



Deciphering $G \times E$ interaction for sugarcane yield and quality through integrated AMMI, GGE biplot, and AMMI stability parameters

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Abstract

The present study evaluated 19 sugarcane genotypes, including two standard checks, across multiple environments to assess stability and performance for cane yield and commercial cane sugar yield (CCSY). Combined ANOVA revealed significant genotype, environment, and $G \times E$ interaction effects. AMMI analysis identified Co 18009, Co 18024, and Co 11015 as stable for cane yield, and Co 17003, Co 17013, and Co 8009 for CCSY. Stability parameters, including AMMI Stability Value, Modified AMMI Stability Value, Genotypic Stability Index, Averages of the squared eigenvector values stability statistic, sums of the absolute values of the IPC scores, Mean performance and stability in multi-environment trials, and Multi-trait Stability Index, largely supported these findings. GGE biplot analysis further confirmed Co 12009, Co 18009, and Co 11015 as superior and widely adaptable genotypes. Overall, Co 18009 and Co 12009 consistently exhibited high performance and stability across environments. These genotypes are promising candidates for further multilocation evaluation and potential commercial release across diverse agro-climatic regions of India.

Keywords: Sugarcane, Genotype $\times$ Environment interaction, Stability analysis, Cane yield, Commercial cane sugar yield.

INTRODUCTION

Sugarcane (*Saccharum officinarum*) is one of the most important commercial crop globally, primarily cultivated for sugar production, ethanol, and other by-products like molasses, bagasse, and press mud (Aswini *et al.*, 2025). India is the leading global producer and consumer of sugar and ranks as the second-largest sugar exporter worldwide (Solomon *et al.*, 2024). Despite its significant economic importance, sugarcane cultivation faces several challenges, including declining yield, vulnerability to biotic and abiotic stresses and the impacts of climate change (Nunavath *et al.*, 2025).

Ensuring a steady supply of new sugarcane varieties suited to diverse agroclimatic conditions is crucial for farmers and the country's sugar industry (Singh *et al.*, 2022 a, b; Charumathi *et al.*, 2025; Vinu *et al.*, 2025). Breeders typically focus on yield-related traits and phenotypic expressions when selecting crop cultivars for different mega-environments. Factors such as temperature, humidity, soil texture and fertility, and precipitation significantly influence yield variations in genotypes due to environmental changes (Shanthi *et al.*, 2023). In plant breeding programs, evaluating the stability and adaptability of genotypes is essential for selecting superior varieties. Assessing the yield and quality stability of a new genotype is a critical step before its commercial release (Hafeez *et al.*, 2023; Rao, 2023).

Genotype stability is heavily influenced by environmental factors (E), genetic makeup (G), and genotype-by-environment interaction (GEI), leading to significant

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variations in cultivar performance across different locations and growing seasons (Pour-Aboughadareh *et al.*, 2022). Sugarcane shows a distinct link between its adaptability and sugar accumulation, highlighting the need to develop varieties capable of responding well to varying conditions (Kumar *et al.*, 2023). To evaluate performance, plant breeding programs often rely on regional variety trials or multi-environment trials (MET), assessing key traits and phenotypic expressions (Kondombo *et al.*, 2024). These evaluations serve as selection criteria for recommending suitable cultivars in specific mega-environments (Dang *et al.*, 2024). In multilocal yield studies

aimed at identifying superior, stable, high-yielding genotypes, researchers face two primary challenges: genetic variability among genotypes and environmental differences at target sites. To address these challenges, two main strategies are employed. The first involves developing highly productive and stable genotypes capable of adapting to diverse environments. If this proves ineffective, the alternative approach is to cluster similar environments into relatively uniform mega-environments and recommend specific genotypes for each.

Various statistical methods, including parametric and non-parametric approaches, are used to analyse genotype-environment interactions (GEI) (Eberhart and Russel, 1966; Perkins and Jinks, 1968; Francis and Kannenbaerg, 1978). However, conventional univariate techniques may fall short in capturing the complexity of GEI. As a result, multivariate methods are gaining popularity for offering a more in-depth and comprehensive evaluation (Gauch, 1988; Mehareb *et al.*, 2022; Meena *et al.*, 2024). Biplot methods are commonly used to visually represent the relationships among genotypes (G), environments (E), and their interactions (GEIs), helping to identify stable genotypes and understand interaction patterns across different environments (Hashim *et al.*, 2021). Two frequently applied biplot models in multivariate analysis are the AMMI biplot (Gauch, 2006; Gauch *et al.*, 2008) and the GGE biplot (Yan *et al.*, 2000; Yan *et al.*, 2007). AMMI is capable of detecting and visualizing genotype-environment interactions (GEI) in a multi-dimensional space through a biplot (Božović *et al.*, 2018; Azam *et al.*, 2020; Khan *et al.*, 2021). The graphic analysis of the AMMI biplot offers a straightforward approach for breeding researchers, enabling them to draw conclusions about phenotypic stability, genotype performance, genetic divergence between genotypes, and the environments that support optimal performance (Hossain *et al.*, 2023; Mullualem *et al.*, 2024). In contrast, GGE biplot analysis complements the environmental stratification of AMMI biplots and helps researchers gain a deeper understanding of complex genotype-environment interactions in multi-environment breeding trials (Wodebo *et al.*, 2023; Wang *et al.*, 2023; Demelash *et al.*, 2024). By using mega-environment analysis, ranking biplots for genotypes, and comparison biplots for environments, GGE biplots offer enhanced discriminating power and a clearer representation of environmental differences. The AMMI stability parameters help assess yield stability by minimizing the effects of genotype-environment interaction noise (Ajay *et al.*, 2020; Pour-Aboughadareh *et al.*, 2022; Anuradha *et al.*, 2022; Greveniotis *et al.*, 2023; Durai *et al.*, 2025). These models improve the analysis and interpretation of GE interactions, facilitating the identification of stable, high-yielding genotypes.

Considering the substantial impact of genotype-environment (GE) interactions on cane yield and quality, stability analysis is crucial for identifying genotypes that remain stable across different environments and

years. Hence, this study focused on identifying superior, stable, and high-yielding sugarcane clones from a set of seventeen test entries and two check varieties.

MATERIAL AND METHODS

Seventeen test entries along with two check varieties (**Table 1**) were evaluated in a randomized complete block design (RCBD) with three replications at two locations, namely Ponni Sugars Ltd., Erode and Mohanur. The trials were conducted over three years (2018-2021), comprising two plant crops and one ratoon crop at Ponni Sugars Ltd., Erode, and one plant crop at Mohanur, Tamil Nadu, thus constituting four distinct environments. These environments were defined as: E1—Year 1 at Ponni Sugars Ltd., Erode (first plant crop); E2—Year 2 at Ponni Sugars Ltd., Erode (second plant crop); E3—Year 3 at Ponni Sugars Ltd., Erode (ratoon crop); and E4—Year 1 at Mohanur. Observations were recorded on ten quantitative traits, including five cane yield and yield-contributing traits—number of millable canes (NMC), cane height (CH), cane diameter (CD), single cane weight (SCW), and cane yield (CY)—and five juice quality traits, namely early sucrose percentage (ESUC), juice brix percentage (Brix), sucrose percentage at harvest (SUC), commercial cane sugar percentage (CCSP), and commercial cane sugar yield (CCSY). NMC was recorded as thousand canes per hectare, CH in centimetres, CD as stalk diameter, and SCW as the average weight (kg) of five randomly selected canes. CY was expressed in tonnes per hectare. Juice quality traits were determined from extracted juice samples. CCSP was calculated as $[1.022 \times \text{Pol} (\%) - 0.292 \times \text{Brix} (\%)]$, while commercial cane sugar yield (CCSY) (t/ha) was estimated as $(\text{CCSP} \times \text{CY})/100$.

Statistical analysis

A combined analysis of variance (ANOVA) was conducted using the Statistical Tool for Agricultural Research (STAR), Version 2.0.1. Additional statistical evaluations were performed using R software (version 4.1.1). For additive main effects and multiplicative interaction (AMMI) analysis, the “metan” package in R (Olivoto *et al.*, 2020) was utilized. AMMI was applied to evaluate prediction accuracy across multiple environments for all the studied traits, following the method described by Gabriel (1978). The AMMI Stability Value (ASV), a metric proposed by Purchase *et al.* (2000), was employed to assess the stability of genotypes across diverse environments. To simultaneously consider both performance and stability, the Genotype Selection Index (GSI) was computed for each genotype by integrating the trait mean and the AMMI Stability Value into a single metric. In addition to the GSI, several other AMMI-based stability parameters were computed using the ‘ammistability’ package (Ajay *et al.*, 2020) in R version 4.1.1. These included the Eigenvector Variance (EV), which represents the average of the squared eigenvector scores as outlined by Zobel *et al.* (1994); the Sum of the Absolute Value of the IPC scores (SIPC), described by Sneller *et al.* (1997); and

Table 1. Plant materials under the current study

S.No.	Genotype	Designation	Remarks
1	Co 12008	G1	Test entry
2	Co 12009	G2	Test entry
3	Co 14002	G3	Test entry
4	Co 14005	G4	Test entry
5	Co 14027	G5	Test entry
6	Co 15015	G6	Test entry
7	Co 15018	G7	Test entry
8	Co 16009	G8	Test entry
9	Co 16010	G9	Test entry
10	Co 16018	G10	Test entry
11	Co 17001	G11	Test entry
12	Co 17003	G12	Test entry
13	Co 17004	G13	Test entry
14	Co 17012	G14	Test entry
15	Co 17013	G15	Test entry
16	Co 18009	G16	Test entry
17	Co 18024	G17	Test entry
18	Co 86032	G18	Standard
19	Co 11015	G19	Standard

the Modified AMMI Stability Value (MASV), calculated according to the methodology proposed by Zali *et al.* (2012). These additional stability metrics contributed to a more comprehensive evaluation of genotype performance and adaptability across diverse environmental conditions. GGE (Genotype plus Genotype-by-Environment) biplot analysis was performed using the “metan” package (Olivoto *et al.*, 2020) within the R statistical environment (version 4.1.1). MPS and MTSI, considering both cane yield and commercial cane sugar yield, were estimated using the “metan” package (Olivoto *et al.*, 2020) in the R statistical environment (version 4.1.1).

RESULTS AND DISCUSSION

Combined ANOVA for yield and quality traits of sugarcane Combined ANOVA analysis showed significant effects of genotype, environment, and their interaction ($G \times E$) on all traits. (Table 2). Since the genotype-by-environment ($G \times E$) interaction is significant for all traits, additional evaluation of genotype stability should be conducted using AMMI, GGE, and other stability parameters. These analyses offer valuable insights into how genotypes behave across varying environments.

Yield and quality traits in sugarcane are largely quantitative in nature and significantly influenced by environmental factors. Without multi-environment testing (MET), it becomes challenging to accurately assess the true genetic potential of genotypes, and location-specific varieties may remain unidentified. Often, the genetic performance of a genotype can be masked by environmental effects.

Numerous studies in sugarcane have examined genotype $\times$ environment ($G \times E$) interactions, which help to unravel these effects and facilitate the identification of both location-specific and broadly adapted, stable genotypes across diverse environments (Adilakshmi *et al.*, 2025).

Significant effects of genotype, environment, and their interaction on cane and CCS yield were observed in a multi-environment analysis involving 14 sugarcane clones tested across seven locations in Egypt (Mehareb *et al.*, 2022). Similarly, a study assessing 24 sugarcane genotypes under varying levels of salt stress reported notable main effects and genotype $\times$ environment ($G \times E$) interactions for all evaluated traits (Kumar *et al.*, 2023). In another extensive evaluation, 27 genotypes tested across 27 distinct environments also exhibited highly significant genotypic, environmental, and $G \times E$ interaction effects (Appunu *et al.*, 2024). A trial with 13 clones, including seven test entries and six released varieties, was conducted at ICAR-SBI, Coimbatore during 2022–23 and 2023–24 in RBD with three replications across first plant, second plant, and ratoon crops (Durai *et al.*, 2025). Combined ANOVA showed significant genotype, environment, and $G \times E$ interaction effects for all traits studied. However, environmental effects were non-significant for cane diameter and single cane weight. In the present study involving 19 genotypes, including two checks, combined ANOVA revealed significant effects of genotype, environment, and genotype $\times$ environment ($G \times E$) interaction for all evaluated traits.

Table 2. Combined ANOVA for yield and quality traits of sugarcane

Source	Df	Brix	ESUC	SUC	CCSP	NMC	CH	CD	SCW	CY	CCSY
GEN	18	14.58**	14.19**	19.43**	29.28**	3156.13**	9050.50**	0.27**	0.40**	4047.96**	83.52**
ENV	3	50.22**	140.62**	53.85**	11.68**	13699.71**	196091.1**	4.57**	13.74**	58106.26**	545.37**
G × E	54	2.30**	2.84**	2.95**	1.87**	414.59**	1954.97**	0.03**	0.13**	1090.98**	14.38**
Pooled error	144	0.56	0.76	0.53	0.34	94.88	495.23	0.02	0.02	219.64	3.95
Total	227										

** Significant at 1% level of probability; Early sucrose (ESUC), Sucrose (SUC), number of millable canes (NMC), cane height (CH), cane diameter (CD), single cane weight (SCW), cane yield (CY), early sucrose percentage (ESUC), juice brix percentage (Brix), sucrose percentage at harvest (SUC), commercial cane sugar percentage (CCSP), and commercial cane sugar yield (CCSY).

AMMI analysis for yield and quality parameters of sugarcane

The analysis of variance (ANOVA) showed that significant individual effects of Genotypes (G), Environments (E) and genotype × environment interaction (G × E) for sucrose, commercial cane sugar percentage, cane yield and commercial cane sugar yield (Table 3). Among these traits, the environmental main effects were higher for cane yield (7.87 %) and lower for sucrose (4.96 %). The genotype main effect for commercial cane sugar yield (80.90%) was higher than cane yield (73.74 %). The G × E interaction effects were greater for commercial cane sugar percentage (20.84 %) and the lowest for commercial cane sugar yield (13.82 %). In the principal components (IPCA), the first 2 components were significant for these traits, in which the first PCA explained maximum variance of about 80.47 % for sucrose, 78.04 % for commercial cane sugar percentage, 70.18% for cane yield, and about 66.19 % for commercial cane sugar yield.

Visualization of genotype main effects and environmental interactions using biplot analysis

In the PC1 vs. cane yield analysis, environments E3 and E4 exhibited lower average main effects, whereas environments E1 and E2 displayed the highest main effects, making them favorable for the majority of genotypes (Fig. 1a). Among the genotypes, G1, G6, G15, G12, and G17 showed lower main effects for cane yield,

while G2, G3, G4, G8, and G19 demonstrated higher main effects (Fig. 1a). The AMMI biplot based on PC1 and PC2 scores for number of millable canes indicated that genotypes G9, G11 and G15, being close to the origin, possessed broad environmental adaptability and exhibited stability across environments (Fig. 1b).

For commercial cane sugar yield (CCSY), the PC1 vs. CCSY analysis revealed that environments E3 and E4 had lower average main effects, whereas E1 and E2 recorded the highest main effects, proving beneficial for most genotypes. Genotypes G2, G3, G16, and G19 exhibited higher main effects for CCSY, in contrast to G10, G15, and G12, which showed lower main effects (Fig. 1c). The PC1 vs. PC2 biplot highlighted genotypes G12, G15, and G16 as being positioned near the origin, suggesting they are stable performers across different environments (Fig. 1d).

AMMI biplot analysis of 12 advanced sugarcane clones along with three standards identified CoSnk 15102, Co 86032, and CoC 671 as stable performers for both cane and commercial cane sugar yield (Yadawad *et al.*, 2023). In another evaluation of 15 clones, genotype G2016-129 showed consistent performance for these traits (Mehareb *et al.*, 2022). Elayaraja *et al.* (2022) reported that Co 11015, Co 09004, Co 0240, Co 13014, and Co 14016 were highly stable and broadly adapted for cane and

Table 3. AMMI Analysis of variance of main effects and interactions for for yield and quality traits of sugarcane

Source	df	ESUC		SUC		CY		CCSY	
		MS	VE (%)	MS	VE (%)	MS	VE (%)	MS	VE (%)
GEN	19	6.88**	4.96	4.32**	5.23	1365.05**	24.08	26.99**	37.50
ENV	3	17.55**	75.95	10.19**	73.93	19368.71**	56.94	26.99**	41.2
G × E	54	2.21**	19.09	1.44**	20.84	358.42**	18.96	178.01**	21.28
IPCA 1	20	3.28**	80.47	2.07**	78.04	1606.55**	55.33	22.56**	54.52
IPCA 2	18	0.94**	19.53	0.69	21.96	918.73**	24.48	12.99**	28.27
Residuals	78	0.54	0	0.40	0	0	0	0.74	0

Early sucrose (ESUC), sucrose (SUC), cane yield (CY) and CCS yield (CCSY)

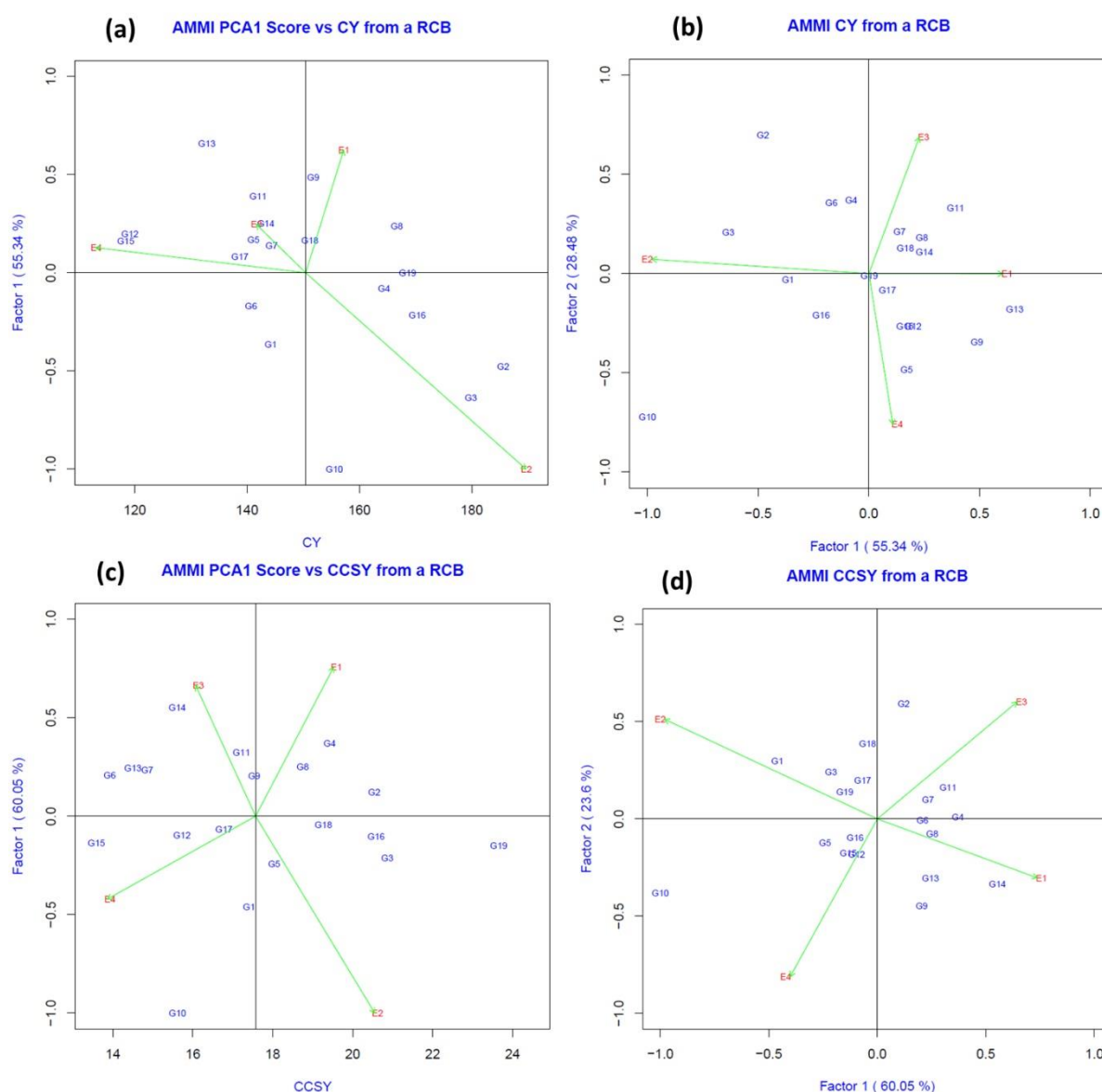


Fig. 1 AMMI Biplot for yield and quality (a) PC1 vs CY (b) PC1 Vs PC2 for CCSY (c) PC1 vs CY (d) PC1 Vs PC2 for CCSY

Note: For genotypes names: refer Table1

commercial cane sugar yield, while Co 15021, Co 11015, Co 15007, Co 13001, and Co 16001 showed greater stability for sucrose percentage. In Chhattisgarh, CoS 8436, VSI 8005, CoC 671, and Co 86032 demonstrated high sugar yield per hectare and stability across locations, making them suitable for commercial cultivation (Verma *et al.*, 2024). Further, AMMI analysis by Meena *et al.* (2024) identified nine genotypes—CoPb 9181, Co 1148, CoPant 03220, BO 91, CoPant 90223, CoBin 9105, CoH 128, CoH 119, and CoH 160—with strong main effects for both cane and CCS yield, while BO 101, BO 147, and CoP 2061 were superior for cane yield, and CoSe 95436, BO 110, CoH 160, and CoPant 84212 for commercial

cane sugar yield. In this study, AMMI analysis showed significant effects of genotype, environment and their interaction and revealed that genotypes G16, G17, and G19 were stable for cane yield, while G12, G15, and G16 showed stability for commercial cane sugar yield. Genotypes near the origin in the PC1 vs. PC2 biplots indicated broad adaptability and consistent performance across environments.

Different stability parameters

Based on the AMMI Stability Value (ASV), genotypes G19, G17, and G7 were identified as the most stable for cane yield due to their lower ASV scores, indicating greater

yield consistency across environments. For commercial cane sugar yield, genotypes G17, G16, and G12 emerged as the most stable performers (**Table 4**). These findings were corroborated by the Modified AMMI Stability Value (MASV), which showed similar stability rankings. The Genotypic Stability Index (GSI) further highlighted G19, G16, and G18 as highly stable genotypes for cane yield, while G16, G19, and G3 were ranked highest for commercial cane sugar yield stability (**Table 4**). According to the averages of the squared eigenvector values (EV), genotypes G16, G17, G18, and G4 exhibited high stability for cane yield, with G16 also showing superior stability for commercial cane sugar yield (**Table 4**). In terms of the Sums of the Absolute Value of the IPC Scores (SIPC), G19 was the most stable genotype for cane yield, followed by G17. For CCSY, G16 demonstrated the highest stability (**Table 4**).

According to Purchase *et al.* (2000), genotypes with AMMI stability values close to zero are considered stable, while larger AMMI stability values (ASV) values indicate environment-specific adaptation. In a study, genotypes G7, G5, and G8 showed the lowest ASV and were identified as the most stable for cane yield, while G7, G5, G8, and G3 were stable for commercial cane sugar yield (Durai *et al.*, 2025). The Genetic Stability Index, which combines mean yield and AMMI stability value (Farshadfar *et al.*, 2011; Bose *et al.*, 2014), ranked G5,

G6, and G4 highest for cane yield and G6, G3, and G5 for CCS yield. Stability was further confirmed using low Averages of the squared eigenvector values stability statistic (EV) and sums of the absolute value of the IPC scores values, where G7, G6, G3, and G8 showed consistency (Durai *et al.*, 2025). These genotypes are promising candidates for commercial cultivation across diverse environments. In the present study, based on AMMI stability value, genotypes G19, G17, and G7 were most stable for cane yield, while G17, G16, and G12 were stable for CCSY. Modified AMMI stability value (MASV) rankings supported these findings. Genotypic stability index identified G19, G16, and G18 as most stable for cane yield, and G16, G19, and G3 for commercial cane sugar yield. According to EV, G16, G17, G18, and G4 were stable for cane yield, with G16 also stable for commercial cane sugar yield. Sums of the absolute values of the IPC scores values analysis ranked G19 and G17 as most stable for cane yield, and G16 as the most stable for commercial cane sugar yield.

GGE analysis for yield and quality traits of sugarcane Mean vs. Stability biplots

The genotypes G2, G3 and G16 along with check G19 were found to be more stable with higher cane yield and commercial cane sugar yield compared to check G18 (**Fig. 2a and 2b**).

Table 4. Mean values, AMMI stability value (ASV), Mean AMMI stability value, EV, SIPC, and genotype selection index (GSI) for the genotypes studied for the traits Cane Yield (CY) and CCS Yield (CCSY)

GEN	CY						CCSY					
	Mean	ASV	GSI	EV	MASV	SIPC	Mean	ASV	GSI	EV	MASV	SIPC
G1	144.20	4.22 ¹³	24 ¹⁰	0.15	6.35	7.08	17.41	2.80 ¹⁷	27 ¹⁴	0.08	3.01	2.57
G2	185.59	6.90 ¹⁶	17 ⁵	0.11	9.20	7.94	20.54	1.54 ¹²	16 ⁷	0.09	2.15	2.09
G3	179.82	7.43 ¹⁷	19 ⁷	0.05	7.65	5.32	20.86	1.37 ⁸	10 ³	0.02	1.51	1.27
G4	164.38	2.38 ⁵	11 ²	0.02	3.97	2.75	19.42	2.18 ¹⁶	21 ⁹	0.02	2.19	1.02
G5	141.13	3.48 ¹²	26 ¹²	0.05	5.61	5.34	18.03	1.45 ¹⁰	18 ⁸	0.01	1.50	1.06
G6	140.69	2.87 ⁹	24 ¹⁰	0.02	4.20	3.17	13.92	1.22 ⁷	25 ¹²	0.02	1.32	0.99
G7	144.36	2.02 ³	13 ³	0.05	3.82	4.76	14.86	1.39 ⁹	25 ¹²	0.03	1.54	1.38
G8	166.66	2.96 ¹¹	16 ⁴	0.03	3.75	4.20	18.75	1.50 ¹¹	18 ⁸	0.02	1.59	1.24
G9	151.77	5.98 ¹⁵	23 ⁹	0.05	6.72	5.69	17.53	1.59 ¹³	22 ¹⁰	0.07	2.01	2.13
G10	155.53	12.30 ¹⁹	26 ¹²	0.21	13.85	11.66	15.62	5.96 ¹⁹	33 ¹⁶	0.18	6.03	3.28
G11	141.96	4.92 ¹⁴	27 ¹³	0.04	5.72	4.92	17.22	1.95 ¹⁵	26 ¹³	0.02	2.01	1.39
G12	119.12	2.78 ⁷	25 ¹¹	0.02	3.72	3.67	15.73	0.71 ³	14 ⁵	0.01	0.87	0.89
G13	132.83	7.67 ¹⁸	35 ¹⁴	0.06	7.84	5.53	14.50	1.60 ¹⁴	31 ¹⁵	0.03	1.76	1.30
G14	143.33	2.96 ¹⁰	22 ⁸	0.03	3.53	3.81	15.61	3.35 ¹⁸	33 ¹⁶	0.07	3.46	2.39
G15	118.38	2.45 ⁶	25 ¹¹	0.03	3.63	3.94	13.58	0.89 ⁴	23 ¹¹	0.01	1.01	0.93
G16	170.29	2.78 ⁸	11 ²	0.02	3.49	3.60	20.59	0.64 ²	5 ¹	0.00	0.73	0.73
G17	138.73	1.08 ²	18 ⁶	0.02	2.02	2.54	16.78	0.61 ¹	15 ⁶	0.03	1.02	1.28
G18	151.16	2.04 ⁴	13 ³	0.02	2.65	3.01	19.27	0.94 ⁵	11 ⁴	0.03	1.34	1.22
G19	168.56	0.05 ¹	5 ¹	0.04	2.46	2.52	23.65	0.94 ⁶	7 ²	0.17	2.04	2.44

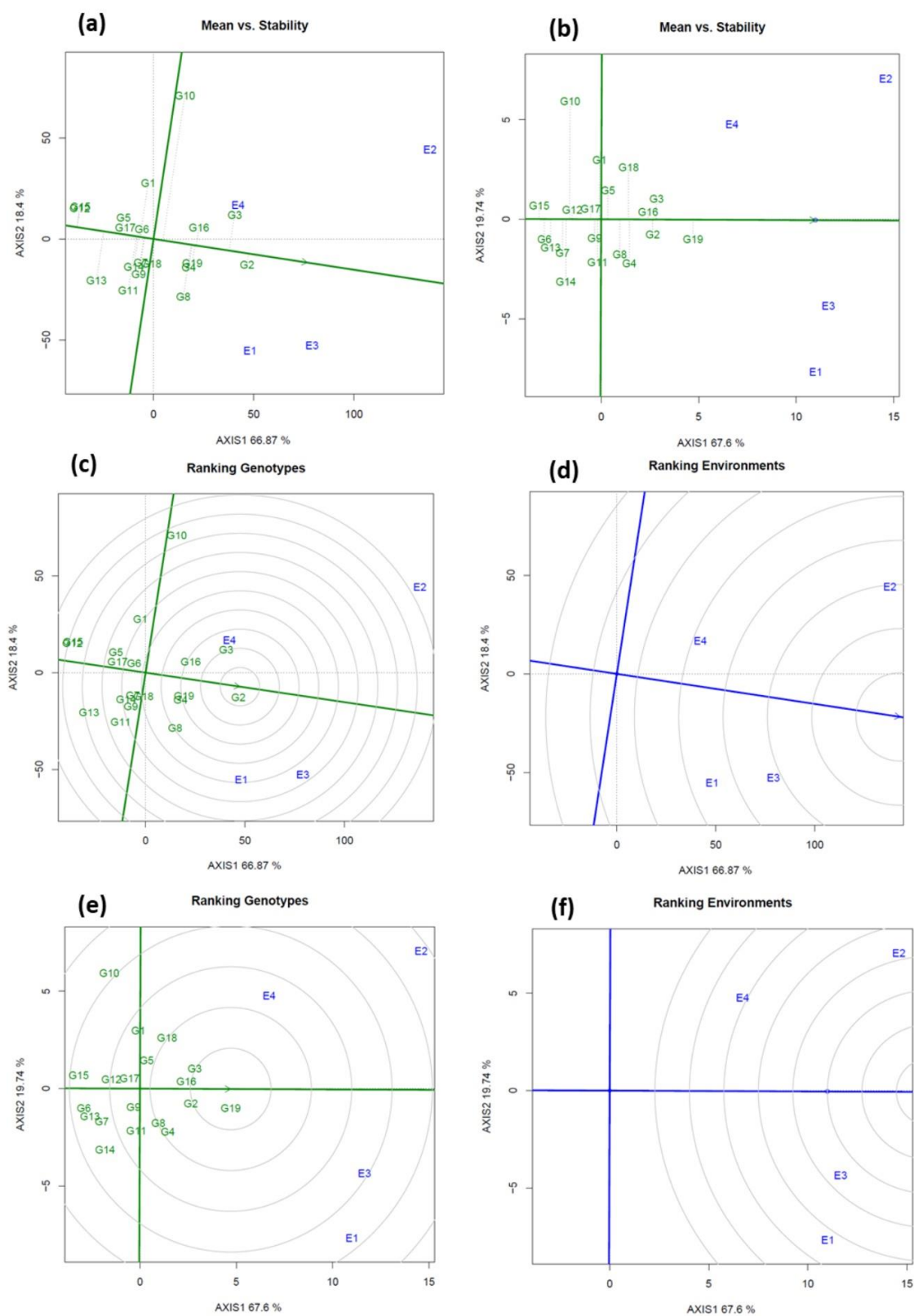


Fig. 2 (a) Mean vs Stability for cane yield (b) Mean vs Stability CCS Yield (c) Ranking of genotype for cane yield (d) Ranking of environment for cane yield (e) Ranking of genotype for CCS Yield (f) Ranking of environment for CCS Yield

Ranking of genotypes and environment

For cane yield, genotype G2 was ranked the highest, followed by G3, while environment E2 emerged as the most favourable (**Fig. 2c and 2d**). In the case of cane yield and commercial cane sugar yield, genotype G19 ranked highest, followed by G3, G2, and G16, with environment E3 identified as the most favourable (**Fig. 2e and 2f**).

Discriminative vs. Representativeness

The GGE biplot analysis of “discriminateness vs. representativeness” is useful for identifying optimal test environments with a strong capacity to differentiate among genotypes. Environment E2 demonstrated high discriminating power for cane yield, as indicated by its long environmental vector (**Fig. 3a**). In contrast, environments E1 and E4 had shorter vectors, suggesting limited discriminating ability, where most genotypes performed similarly for cane yield. For commercial cane sugar yield, environment E4 was found to be representative, while environments E1, E2, and E3 exhibited higher discriminating ability, making them suitable for distinguishing genotype performance (**Fig. 3b**).

WWW

The polygon view of the GGE biplot for cane yield revealed that genotypes G2, G3, G8, G10, G11, G12, G13, and G15 served as vertex genotypes, indicating high responsiveness in specific environments. The four environments were grouped into two distinct mega-environments. The first mega-environment, comprising E1 and E3, showed superior performance of genotypes G2, G4, G8, and G19 (**Fig. 3c**). The second mega-environment included E2 and E4, where genotype G3 exhibited better performance.

For commercial cane sugar yield, the polygon biplot identified G4, G19, G3, G18, G10, G15, G6, G13, and G14 as vertex genotypes. Unlike cane yield, all four environments clustered into a single mega-environment, within which genotypes G2, G3, G4, G8, G16, and G19 were identified as the top performers (**Fig. 3d**).

According to Yan *et al.* (2007), in mean vs. stability (GGE) biplots, genotypes with higher mean yield are positioned to the right of the vertical AEC (average environment coordination) axis passing through the origin. The second axis reflects stability, where genotypes located along the AEC line are considered ideal and high-performing. Genotypes closer to the origin are more stable across environments. The GGE biplot analysis effectively identified stable and high-yielding genotypes across multiple environments for both cane yield and commercial cane sugar yield (CCSY). Genotypes G2, G3, G16, and the check G19 consistently showed superior performance and stability, suggesting their broad adaptability. G2 and G3 were top-ranked for cane yield, with E2 as the most favourable environment, while G19 excelled in CCSY, followed by G3, G2, and G16, with E3 being the most

supportive. The discriminativeness vs. representativeness analysis revealed E2 as the most discriminating for cane yield and E4 as most representative for commercial cane yield. The biplot is segmented by lines radiating from the origin, with each sector representing a mega-environment containing a vertex genotype that shows the highest yield in that zone. Depending on the environment, these vertex genotypes may perform either the best or the worst (Yan and Kang, 2003). Polygon (which-won-where) analysis grouped environments into two mega-environments for cane yield, with G2, G4, G8, and G19 performing well in E1 and E3, and G3 in E2 and E4. For CCSY, all environments formed a single mega-environment, favouring genotypes G2, G3, G4, G8, G16, and G19. These results offer clear direction for selecting stable, high-performing genotypes for commercial cultivation. In a study on genotype × environment (G × E) interaction, Tena *et al.* (2019) reported that clones FG05-424, FG06-750, and the check variety NCO334 exhibited both high productivity and stability, making them suitable for the tested locations based on AMMI and GGE analyses. Similarly, Yadawad *et al.* (2023) identified CoSnk 15102, Co 86032, and CoC 671 as stable genotypes for both cane and CCS yield through GGE biplot analysis involving 12 advanced clones and three standard checks. Mehareb *et al.* (2022) also found G2016-129 to be a consistently high performer for cane and CCS yield in a multi-environment trial. In Chhattisgarh, CoS 8436, VSI 8005, CoC 671, and Co 86032 were recognized as highly productive and stable across locations (Verma *et al.*, 2024). Kumar *et al.* (2023) highlighted Co 15023 as the most stable genotype under saline conditions using AMMI, GSI, SI, and GGE analyses, while Co 0238 was notable for high yield. A multi-location study across 27 environments identified three mega-environments, with genotypes like Co 13018, Co 13003, and Co 11015 performing consistently well. Multi-Trait Stability Index (MTSI) and Multi-Trait Genotype-Ideotype Distance Index (MGIDI) further confirmed Co 11015's superiority, leading to its release for commercial cultivation (Appunu *et al.*, 2024). GGE analysis identified E1 and E2 as a mega-environment for cane yield, while E1 and E3 were identified as the mega-environment for commercial cane sugar yield. Genotypes Co 1148 and CoPb 9181 were found to be reliable and high-performing for both cane yield and CCS yield across these environments (Meena *et al.*, 2024). The AMMI and GGE analyses also highlighted the stability of the gazette-notified varieties Co 15023, Co 0118, and Co 06034 for both cane yield and sucrose percentage. These varieties are well-suited for cultivation in Subtropical India, contributing to sustained sugarcane and sugar production (Kumar *et al.*, 2025). GGE analysis, incorporating mean vs. stability, genotype ranking, and “which-won-where” biplots, revealed that the genotype Co 17001 exhibited higher stability than the standard varieties Co 11015 and Co 86032 for sucrose content, cane yield, and commercial cane sugar yield (Durai *et al.*, 2025).

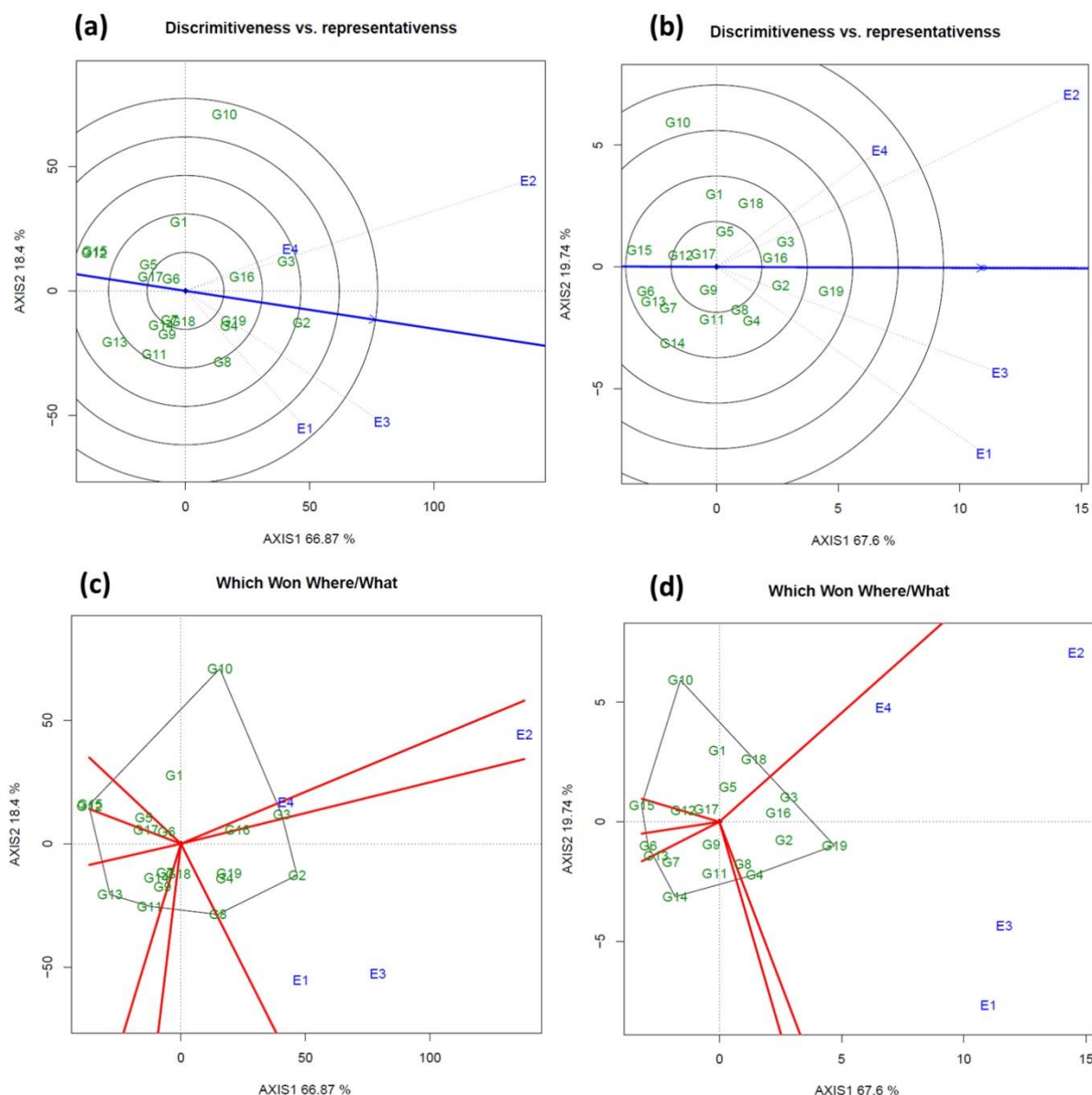


Fig. 3 (a) Discriminativeness vs Representativeness for cane yield (b) Discriminativeness vs Representativeness for CCS yield (c) WWW biplot for cane yield (d) WWW biplot for CCS yield

Mean performance and stability in multi-environment trials (MPS) and Multi-trait stability index (MTSI)

Mean performance and stability in multi-environment trials analysis revealed that genotypes G3, G16, and G19 were found to be superior and were selected for cane yield and commercial cane sugar yield (Fig. 4a). Multi-trait stability index analysis revealed that genotypes G16, G17, and G18 were superior and were selected for the traits cane yield and commercial cane sugar yield (Fig. 4b).

In multi-environment trials (METs), methods such as Mean Performance and Stability (MPS) and the Multi-Trait Stability Index (MTSI) are commonly employed

to select genotypes that demonstrate both consistent performance and high yield across diverse environments (Olivoto *et al.*, 2019; Appunu *et al.*, 2024; Durai *et al.*, 2025). While MPS evaluates stability and performance on a trait-by-trait basis, Multi-Trait Stability Index (MTSI) integrates multiple traits to enable the simultaneous assessment of genotype stability and productivity (Zuffo *et al.*, 2020; Olivoto *et al.*, 2021). In the present study, the mean performance and stability analysis identified genotypes G3, G16, and G19 as superior performers, making them suitable selections for cane yield and commercial cane sugar yield. Meanwhile, the multi-trait stability index analysis highlighted genotypes

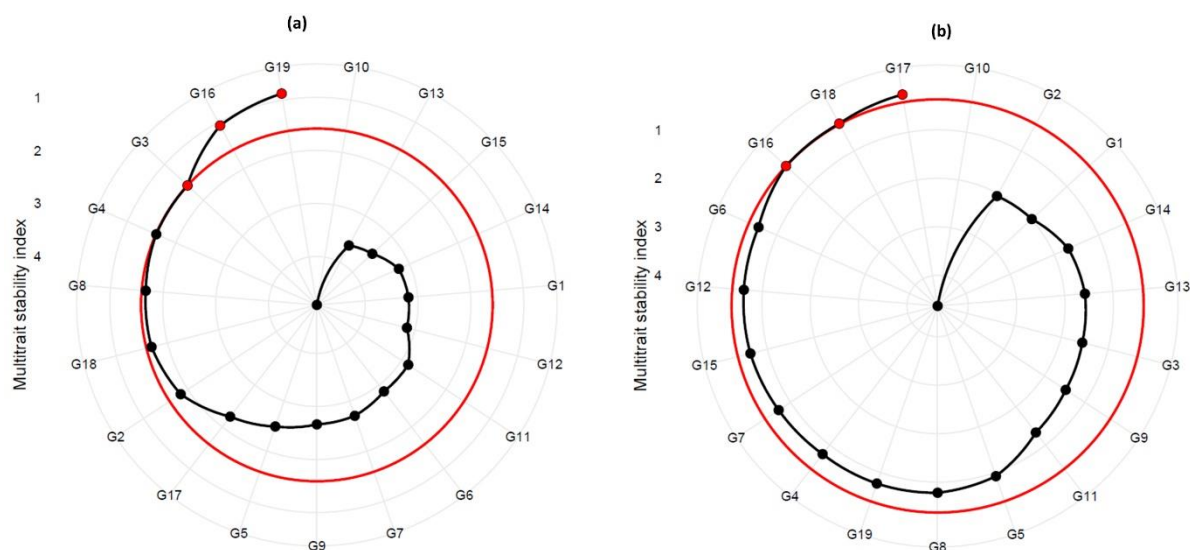


Fig. 4 (a) Mean performance and stability in multi-environment trials (MPS) (b) Multi-trait stability index (MTSI)

G16, G17, and G18 as promising, based on their consistent and high performance across both cane yield and commercial cane sugar yield trait.

The present study, conducted on 19 sugarcane genotypes including two standard checks, revealed significant effects of genotype, environment, and their interaction ($G \times E$) for all evaluated traits based on combined ANOVA. AMMI analysis confirmed these findings and further identified Co 18009, Co 18024, and Co 11015 as stable for cane yield, while Co 17003, Co 17013, and Co 8009 demonstrated stability for commercial cane sugar yield. Stability analysis using the AMMI stability value ranked Co 11015, Co 18024, and Co 15018 as the most stable for cane yield, whereas Co 18024, Co 18009, and Co 17003 were found stable for commercial cane sugar yield. These results were supported by modified AMMI stability value rankings. The genotype stability index further identified Co 11015, Co 18009, and Co 86032 as stable for cane yield, and Co 18009, Co 11015, and Co 14002 for commercial cane sugar yield. Environmental variance analysis also highlighted Co 18009, Co 18024, Co 86032, and Co 14005 as stable for cane yield, with Co 18009 showing consistent stability for commercial cane sugar yield. Sums of the absolute value of the IPC scores (SIPC) ranked Co 11015 and Co 18024 as most stable for cane yield, and Co 18009 as most stable for commercial cane sugar yield. GGE biplot analysis effectively identified genotypes with both high performance and wide adaptability. Genotypes Co 12009, Co 18009, and the check Co 11015 consistently showed superior performance and stability across multiple environments. The Mean performance and stability in multi-environment trials (MPS) analysis identified Co 14002, Co 18009, and Co 11015 as superior genotypes, while the Multi-trait stability index approach highlighted Co 18009, Co 18024, and Co 86032 as the

most promising performers. Considering the collective findings from Additive Main Effect and Multiplicative Interaction (AMMI), AMMI stability value, modified AMMI stability value, genotypic stability index, averages of the squared eigenvector values stability statistic, sums of the absolute value of the IPC scores, mean performance and stability in multi-environment trials, Multi-trait stability index and GGE biplot analyses, genotypes Co 18009 (G16) and Co 12009 (G2) emerged as the most promising and stable performers for both cane yield and commercial cane sugar yield, outperforming the standard checks Co 11015 and Co 86032. These genotypes hold strong potential for commercial release and should be further evaluated across diverse agro-climatic zones in India to assess their suitability for widespread cultivation.

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