptors and guidelines outlined by the Protection of Plant Varieties and Farmers' Rights Authority (PPV and FRA, 2001) under the DUS (Distinctiveness, Uniformity, and Stability) criteria (Blakeney, 2001). Observations included yield and juice quality parameters, such as the number of tillers ('000 ha^{-1}) at 120 and 240 days after planting (DAP) and the number of millable canes (NMC), which were manually counted within the net plot area. Stalk length was determined by averaging measurements from five randomly selected canes. The NMC was recorded and expressed in thousands per hectare ('000 ha^{-1}). Single cane weight was obtained by weighing ten randomly selected canes individually and taking the average. Cane yield (t ha^{-1}) was calculated by harvesting the middle four rows of each plot, with the recorded yield subsequently extrapolated to a

Table 1. *List of the clones used in the experiment*

S.No	Clone	Pedigree
1	2017A36	CoA12321 X Co775
2	2017A65	CoA12321 X Co775
3	2017A236	CoA13327 X CoH15
4	2017A253	CoT8201 X Co94008
5	2017A340	Co0235GC
6	2017A396	CoV89101 X CoT8201
7	2017A408	CoV89101 X CoT8201
8	2017A457	CoV89101 X CoT8201
9	2017A405	CoV89101 X CoT8201
10	2017A553	CoV89101 X ISH69
11	87A298 (S)	Co 7704 X CoC 671

per-hectare basis. For juice analysis, five canes were randomly selected from clumps at the 10th and 12th months of growth. Brix and sucrose content were quantified using a Brix refractometer and a sucrolyser, respectively. The Commercial Cane Sugar (CCS) yield (t ha^{-1}) was estimated using the formula: (Cane yield × CCS%)/100. CCS percentage was determined using the formula: (Sucrose% × 1.022) - (Brix% × 0.292). Jaggery yield was calculated using the formula: (Jaggery weight/ Cane weight) × Cane yield (t ha^{-1}), and Fiber (%) was determined using the formula: Dry weight (g)/Fresh weight) × 100.

The OPSTAT software was used to analyze genetic variance from the pooled data. All statistical analyses were conducted with this software. Genotypic and phenotypic variation was estimated following the methodology of Burton and De Vane (1953), while the phenotypic and genotypic coefficients of variation were calculated using the approach described by Singh and Chaudhary (1999). Broad-sense heritability for each trait was determined using the formula provided by Allard (1960). Genetic advance was computed based on the method outlined by Johnson *et al.* (1955). Genotypic correlation was estimated using the standard procedure described by Singh and Chaudhary (1999). Additionally, genotypic correlation coefficients were partitioned into direct and indirect effects following the procedure suggested by Dewey and Lu (1959).

RESULTS AND DISCUSSION

Analysis of variance

The mean squares obtained from the pooled analysis of variance for cane yield and quality traits among eleven clones, evaluated in two plant and ratoon crops, are presented in Table 2. The results indicate that significant variance ($P < 0.01$) was observed among the eleven clones for all traits. These significant differences suggest a substantial amount of genetic variation among the clones, and all traits are affected by the growing seasons. Comparable findings have been reported in studies conducted by Shanmuganathan *et al.* (2015) and Yadawad *et al.* (2022) on sugarcane for all traits.

Genetic variability analysis

The effectiveness of crop breeding depends largely on the genetic diversity within the population and the magnitude of the trait heritability (Kumar *et al.,* 2024). A plant breeder must analyze the genetic variation in the existing population to select desirable traits for trait modeling (Reddy *et al.,* 2024). The genetic variance components for yield and quality-related traits among eleven clones over three growing seasons are presented in Table 3. The results of this study indicate that the phenotypic coefficient of variance is higher than the genotypic coefficient of variance for cane yield and quality traits. This suggests that environmental factors and seasonal changes significantly influence the expression of these traits. In the ratoon season, shoot density shows a high degree of variability compared to plant crops, indicating that this trait is particularly affected by seasonal factors. Cane yield, CCS (Commercial Cane Sugar) yield, and jaggery yield exhibit a greater magnitude of variability in the first plant crop than in the second plant and ratoon crop. This implies that these traits are influenced by seasonal conditions. In contrast, remaining yield traits display a moderate degree of consistent variability across crop seasons, suggesting they are less affected by seasonal changes. Quality traits such as sucrose (%), Brix (%), and CCS (%) show a lower degree of genetic variance but have a high magnitude of heritability throughout crop seasons. This indicates that these traits might respond slowly to selection for genetic improvement. Estimating genetic variation from adoptable traits is crucial for developing effective selection strategies and understanding the genetic relationships among traits as they vary with crop seasons. Barreto *et al.* (2021) reported a similar finding for juice quality traits, which exhibit lower variability due to trait expression depending on the mean of the trait across crop cycles in sugarcane. Similar findings have been reported by Kumar *et al.* (2024) and Tolera *et al.* (2024) for cane yield and CCS yield in sugarcane.

In this study cane yield showed greater genetic variability (*e.g.*, GCV of 20.5% in the first plant crop) compared to sucrose percentage (GCV of 5.4%), a pattern consistent across the three crop seasons. This difference reflects the polygenic nature of cane yield, which integrates traits like stalk length, single cane weight, and number of millable canes, each trait displaying substantial variability (*e.g.,* GCV of 18.4% for stalk length and 16.5% for millable canes in the first plant crop). These traits are highly sensitive

Table 2. *Combined pooled analysis of variance for 12 characters in eleven sugarcane genotypes across three seasons*

	Sum of Mean Squares				
Degrees of Freedom	Genotypes	Seasons	Rep * Loc	Genotype*Location	Error
	10	2	6	20	60
Cane yield (t ha^{-1})	23507.92**	99658.28**	98.03	5069.26**	1.00
No. of shoots at 120 DAP ('1000 ha^{-1})	10341.35**	82455.04**	235.94	2430.60**	1.00
No. of shoots at 240 DAP ('1000 ha^{-1})	7055.30**	433474.98**	180.93	2086.90**	1.00
No. of millable canes ('000 ha^{-1})	2851.61**	34511.96**	126.24	505.51**	1.00
Stalk length (cm)	101651.63**	774033.74**	259.91	16999.29**	1.00
Single cane weight (kg)	101651.63**	1109.67**	0.64	18.89**	1.00
CCS yield (t ha^{-1})	322.75**	827.85**	81.61	68.97**	1.00
Jaggery yield (t ha^{-1})	21.56**	25.51**	6.80	12.28**	1.12
Brix (%)	67.33**	4457.90**	57.23	38.88**	1.00
Sucrose (%)	76.49**	473.39**	53.05	37.06**	1.00
CCS (%)	56.09**	1807.32**	66.15	24.50**	1.00
Fiber percentage (%)	53.47**	12668.99**	74.51	257.36**	1.00

**= significant at 1%

to environmental factors and seasonal changes, contributing to their elevated variability, particularly in the first plant crop. In contrast, sucrose percentage, along with Brix (GCV of 4.7%) and CCS percentage (GCV of 6.2%), exhibits lower genetic variance due to its dependence on fewer genes with stronger additive effects, resulting in more stable expression across crop cycles, as noted by Barreto *et al.* (2021) for juice quality traits. The higher phenotypic coefficient of variance (PCV) relative to genotypic coefficient of variance (GCV) for cane yield (*e.g.,* 20.5% GCV vs. 20.5% PCV in the first plant crop) further underscores the role of environmental influence, while the closer GCV and PCV values for sucrose percentage (*e.g.,* 5.4% vs. 5.6%) indicate less environmental impact.

Drawing from these findings, the increased genetic variance for cane yield and related traits in the first plant crop suggests that early selection should target these traits to maximize yield potential, whereas quality traits like sucrose percentage, with lower variability and consistent heritability, may benefit from selection in later stages, such as the ratoon crop. Notably, the observed decline in variability for cane yield (GCV from 20.5% in the first plant crop to 17.9% in the ratoon crop) and the moderate variability of sucrose percentage across seasons highlight a potential reduction in genetic potential over time, emphasizing the need to identify and select ratoon-adapted genotypes to sustain productivity.

The analysis of heritability guided the identification of genotypes from a broad genetic base. In the current study, cane yield and quality traits showed high heritability (>60%) across the three crop seasons. This indicates a high degree of association between phenotypic and genotypic values and suggests a low environmental impact on the expression of these traits. Since these traits are governed by polygenes, selection for them is effective, and this information can help plant breeders make more informed decisions. However, heritability alone does not indicate the amount of genetic improvement that can be achieved by selecting a specific genotype. The success of selection depends not only on heritability but also on genetic advance (GA) (Alam *et al.,* 2017). Therefore, understanding both heritability and genetic advance is crucial. In this study, high heritability was observed alongside a high genetic advance percentage of the mean for cane yield and yield-related traits, except for sucrose percentage, Brix, and CCS percentage, which exhibited high heritability with moderate genetic advance across the three crop seasons. These traits predominantly exhibit additive gene action, meaning that simple selection methods could effectively improve these traits. In contrast, the quality traits

Table 3. *Genetic parameters of yield and quality related traits in eleven sugarcane clones over three seasons*

	Heritability			GCV			PCV			Gen-Advance			Gen-Adv % Means		
Trait	I P	II P	RA	I P	II P	RA	I P	II P	RA	I P	II P	RA	I P	II P	RA
No. of shoots at 120 DAP ('1000 ha^{-1})	99.8	99.9	100.0	9.0	16.3	34.4	9.0	16.3	34.4	23.7	43.7	69.0	18.5	33.5	70.8
No. of shoots at 240 DAP ('1000 ha^{-1})	100.0	99.5	99.9	14.9	11.3	20.5	14.9	11.3	20.6	34.1	25.1	38.7	30.8	23.2	42.3
Stalk length (cm)	100.0	100.0	100.0	18.4	20.5	18.6	18.4	20.5	18.6	108.6	118.7	110.1	38.0	42.2	38.3
Single cane weight (kg)	89.1	88.1	94.4	13.7	11.3	13.2	14.6	12.0	13.6	0.3	0.2	0.2	26.7	21.8	26.4
No. of millable canes ('000 ha^{-1})	99.9	99.6	99.7	16.5	10.6	16.0	16.5	10.6	16.1	34.8	22.0	25.9	34.0	21.8	33.0
Cane yield (t ha^{-1})	100.0	99.9	100.0	20.5	15.9	17.9	20.5	15.9	17.9	46.9	30.7	31.1	42.3	32.7	36.8
CCS yield (t ha^{-1})	97.9	98.5	97.7	21.1	19.1	17.1	21.3	19.2	17.3	5.6	4.5	3.8	43.0	39.0	34.8
Jaggery yield (t ha^{-1})	99.1	98.1	98.0	25.5	18.5	18.5	25.6	18.7	18.7	5.3	3.9	4.3	52.3	37.7	37.8
Brix (%)	93.5	92.6	95.4	4.7	6.0	6.0	4.8	6.3	6.2	1.7	2.2	2.3	9.3	11.9	12.1
Sucrose (%)	94.5	94.6	93.5	5.4	6.1	5.3	5.6	6.2	5.4	1.8	2.1	1.8	10.8	12.1	10.5
CCS (%)	90.0	94.2	89.8	6.2	6.5	5.9	6.5	6.7	6.2	1.4	1.6	1.5	12.1	13.0	11.5
Fiber percentage (%)	98.9	97.5	98.5	12.4	9.7	21.6	12.4	9.8	21.7	4.2	2.2	4.3	25.3	19.6	44.0

I P= first plant crop, II P= second plant crop, RA= ratoon crop, GCV= genotypic coefficient of variation and PCV= phenotypic coefficient of variation also showed high heritability with moderate genetic advance, implying both additive and non-additive gene actions. This suggests that most of the variance for the expression of these traits is controlled by environmental factors (Kumar *et al.,* 2024). Similar results, with high heritability and a high genetic advance percentage of the mean for yield and yield-related traits, were found in previous studies reported by Tena *et al.* (2016) and Alam *et al.* (2017) in sugarcane. deMelo *et al.* (2024) reported high heritability and moderate genetic advance for juice quality traits in sugarcane, which agrees with the results of the current study.

The high heritability (>60%) observed for cane yield and quality traits across the three crop seasons indicates a strong genetic basis for these traits and a low environmental influence on their expression. For breeding programs, this suggests that phenotypic selection can reliably predict genotypic performance, making direct selection for high-yielding varieties an effective approach. Specifically, traits like cane yield, with high heritability and high genetic advance percentage of the mean, are ideal targets for simple selection methods such as mass selection or recurrent selection. Breeders can prioritize genotypes with superior cane yield from the first plant crop, where variability and genetic advance are greatest, to develop high-yielding varieties. For quality traits like sucrose percentage, which show high heritability but moderate genetic advance, a combination of selection and hybridization can exploit both additive and non-additive gene actions to improve trait expression over generations. This approach leverages the genetic variability identified among the eleven clones to enhance both yield and quality in sugarcane breeding programs.

Correlation studies

Phenotypic and genotypic correlation coefficients generally exhibited similar signs and magnitudes, particularly within the crop. The study aimed to investigate trait associations among clone performance across cultivation seasons for selection purposes. Genetic correlations, being more relevant and meaningful to plant breeders, were exclusively reported in Table 4.

In the present study, cane yield showed a significant positive correlation with several traits across different genotypes. Specifically, there was a strong correlation between cane yield and the number of shoots at 240 DAP (rg = 0.708**, 0.725**, 0.717**), the number of millable canes (rg = 0.868**, 0.815**, 0.941**), and CCS yield (rg = 0.958**, 0.915**, 0.921**) over the crop seasons. Additionally, the number of shoots at 120 DAP (rg = 0.583**, 0.558**) and stalk length (rg = 0.474**, 0.534**) exhibited significant correlation to cane yield in both first plant and second plant crops. In the ratoon crop, cane yield positively correlated with fiber content (rg = 0.647**), while in the plant crop, the correlation was negative (rg = -0.431*, - 0.272). Furthermore, Brix percentage showed a negative correlation with cane yield in the ratoon crop (rg = -0.431*), but a positive correlation in the second plant crop (rg = 0.350*). These findings indicate that the season of the crop does not significantly impact the associations between these traits. The correlations observed across different crop seasons were consistent with those found in individual crop stages. Sucrose percentage and CCS percentages are positively correlated throughout the crop's growth period. In plant crops, stalk length is significantly positively correlated with sucrose (%), Brix percentage, and CCS percentage; however, this correlation decreases in the ratoon crop. Additionally, the correlation between cane yield, stalk weight, and sucrose (%) was stronger in the plant crops compared to the ratoon crop. These results suggest that selecting genotypes with high cane yield, greater stalk length, a higher number of shoots, and elevated CCS yield is beneficial for plant crops, while prioritizing quality levels is more suitable for ratoon crops. Similar findings reported by Tolera *et al.* (2024) observed a strong correlation between cane yield and the number of millable canes, as well as CCS yield at the genotypic level, highlighting the importance of these traits in yield improvement. Similarly, Jeena (2023) found significant associations between cane yield and CCS yield, number of millable canes, number of tillers, single cane weight, and cane height at both genotypic and phenotypic levels, reinforcing their role as selection criteria in breeding programs. Milligan *et al.* very old reported a positive correlation between cane yield and stalk length across three crop cycles, emphasizing the stability of this relationship over time.

However, some traits exhibit weaker associations with yield. Tena *et al.* (2016) reported a low degree of association between cane yield and sucrose (%) at the

Table 4. *Genotypic correlations for each season across twelve agronomic and quality traits*

		Cane yield (t ha^{-1})	No. of shoots at 120 DAP ('1000 ha^{-1})	No. of shoots at 240 DAP ('1000 ha^{-1})	No. of millable canes ('000 ha^{-1})	Stalk length (cm)	Single cane weight (kg)	CCS yield (t ha^{-1})	Jaggery yield (t ha^{-1})	Brix (%)	Sucrose (%)	CCS (%)	Fiber percentage (%)
No. of shoots at 120 DAP ('1000 ha^{-1})	IP	0.58**	1										
	IIP	0.19	1										
	R	0.55**	1										
No. of shoots at 240 DAP ('1000 ha^{-1})	IP	0.70**	0.83**	1									
	IIP	0.72**	0.41*	1									
	R	0.71**	0.88**	1									
No. of millable canes ('000 ha^{-1})	IP	0.86**	0.56**	0.73**	1								
	IIP	0.81**	0.35*	0.91**	1								
	IP	0.94**	0.69**	0.81**	1								
Stalk length (cm)	IP	0.53**	0.85**	0.70**	0.45**	1							
	IIP	0.47**	0.62**	0.69**	0.52**	1							
	R	0.25	0.88**	0.70**	0.380*	1							
Single cane weight (kg)	IP	0.21	-0.21	0.00	0.29	-0.26	1						
	IIP	-0.05	0.31	-0.42*	-0.4**	0.03	1						
	R	0.64**	0.00	0.1	0.55**	-0.23	1						
CCS yield (t ha^{-1})	IP	0.95**	0.59**	0.69**	0.87**	0.60**	0.09	1					
	IIP	0.91**	0.31	0.72**	0.73**	0.59*	0.12	1					
	R	0.92**	0.39*	0.60**	0.76**	0.18	0.51**	1					
Jaggery yield (t ha^{-1})	IP	0.66**	0.07	0.33	0.44**	0.25	0.15	0.81**	1				
	IIP	0.19	0.02	-0.18	0.13	-0.09	0.18	0.07	1				
	R	0.19	0.02	-0.18	0.13	-0.09	0.18	0.07	1				
Brix (%)	IP	-0.21	-0.3	-0.29	-0.06	-0.35*	-0.3	0	-0.27	1			
	IIP	0.35*	0.58**	0.46**	0.35*	0.59**	0.27	0.66**	0.62**	1			
	R	-0.43*	-0.68**	-0.64**	-0.63**	-0.39*	-0.31	-0.09	0.05	1			
Sucrose (%)	IP	-0.04	0.03	-0.05	0.09	0.11	-0.31	0.22	-0.28	0.83**	1		
	IIP	0.12	0.55**	0.29	0.17	0.51**	0.38*	0.50**	0.49**	0.93**	1		
	R	-0.14	-0.26	-0.26	-0.35*	-0.08	-0.32	0.15	0.08	0.57**	1		
CCS (%)	IP	-0.03	0.07	-0.03	0.15	0.18	-0.27	0.24	-0.26	0.67**	0.95**	1	
	IIP	0.1	0.21	0.03	-0.07	0.34*	0.52**	0.47**	0.63**	0.76**	0.86**	1	
	R	0	-0.04	-0.04	-0.16	0.09	-0.34	0.26	0.04	0.46**	0.97**	1	
Fiber percentage (%)	IP	-0.27	0.01	-0.12	-0.11	0.26	-0.12	-0.13	-0.11	0.19	0.38*	0.51**	1
	IIP	-0.43*	-0.29	-0.40*	-0.34*	-0.58**	0.15	-0.38*	-0.33	-0.24	0	-0.07	1
	R	0.64**	0.46**	0.58**	0.79s**	0.08	0.34*	0.39*	0.27	-0.61**	-0.43*	-0.27	1

** = Significant at 1 % and * = Significant at 5 % level of significance, IP= first plant crop, IIP= second plant crop, RA= ratoon crop

Table 5. *Genotypic path coefficient analysis of cane yield and juice quality traits for each crop season among eleven clones*

		No. of shoots at 120 DAP (‘1000 ha^{-1})	No. of shoots at 240 DAP (‘1000 ha^{-1})	No. of millable canes (‘000 ha^{-1})	Stalk length (cm)	Single cane weight (kg)	CCS yield (t ha^{-1})	Jaggery yield (t ha^{-1})	Brix (%)	Sucrose (%)	CCS (%)	Fiber percentage (%)
No. of shoots at 120 DAP (‘1000 ha^{-1})	IP	0.11	-0.01	-0.04	-0.08	-0.01	0.61	0.03	-0.02	-0.02	0.01	0.00
	IIP	-0.17	-0.18	0.22	-0.08	0.04	0.39	-0.03	0.07	-0.11	-0.01	0.06
	R	0.87	1.00	0.68	-1.05	0.00	-0.27	0.01	-0.44	0.12	-0.03	-0.33
No. of shoots at 240 DAP (‘1000 ha^{-1})	IP	0.09	-0.02	-0.05	-0.07	0.00	0.71	0.03	-0.02	0.02	0.00	0.00
	IIP	-0.07	-0.44	0.56	-0.09	-0.05	0.89	-0.15	0.06	-0.06	0.00	0.08
	R	0.77	1.13	0.79	-0.83	0.05	-0.41	-0.05	-0.41	0.12	-0.03	-0.41
No. of millable canes (‘000 ha^{-1})	IP	0.06	-0.01	-0.07	-0.04	0.01	0.89	0.05	-0.01	-0.04	0.01	0.00
	IIP	-0.06	-0.40	0.62	-0.07	-0.06	0.90	-0.20	0.04	-0.04	0.00	0.07
	R	0.60	0.92	0.97	-0.45	0.29	-0.52	0.04	-0.41	0.16	-0.11	-0.56
Stalk length (cm)	IP	0.10	-0.01	-0.03	-0.09	-0.01	0.62	0.02	-0.03	-0.05	0.02	0.00
	IIP	-0.11	-0.30	0.32	-0.12	0.00	0.73	-0.11	0.07	-0.10	-0.02	0.11
	R	0.77	0.79	0.37	-1.18	-0.13	-0.13	-0.02	-0.26	0.04	0.06	-0.06
Single cane weight (kg)	IP	-0.03	0.00	-0.02	0.03	0.03	0.10	0.02	-0.02	0.12	-0.02	0.00
	IIP	-0.06	0.18	-0.28	0.00	0.13	0.15	-0.07	0.03	-0.08	-0.03	-0.03
	R	0.00	0.11	0.54	0.28	0.53	-0.35	0.05	-0.20	0.15	-0.22	-0.25
CCS yield (t ha^{-1})	IP	0.07	-0.01	-0.06	-0.06	0.00	1.02	0.05	0.00	-0.09	0.02	0.00
	IIP	-0.06	-0.31	0.45	-0.07	0.02	1.23	-0.36	0.08	-0.10	-0.03	0.07
	R	0.34	0.69	0.75	-0.22	0.27	-0.68	0.02	-0.06	-0.07	0.17	-0.28
Jaggery yield (t ha^{-1})	IP	0.05	-0.01	-0.04	-0.03	0.01	0.72	0.08	-0.02	0.11	-0.02	0.00
	IIP	-0.01	-0.15	0.27	-0.03	0.02	1.00	-0.45	0.08	-0.10	-0.03	0.06
	R	0.02	-0.21	0.13	0.11	0.10	-0.05	0.26	0.03	-0.04	0.03	-0.19
Brix (%)	IP	-0.03	0.01	0.00	0.03	-0.01	0.00	-0.02	0.08	-0.33	0.06	0.00
	IIP	-0.10	-0.21	0.22	-0.07	0.04	0.82	-0.28	0.12	-0.19	-0.04	0.05
	R	-0.59	-0.73	-0.62	0.47	-0.16	0.07	0.01	0.64	-0.26	0.30	0.43
Sucrose (%)	IP	0.00	0.00	-0.01	-0.01	-0.01	0.23	-0.02	0.07	-0.39	0.08	-0.01
	IIP	-0.10	-0.13	0.11	-0.06	0.05	0.62	-0.22	0.12	-0.20	-0.05	0.00
	R	-0.23	-0.29	-0.34	0.11	-0.17	-0.10	0.02	0.37	-0.45	0.63	0.31
CCS (%)	IP	0.01	0.00	-0.01	-0.02	-0.01	0.26	-0.02	0.05	-0.37	0.09	-0.01
	IIP	-0.04	-0.01	-0.05	-0.04	0.07	0.58	-0.28	0.09	-0.18	-0.06	0.02
	R	-0.04	-0.05	-0.16	-0.11	-0.18	-0.18	0.01	0.30	-0.44	0.65	0.19
Fiber percentage (%)	IP	0.05	0.18	-0.22	0.07	0.02	-0.47	0.15	-0.03	0.00	0.00	-0.19
	IIP	0.40	0.66	0.77	-0.10	0.18	-0.27	0.07	-0.39	0.20	-0.18	-0.70
	R	0.05	0.18	-0.22	0.07	0.02	-0.47	0.15	-0.03	0.00	0.00	-0.19

IP= first plant crop, IIP= second plant crop, RA= ratoon crop genotypic level, suggesting that high sucrose content does not always translate into higher cane yield. Conversely, Alam *et al.* (2017) found that sucrose (%) was positively correlated with Brix (%) and CCS (%), which are key indicators of sugar recovery, making them valuable selection parameters for both yield and quality improvement. Additionally, de Melo *et al.* (2024) reported that qualitative trait associations with yield were less affected by seasonal variations, indicating the potential for stable selection strategies across different environments.

Our study results agree with previous researchers by showing that the relationship between cane yield and yield-related traits (like millable canes, CCS yield, and stalk length) stays consistent across different crop seasons. However, quality traits like fiber content and Brix percentage change depending on the crop season. This means that selection strategies should be adjusted based on the crop season, focusing on yield-related traits in plant crops and quality traits in ratoon crops. These findings provide useful guidance for sugarcane breeding programs to improve both yield and quality across different growing cycles.

Path coefficient analysis

Path coefficient analysis was conducted at the genotypic level to differentiate the correlation into direct and indirect effects of various yield and quality contributing traits on the dependent variable. The results are presented in Table 5. The analysis revealed that cane yield had the maximum positive direct effect on single cane weight, CCY yield, jaggery yield, brix(%), and CCS (%) in both plant and ratoon crops. In the ratoon crop, the number of shoots had a direct effect on cane yield. CCY yield, jaggery yield, and brix (%) showed both a significant positive correlation and a positive direct effect across all crop seasons, indicating that selection should focus on these traits. The residual effect was not estimated for the cause-and-effect relationship from the other variables, so it remains dependent on errors (Milligan *et al.,* 1990). Tolera *et al.* (2024) stated that indirect effects were nearly as important as direct effects on sucrose. The strong correlation between purity and Brix suggests that either could predict sucrose; however, both are typically measured together to avoid extra effort. Tabassum *et al.* (2023) reported that indirect effects varied with intra-row spacing. Stalk number had a stronger indirect effect on plant weight through stalk length than its direct effect. In contrast, at narrow spacing, stalk length had a greater indirect effect on plant weight through stalk number than its direct effect.

CONCLUSION

Based on our findings, breeders should prioritize cane yield and related traits (*e.g.,* number of millable canes, stalk length, CCS yield, and single cane weight) in the plant crop, where genetic variability and genetic advance are highest, to maximize yield potential early. In contrast, quality traits like sucrose percentage and CCS percentage, with high heritability but moderate genetic advance, should be targeted in the ratoon crop, where variability stabilizes, and ensuring sustained sugar recovery. For geographical application, regions with pronounced seasonal variation (*e.g.,* tropical climates) can leverage early selection for yield in plant crops, while subtropical areas with stable conditions may focus on quality traits across seasons. Selecting ratoon-adapted genotypes is key for sustained productivity in multi-cycle systems. Selecting for higher cane yield should focus on stalk length, fiber content, shoot number, sucrose percentage, brix percentage, and single cane weight, considering seasonal influences.

CONFLICTS OF INTEREST

The authors report no conflicts of interest.

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