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RESEARCH ARTICLE

Stability analysis for identification of stable genotypes of sugarcane (*Saccharum* spp.) through AMMI model

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Abstract

Genotype × Environment interaction for cane yield, commercial cane sugar yield (CCS yield) and sucrose percentage in sugarcane (*Saccharum* spp.) was studied across three environments during 2017-18 and 2018-19 crop seasons to identify stable variety. To assess performance of 22 genotypes, additive main effect and multiplicative interaction (AMMI) model was used. The G×E interactions of sugarcane genotypes across environments were analysed to assess their stability for cane yield, CCS yield and sucrose percentage. Analysis of variance indicated that genotype, environment and genotype × environment interactions were highly significant. The AMMI analysis of variance across three environments showed high total variation for cane yield (38.56%), CCS yield (42.09%) and sucrose (35.87%). This revealed that environments were diverse and significantly influenced the stability of the genotypes. Based on mean performance across the environments and stability, the genotypes *viz*., Co 11015, Co 09004, Co 0240, Co 13014, and Co 14016 were found superior for both cane yield and CCS yield. For sucrose percentage, the genotypes, namely, Co 15021, Co 11015, Co 15007, Co 13001 and Co 16001 were found superior and stable across the environments. Number of millable cane, single cane weight and cane diameter were highly correlated with cane yield and therefore, needs special importance during selection for improvement of cane yield and CCS yield.

Keywords: Adaptability, AMMI model, G×E interaction, sugarcane, stability

Introduction

Sugarcane (*Saccharum* spp.) is the most important commercial crop widely cultivated in both sub tropical and tropical regions of the world. In India, it is grown for the production of sugar as well as other industrial products. Being highly polyploid and highly heterozygous, sugarcane breeding is very complex and challenging (Guddadamath et al. 2014). The main objective of the sugarcane breeder is to develop varieties with high cane yield, increased commercial cane sugar (CCS) yield, wider adaptability to varied environmental conditions and tolerance to prevailing biotic and abiotic stresses. The central region of Tamil Nadu is mainly covered with black cotton soil wherein temperature ranges from 22 to 39°C with a relative humidity of 60%. The average rainfall receives around 861 mm mainly from North East Monsoon followed by South West monsoon during June-November. Under the changing climate, the region needs stable and high yeilding varieties to fulfill the requirement of farmers and sugar mills of this region. Productivity of sugarcane varies from region to region which necessitated for development of varieties for location specific and also varieties suitable for multi locations (Sanghera et al. 2018). In multi location testing, genotype performance differ from one location to other locations for cane and sugar yield which implies the pre-dominant role of the Genotype×Environment (G×E) interaction in expressing the agronomically important traits. Hence, care should be taken to include the effect of G×E interaction during selection of genotypes for cane and CCS yeild (Milligan et al. 1990; Meena et al. 2017). Breeders during selection identify genotypes

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which have less Genotype×Environment interaction with high cane and sugar yield in sugarcane (Kumar et al. 2007). Several models were used to estimate and understand the G×E interaction of phenotypic expression of a genotype. The additive main effect and multiplicative interation (AMMI) is one of the most effective method to analyse the multi location trials in different crops (Gajghate et a. 2021; Reddy et al. 2022; Philanim et al. 2022), as if simultaneously uses the analysis of variance (ANOVA) and Principal Component Analysis (PCA) (Crossa et al. 1990; Gauch and Zobel et al. 1988; Mahadevaiah et al. 2021).

In sugarcane, the cane and sugar yields are contributed by many parameters which are complex in nature. Biplot analysis of AMMI expresses genotype and environment interaction graphically based on PCA. The AMMI enables selection of stable genotyes across locations and location specific genotypes in sugarcane (Meena et al. 2017; Kumar et al. 2018; Tena 2019). In AMMI biplot, the genotypes were positioned using means Vs IPCA 1 in AMMI 1 biplot and IPCA 1 and IPCA 2 scores in AMMI 2 biplot which depicts the stability of the genotypes and their interaction effects across environments and on specific environment. In the biplot, genotypes nearer to the origin point indicates the more stable across the environments and the genotypes which away from origin were unstable one that is having more genotype×environment interaction (Meena et al. 2017). For successful selection, interrelationship among the different traits is very useful and effect of selection based associated traits is important especially for those with low heritability or difficulty in measuring them. For sugarcane breeder, character association studies of component traits of cane yield and sugar yield are useful for selection of ideal genotypes and also to understand the modification in one character while selecting for other associated character. Path analysis gives knowledge about the traits which contributes directly or indirectly through other traits for cane yield by partitioning of total correlation into direct and indirect effect. The objective of the present experiment was to study G×E interactions of sugarcane genotypes across environments and to evaluate stability of the sugarcane genotype for cane yield, CCS yield and sucrose % (Pol %) across tested environments using AMMI method. Character association using correlation and path analysis among the different yield component and quality traits in sugarcane was also studied for effective selection.

Materials and methods

Twenty advanced selections of sugarcane clones developed at ICAR-Sugarcane Breeding Institute, Coimbatore, were evaluated with two standards for cane yield, sugar yield and juice sucrose % for three crops *viz.,* first plant crop (2017-18), second plant crop (2018-19), and ratoon crop (2018-19) (Environment I, II, III, respectively) at in different cane growing areas of Dhanalakshmi Srinivasan Sugars Private Limited, Perambalur, Tamil Nadu. The experiment was conducted with 20 genotypes namely, Co 0238, Co 0240, Co 06031, Co 09004, Co 11015, Co 13001, Co 13003, Co 13006, Co 13014, Co 13018, Co 13020 Co, 13021, Co 14008, Co 14016, Co 14026, Co 15005, Co 15007, Co 15021, Co 16001 and Co 16002 with two checks, Co 86032 and CoV 94101. The material was planted in a randomized block design (RBD) with three replications in 2017-18 as the first plant crop in 8 rows of 6 m length and 1.2 m spacing between the rows. After the harvest of the first plant crop, the trial was ratooned during the year 2018-19. The second plant crop was again planted with the same set of genotypes in three replications during 2018-19. Gap filling was not done in the ratoon crop to understand the performance of ratooning potential of the genotypes. All the standard agronomic practices were followed to raise a good crop stand.

Agronomic data were recorded for cane yield (t/ha), number of millable canes (NMC) per hectare and single cane weight (SCW) (kg), cane length (cm), cane diameter (cm) and HR brix percentage. Five randomly selected canes from each entry were initially for recording SCW, cane length, cane diameter and HR Brix %. Cane yield per plot was recorded and expressed as per hectare. The juice was extracted in the crusher and was clarified using lead subacetate. Juice quality parameters such as brix % in the clarified raw juice, sucrose % in juice, purity % in juice were estimated at 12th month using the standard procedures (Chen 1985). From the above data, commercial cane sugar % (CCS %) and commercial cane sugar yield (CCS yield t/ha) at 12th month were calculated (Chen and Chou 1993). The three environments were considered from data recorded in two plant crop and one ratoon crop. The effect of sugarcane genotypes were studied for individual environment and across the environment. The AMMI model was used to understand different genotypes' adaptability and phenotypic stability across locations. The biplot used in AMMI analysis is AMMI 1 and AMMI 2 biplots. The biplot means two types of points referring to genotypes and environments plotted in the same axis to understand its interrelationship. In AMMI 1 biplot, main effects (mean cane yield) and IPCA 1 scores of both clones and environments were plotted in the X and Y axis of the graph, respectively; and in AMMI 2 biplot the scores of IPCA 1 and IPCA 2 were used in X and Y coordinate, respectively to plot the graph. AMMI stability value (ASV) was calculated according to Purchase et al. (2000). The combined analysis of variance for across test environments as well as AMMI analysis was done using R software, version 3.6.3, package agricolae (R team 2021, https://www.R-project.org/). Pearson correlation coefficient and path analysis was done among the yield, its component traits and quality traits using web based programme OPSTAT. The total correlation coefficients of different yield contributing traits in relation to cane yield was

Table 1. AMMI analysis of variance for cane yield, CCS yield and sucrose % across three environments

Sources of variation	df	Sum of squares (SS)			Mean squares (MS)			% SS		
		Cane yield	CCS yield	Sucrose %	Cane yield	CCS yield	Sucrose %	Cane yield	CCS yield	Sucrose %
Genotype	21	37469	579.18	54.64	1784.20**	27.58**	2.60**	31.55	25.89	18.43
Replication	6	1600	34.96	1.40	266.70**	5.83**	0.23	1.35	1.56	0.47
Environment	2	45795	941.55	106.36	22897.40**	470.78**	53.18**	38.56	42.09	35.87
GxE interaction	42	26846	498.75	60.24	639.20**	11.87**	1.43**	22.60	22.30	20.32
Residuals	126	7060	182.47	73.85	56.00	1.45	0.59			

** 1% level of significance

Table 2. Mean performance of sugarcane genotypes with respect to cane yield (t/ha), CCS yield (t/ha) and Sucrose (%) in three environments

S. No.	Entries	Cane yield (t/ha)				CCS yield (t/ha)				Sucrose %			
		I Plant	II Plant	Ratoon	Mean	I Plant	II Plant	Ratoon	Mean	I Plant	IIPlant	Ratoon	Mean
1	Co 0238	92.21	114.23	94.83	100.43	12.20	14.13	12.40	12.91	18.95	17.90	18.20	18.35
2	Co 0240	138.46	131.95	138.69	136.37	17.81	16.68	16.69	17.06	18.43	17.80	16.89	17.71
3	Co 06031	128.84	157.22	103.44	129.83	16.36	21.00	11.67	16.35	18.11	18.62	15.89	17.54
4	Co 09004	119.17	139.20	107.83	122.07	16.89	18.46	13.14	16.16	20.37	18.51	17.11	18.66
5	Co 11015	141.19	150.17	109.79	133.72	19.68	18.79	12.21	16.90	19.88	17.86	16.05	17.93
6	Co 13001	97.85	125.71	89.08	104.22	13.64	16.08	11.23	13.65	20.09	18.85	17.90	18.95
7	Co 13003	119.03	119.80	95.16	111.33	16.66	14.73	11.96	14.45	19.93	17.42	17.88	18.41
8	Co 13006	72.37	166.38	91.05	109.93	9.34	19.63	11.77	13.58	18.77	16.89	18.05	17.90
9	Co 13014	136.95	172.75	121.36	143.69	18.13	22.71	13.07	17.97	18.87	18.55	15.39	17.61
10	Co 13018	133.52	170.20	93.19	132.30	17.34	20.86	11.38	16.53	19.10	17.46	17.29	17.95
11	Co 13020	101.28	91.55	68.22	87.02	13.07	11.21	8.12	10.80	18.25	17.48	17.10	17.61
12	Co 13021	108.52	152.49	95.61	118.87	14.63	17.87	11.24	14.58	19.26	16.77	16.74	17.59
13	Co 14008	129.88	136.49	108.49	124.95	15.41	16.48	12.64	14.84	17.15	17.27	16.75	17.06
14	Co 14016	140.59	169.22	106.54	138.78	18.13	21.09	13.82	17.68	18.43	17.72	18.04	18.06
15	Co 14026	116.19	111.27	103.56	110.34	14.28	13.95	12.19	13.48	17.72	17.85	16.65	17.40
16	Co 15005	103.19	121.96	101.76	108.97	13.14	15.67	12.78	13.86	18.41	17.88	17.57	17.95
17	Co 15007	118.50	121.59	91.46	110.52	16.96	16.11	12.03	15.03	20.34	18.42	18.53	19.09
18	Co 15021	123.99	141.83	97.28	121.04	16.73	18.29	11.69	15.57	19.31	17.67	17.61	18.20
19	Co 16001	125.78	119.68	118.42	121.29	16.82	14.99	14.31	15.37	19.04	18.28	17.35	18.22
20	Co 16002	117.45	156.20	86.74	120.13	15.56	20.91	10.98	15.82	19.20	18.77	18.47	18.81
21	Co 86032 (Check 1)	130.51	155.21	107.16	130.96	17.23	20.40	12.62	16.75	18.68	18.45	16.42	17.85
22	CoV 94101 (Check 2)	141.14	142.33	118.56	134.01	19.02	16.88	13.74	16.54	18.97	16.77	16.25	17.33
	Mean	119.85	139.43	102.19	120.49	15.87	17.59	12.35	15.27	18.97	17.87	17.19	18.01
	CD	11.64	12.80	12.66		2.15	2.00	1.81		1.68	0.98	1.02	
	CV	5.87	5.55	7.49		8.18	6.88	8.86		5.35	3.31	3.58	

I Plant crop (E1), II Plant crop (E2) and Ratoon crop (E3)

partitioned into components of direct and indirect effects by following the method given by Dewey and Lu (1959).

Results and discussion

Analysis of variance

The AMMI analysis of variance for cane yield, commercial cane sugar yield and sucrose % indicated that presence of significant variation among the genotypes, environments and genotype × environment (G×E) interaction. Difference in G×E interaction among the genotypes implied that genotypes performed differently to the environmental conditions. The AMMI analysis of variance for cane yield across three environments indicated that 38.56% of the total variation was due to the environmental effects, 31.55% due to the genotypic effects and 22.60% was attributed by the G×E interaction effects (Table 1). Large values of SS for

Table 3. Mean, AMMI stability value (ASV) and ranking of AMMI stability value (rASV) for cane yield, CCS yield and sucrose % across three environments

S. No.	Entries	Cane yield (t/ha)			CCS yield (t/ha)			Sucrose %		
		ASV	rASV	Mean	ASV	rASV	Mean	ASV	rASV	Mean
1	Co 0238	2.99	6	100.43	1.30	11	12.91	0.63	13	18.35
2	Co 0240	10.07	21	136.37	2.18	21	17.06	0.19	2	17.71
3	Co 06031	3.67	10	129.83	1.83	17	16.35	1.10	21	17.54
4	Co 09004	0.99	1	122.07	0.06	1	16.16	0.73	17	18.66
5	Co 11015	1.80	4	133.72	1.08	10	16.89	1.04	20	17.93
6	Co 13001	1.44	3	104.22	0.30	2	13.65	0.21	3	18.95
7	Co 13003	4.51	12	111.33	1.60	15	14.45	0.69	15	18.41
8	Co 13006	16.47	22	109.93	3.24	22	13.58	1.02	19	17.90
9	Co 13014	4.32	11	143.69	1.92	18	17.97	1.40	22	17.61
10	Co 13018	8.35	19	132.30	1.68	16	16.53	0.29	4	17.35
11	Co 13020	6.36	16	87.02	1.51	13	10.80	0.30	5	17.61
12	Co 13021	6.27	15	118.87	0.75	5	14.58	0.59	12	17.59
13	Co 14008	3.18	8	124.95	0.56	4	14.84	0.67	14	17.06
14	Co 14016	5.14	14	138.78	0.87	6	17.68	0.76	18	18.06
15	Co 14026	7.67	18	110.34	1.48	12	13.48	0.52	11	17.40
16	Co 15005	3.01	7	108.97	0.92	7	13.86	0.46	8	17.95
17	Co 15007	3.51	9	110.52	1.02	8	15.03	0.45	7	19.09
18	Co 15021	1.21	2	121.04	0.50	3	15.57	0.34	6	18.20
19	Co 16001	8.78	20	121.29	2.10	19	15.37	0.16	1	18.22
20	Co 16002	7.38	17	120.13	2.16	20	15.82	0.51	10	18.81
21	Co 86032	2.32	5	130.96	1.07	9	16.75	0.72	16	17.85
22	CoV 94101	4.56	13	134.01	1.59	14	16.55	0.50	9	17.33
	Mean			120.49			15.27			18.01

environments (45795) revealed that environments were diverse and could significantly influence the variation in cane yield. For cane yield, significant G×E interaction was recorded, which implies different genotypes' performance across the environments (Rea et al. 2011; Meena et al. 2017; Kumar et al. 2018). For CCS yield, AMMI analysis found that 42.09% of the variation was due to the environmental effects, 25.89% due to the genotypic effects and 22.30% due to G×E interaction effects. For sucrose % the total variance observed due to environmental effect was high (35.87%) followed by effects due to G×E interaction (20.32%) and effects due to genotype (18.43%). The accumulation of sucrose is influenced by the prevailing environment (Inman-Bamber et al. 2010) and also genotypes differ in their ability to produce and accumulate the sucrose. The significant G×E interaction revealed that genotypes responded differently across the environments (Pedro et al. 2013; Kumar et al. 2018) and were the major cause of genetic variation in sugarcane (Meena et al. 2017; Rea et al. 2017). The significant effect of the G×E interaction, explains differential behavior of genotypes in different environments which led to change the rank of the genotype in different environments, by refined analysis of G×E will increase the selection efficiency and clear-cut recommending of genotypes for commercial use. In this regard, AMMI analysis is the potential tool to precisely understand the factors contributing to the G×E interaction.

Performance of cane yield (t/ha) across the environments

Mean performance for cane yield (t/ha), sugar yield (t/ha) and sucrose (%) under three environments as the first plant crop (E1), second plant crop (E2) and ratoon crop (E3) are presented in Table 2. An ideal genotype should possess high average cane yield across the environments where it was tested. The mean cane yield of 20 genotypes ranged from 87.02 t/ha (Co 13020) to 143.69 t/ha (Co 13014). The mean performance of Co 13014 (143.69 t/ha), Co 14016 (138.78t/ha), Co 0240 (136.37 t/ha), Co 11015 (133.72 t/ha) and Co13018 (132.30 t/ha) were higher for cane yield over the best check Co 86032 (130.96 t/ha). The highest cane yield was recorded in Environment-2 (second plant crop) (139.43 t/ha) followed by Environment-1 (first plant crop) (119.85 t/ha) and Environment-3 (ratoon crop) (102.19 t/ha). Mean cane yield

Table 4. Correlation coefficient of yield component and quality traits of sugarcane genotypes

Characters	CCS Yield (t/ha)	Number of Millable Canes/ha	Cane Length (cm)	Cane Diameter (cm)	Single Cane Weight (kg)	Sucrose %	Brix %	Purity %	CCS %	HR Brix %
Number of Millable Canes/ha	0.488*									
Cane Length (cm)	0.499*	0.103^{NS}								
Cane Diameter (cm)	0.224^{NS}	-0.493*	0.100^{NS}							
Single Cane Weight (kg)	0.369^{NS}	-0.493*	0.485*	0.803**						
Sucrose %	-0.065^{NS}	0.098^{NS}	-0.444*	-0.357^{NS}	-0.503*					
Brix %	-0.197^{NS}	0.225^{NS}	-0.445*	-0.566**	-0.637**	0.871**				
Purity %	0.277^{NS}	-0.297^{NS}	0.108^{NS}	0.534*	0.411^{NS}	-0.033^{NS}	-0.517*			
CCS %	0.013^{NS}	0.015^{NS}	-0.398^{NS}	-0.205^{NS}	-0.375^{NS}	0.962**	0.705**	0.240^{NS}		
HR Brix %	-0.445*	-0.107^{NS}	-0.470*	-0.315^{NS}	-0.461*	0.629**	0.697**	-0.286^{NS}	0.526*	
Cane Yield (t/ha)	0.967**	0.485*	0.591**	0.245^{NS}	0.437*	-0.301^{NS}	-0.362^{NS}	0.201^{NS}	-0.236^{NS}	-0.578**

*Significant at 5% level of probability **Significant at 1% level of probability CCS - Commercial Cane Sugar

Table 5. Path coefficient for direct (bold) and indirect effects on cane yield (t/ha) of sugarcane genotypes

Characters	CCS Yield (t/ha)	Number of Millable Canes/ha	Cane Length (cm)	Cane Diameter (cm)	Single Cane Weight (kg)	Sucrose %	Brix %	Purity %	CCS %	HR Brix %
CCS Yield (t/ha)	**0.935**	0.011	0.004	-0.007	0.009	-0.017	-0.008	0.027	-0.007	0.020
Number of Millable Canes/ha	0.456	**0.022**	0.001	0.014	-0.012	0.026	0.010	-0.029	-0.008	0.005
Cane Length (cm)	0.467	0.002	**0.009**	-0.003	0.011	-0.117	-0.019	0.011	0.209	0.021
Cane Diameter (cm)	0.210	-0.011	0.001	**-0.029**	0.019	-0.094	-0.024	0.053	0.108	0.014
Single Cane Weight (kg)	0.345	-0.011	0.004	-0.023	**0.023**	-0.132	-0.027	0.041	0.198	0.020
Sucrose %	-0.061	0.002	-0.004	0.010	-0.012	**0.263**	0.037	-0.003	-0.507	-0.028
Brix %	-0.184	0.005	-0.004	0.016	-0.015	0.229	**0.042**	-0.051	-0.371	-0.031
Purity %	0.259	-0.007	0.001	-0.016	0.010	-0.009	-0.022	**0.099**	-0.126	0.013
CCS %	0.012	0.001	-0.004	0.006	-0.009	0.253	0.030	0.024	-0.526	-0.023
HR Brix %	-0.416	-0.002	-0.004	0.009	-0.011	0.166	0.029	-0.028	-0.277	**-0.044**

Residual effect = 0.0012

over three environments was 120.49 (t/ha). Guddadamath et al. (2014) studied eight genotypes with four checks for cane yield at four locations and reported significant difference in mean cane yield across four environments. To understand the additive effect on the analysis of variance, and also to study the main component's multiplicative effect, AMMI model generates biplots which are useful to analyse the genotypes and environment simultaneously (Sumertajata 2007). The AMMI 1 biplot was depicted using means vs IPCA 1 scores found that among the 22 genotypes evaluated for cane yield, 12 clones have recorded higher cane yield than the average mean yield (120.49 t/ha) which were fallen in the right side of the midpoint of the perpendicular line in AMMI 1 biplot. Due to low mean yield, the remaining clones fell in the left side of AMMI 1 biplot. Among the entries recorded above the overall mean cane yield, Co 15021, Co 14026, Co 11015 and Co 15007 were found as low positive interaction with the environment whereas, CoV 94101, Co 13001, Co 14016, Co 15005, Co 13018 and Co 0240 clones had low negative interaction as observed from their low IPCA scores (Fig. 1a). The present results are supported by the earlier findings of Regis et al. (2018) in sugarcane. The genotypes close to origin, found more stability over the environment, whereas the genotypes farther away from the origin had the low stability (Meena et al. 2017 and Kumar et al. 2018). The interpretation of AMMI model through Biplot analysis is easy to understand the performance of the genotypes (Mahadevaiah et al. 2021).

AMMI 2 biplots were depicted through IPCA 1 and IPCA 2 scores to understand the stability of genotypes and their interaction effects of genotypes and environments. The clones present near to origin that is IPCA equal to zero were

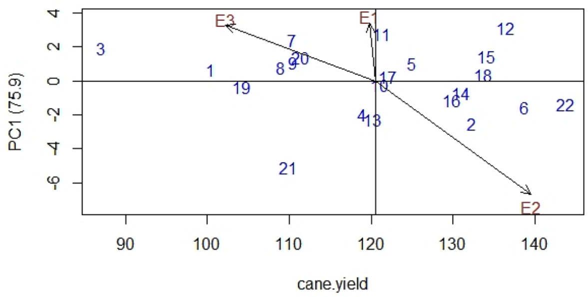

Fig. 1a. AMMI 1 biplot showing cane yield vs PC 1 from 22 genotypes across three environments

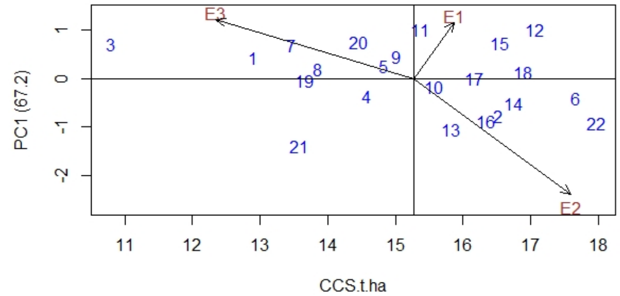

Fig. 2a. AMMI 1 biplot showing CCS yield vs PC 1 from 22 genotypes across three environments

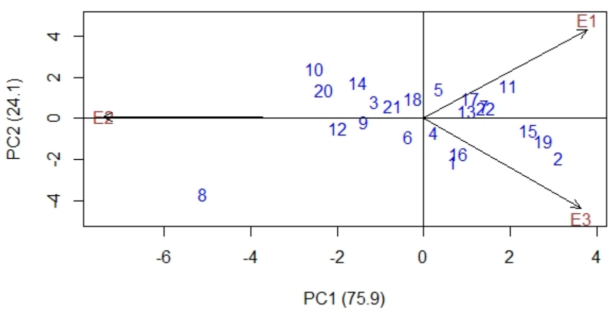

Fig. 1b. AMMI 2 biplot showing PC1 vs PC2 for cane yield (t/ha) from 22 genotypes across three environments

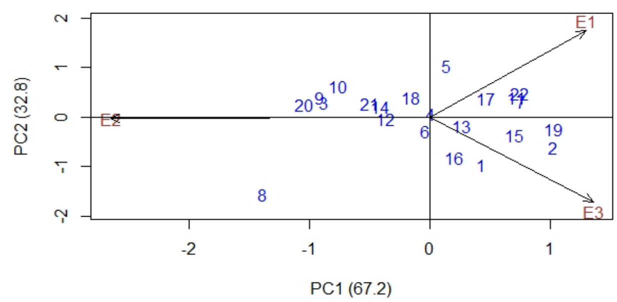

Fig. 2b. AMMI 2 biplot showing PC1 vs PC2 for CCS yield (t/ha) from 22 genotypes across three environments

more stable than the clones positioned away from the origin. The high interaction effect was observed in the genotypes positioned far away from the origin and found that these clones are sensitive to environmental interaction. For cane yield, a contribution of 75.9% was by PC1 and 24.1% was by PC2 were observed (Fig. 1b). Similar findings of higher contribution of genotypes were reported by Guerra et al. (2009) and Silveira et al. (2013). This found that interaction sum of squares of 100 per cent from IPCA 1 and IPCA 2 indicates that the first two IPCA were sufficient to explain the G×E interaction of 22 genotypes evaluated. Based on this, the genotypes *viz*., Co 11015, Co 15007, Co 14008, Co 15005, Co 09004, Co 13001, Co 86032 and Co 15021 were identified which were found near to zero axis of AMMI 2 biplot which is less interaction with environment and these genotypes were found as stable over different environments (Fig. 1b). Similar findings for cane yield in sugarcane using AMMI analysis were reported by Magalhaes et al. (2018) and Kumar et al. (2018). Co 13006 and Co 13018 were away from the zero axis, indicating that these genotypes were found to have low stability, while other genotypes fall under intermediate stability. AMMI Stability Value (ASV) is quantitatively measuring the stability value of genotypes as described by Purchase et al. 2000. Based on the results of AMMI model, the ranking of genotypes was ideal method of selection of stable genotypes for varied environments. ASV was calculated using the IPCA1 and IPCA2 scores of each genotype and based on their given rank (Table 3). The genotypes with high mean yield and the least ASV score were considered as more stable genotypes (Rea et al. 2017). The genotypes with high cane yield over the grand mean with low ASV were found in the genotypes namely, Co 09004 (0.99), Co 15021 (1.21), Co 11015 (1.80), Co 86032 (2.32), Co 14008 (3.18), Co 06031 (3.67), Co 13014 (4.32), CoV 94101 (4.56) and Co 14016 (5.14)) (Table 3). These genotypes were found as stable across the environments. The clones with high ASV and higher cane yield than the grand mean was recorded by Co 13018 (8.35), Co 16001 (8.78) and Co 0240 (10.07). In general, most stable genotypes, not essentially, all the time yield higher quantity of cane. The clones with high cane yield and low ASV could be utilized in varietal development programmes (Tena et al. 2019; Sheelamary and Karthigeyan 2021).

Performance of CCS yield (t/ha) across the environments

The mean performance of CCS yield for 20 genotypes ranged from 10.80 t/ha (Co 13020) to 17.97 t/ha (Co 13014)

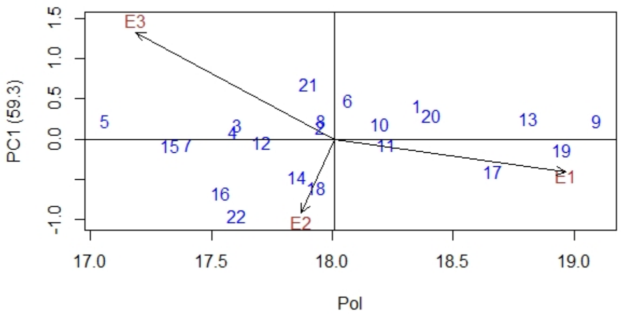

Fig. 3a. AMMI 1 biplot showing Sucrose % (Pol %) vs PC 1 from 22 genotypes across three environments

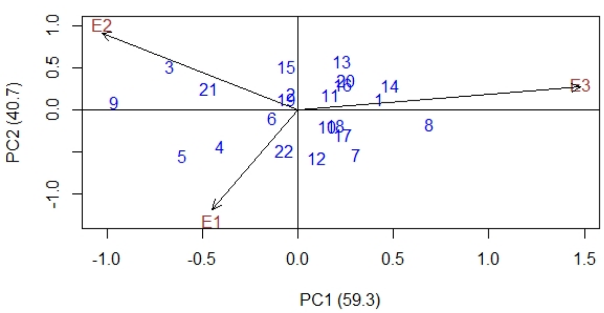

Fig. 3b. AMMI 2 biplot showing PC1 vs PC2 for Sucrose % (Pol %) from 22 genotypes across three environments

(Table 2). The mean commercial cane sugar yield (t/ha) in three environments, the genotypes, Co13014 (17.97 t/ha), Co 14016 (17.68 t/ha), Co 0240 (17.06 t/ha) and Co11015 (16.90 t/ha) recorded higher CCS yield as compared to the better check Co 86032 (16.75 t/ha). The highest CCS yield was found in Environment-2 followed by Environment-1 and Environment-3 (17.59, 15.87 and 12.35 t/ha, respectively). The highest CCS yield was recorded by Co 13014 (22.71 t/ha) in Environment-2 and it was also the highest yield across the environments. On the other hand, the lowest yield was observed in Environment-3, in which the genotype Co 0240 recorded the highest CCS yield (16.69 t/ha). Guddadamath et al. (2014) and Kumar et al. (2018) found comparable results for CCS yield in their studies. Mean commercial cane sugar yield over three environments was 15.27 t/ha. The present results were in accordance with the earlier findings of various sugarcane researchers (Rao et al. 2011; Sandhu et al. 2012; Mahadevaiah et al. 2021). In AMMI 1 biplot, among the genotypes evaluated for CCS yield, 12 clones have recorded higher CCS yield than the average mean CCS yield and these all clones were fall in the right side of the midpoint of the perpendicular line and rest of the clones were fall in the left side of AMMI 1 biplot due to its low CCS yield. Among the entries recorded above the overall CCS yield, the genotypes *viz.*, Co 15021, Co 14026 and Co 15007 found as low positive interaction with environment and CoV 94101, Co 13001, Co 14016, Co 0240 and Co 13018 clones had low negative interaction which observed from their low IPCA scores (Fig. 2a). The clones with high CCS yield near the IPCA equal to zero found as negligible GxE interaction and these clones have wider adaptability over different environments (Naroui Rad et al. 2013; Kumar et al. 2018; Heliyanto et al. 2020).

To understand the stability of genotypes and their interaction effects of genotypes and environments, AMMI 2 biplots are depicted through IPCA 1 and IPCA 2 scores for CCS yield. From AMMI 2 biplot analysis the genotypes *viz.*, Co 15021, Co 09004, Co 14008, Co 15005, Co 13001, Co 13021 and Co 14016 found more stable compared to other clones across the environments (Fig. 2b). Genotypes, Co 13006 and Co 0238 fell in the low stability group while rest of the entries was intermediate group. Similar findings were reported through AMMI analysis in sugarcane for CCS yield after evaluating different clones across the locations by Kumar et al. (2018). The genotypes with high commercial cane sugar yield over the grand mean with low ASV was recorded for the genotypes *viz.*, Co 09004 (0.06), Co 15021 (0.50), Co 14016 (0.87), Co 86032 (1.07) and Co 11015 (1.08), and these genotypes were also found stable across the environments due to their low ASV value (Table 3). The clones with high ASV and higher commercial cane sugar yield than the grand mean was recorded in Co 13018 (1.68), Co 06031 (1.83), Co 13014 (1.92) and Co 0240 (2.18) with a similar trend as observed by Sheelamary and Karthigeyan (2021).

Performance of sucrose % across the environments

The mean performance for sucrose % under the three environments indicated the highest sucrose % in Co 15007 (19.09%) followed by Co 13001 (18.95%), Co 16002 (18.81%) and Co 09004 (18.66%) which was higher than the commercial check Co 86032 (17.85%) (Table 2). The highest sucrose % was recorded in Environment-1 (18.97%) followed by Environment-2 (17.87%) and Environment-3 (17.19%); with the mean sucrose % of 18.01% over the environments. Similar magnitude of environmental variation and G×E interaction for sucrose % were also reported by Guddadamath et al. (2014) and Kumar et al. (2018). Biplot of AMMI analysis for sucrose % was carried out to understand the genotypes which are stable in all the tested locations. The genotypes present near to zero axis showed less interaction between the genotypes and the environment which indicates the more stable genotypes. The position of genotypes in biplot implies that their adaptability to the tested locations (Duarte and Vencovsky 1999). Nine clones out of 22 have recorded higher sucrose % than the average mean sucrose % (18.01) which were fallen in the right side of the midpoint of the perpendicular line. Clones closer to the origin of the axis (IPCA 1) indicated that these clones contribute smaller level of interaction than the clones fall away from the origin.

Among the entries recorded above the overall sucrose % (Co 13014, Co 14008, Co 16002, Co 0238, Co 13018 and Co 13001) were found as low positive interaction with environment and the positions close to IPCA equal to zero found as more stable and environment effect on sucrose % was negligible (Kumar et al. 2018). The clones, Co 16001, Co 15007 and Co 13020 had low negative interaction due to their low IPCA scores. Also due to low sucrose %, the remaining clones were fallen in the left side of AMMI biplot 1 (Fig. 3a).

The biplot of AMMI 2 analysis for sucrose % identified the stable performance in Co 13020, Co 13018, Co 15021, Co 13021, CoV 94101, Co 13001, Co 16001 and Co 0240 of across the tested locations (Fig 3b). Two genotypes, Co 06031 and Co 13021 were found as less stable clones, and the rest showed intermediate stability across locations. The ASV were calculated for all the 22 genotypes and the genotypes with high sucrose % over the grand mean with low ASV were: Co 16001 (0.16), Co 13001 (0.21), Co 15021 (0.34), Co 15007 (0.45), Co 16002 (0.51) and Co 0238 (0.63) and these genotypes were found as stable across the environments (Table 3). The clones Co 13003 (0.69), Co 09004(0.73) and Co 11015(1.04) with high ASV and sucrose % than the grand mean were identified. Sheelamary and Karthigeyan (2021) have also reported sugarcane clones with high ASV value in their study through the AMMI analysis.

Correlation and path coefficient analysis for yield components and quality traits

To carry out the effective breeding program, information on association between the component traits is necessary. The pattern of relationship among the traits of yield and quality traits is determined using correlation. The correlation analysis showed a positive and significant correlation of cane yield with cane length, NMC and single cane weight, and was negatively significant correlation with HR brix and negatively non-significant correlation with juice quality traits *viz*., juice sucrose %, and CCS % (Table 4). On the other hand, number of millable canes (NMC) showed a significant negative association with cane diameter and single cane weight. Similar findings of NMC positive association with cane yield and significant negative association with stalk diameter and single cane weight were reported by Kumar and Kumar (2014). The cane length and cane diameter also had negative and significant correlation with quality traits *viz*., juice sucrose %, brix %, and HR brix %. Similar association between these traits was earlier reported by Singh and Saxena (1997). Positive association of cane diameter with cane yield was also reported by cane workers earlier (Singh and Sharma 1997; Kumar and Kumar 2014). SCW showed positive significant correlation with cane diameter, cane length and cane yield, and SCW being a most important cane yield contributing trait which need to be considered during parental selection for hybridization and varietal identification (Choudhary and Joshi 2005; Kumar and Kumar 2014; Tena et al. 2016). Among the juice quality traits, juice sucrose % showed positive and highly significant correlation with juice brix %, CCS % and purity %, and was negatively correlated with cane yield and its component traits and it was in conformity with the earlier reports found as yield and quality had the antagonistic relationship (Kumar and Kumar 2014). Although the correlations values may be more or less similar but the materials and the environmental conditions were different.

Path coefficient analysis gives an idea about correlation of cane yield with its contributing traits is due to the consequence of direct effect or indirect effects through other traits on cane yield. Cane length, SCW, NMC, sucrose %, brix % and purity % showed positive direct effect on cane yield (Table 5) while cane diameter, CCS% and HR brix % had negative direct effect. The highest positive direct effect on cane yield was through single cane weight followed by number of millable cane. The similar results as direct effect of single cane weight and number of cane on cane yield were reported in sugarcane (Balasundarum and Bhagyalakshmi 1978). Millable cane number showed the highest direct effect on cane yield but had negative effect on cane yield through tiller number, stalk height and brix per cent. The direct effect of stalk height on cane yield was negative but low (Tahir et al. 2014 and Tena et al. 2016). The positive indirect effect of NMC on cane yield was through the cane length, cane diameter, sucrose %, brix % and HR brix %, and negative indirect effect through SCW, purity % and CCS %. Cane length recorded positive indirect effect on cane yield through NMC, cane length, SCW and purity %, CCS % and HR brix %, and negative indirect effect through cane diameter, sucrose % and brix %. Similar finding of stalk length positive contribution for cane yield was reported through number of millable canes and stalk weight, and also that NMC had negative effect on cane yield through cane diameter and Stalk weight (Kumar and Kumar 2014). Cane diameter recorded positive indirect effect on cane yield through cane length, SCW, purity%, CCS% and HR brix %, and negative indirect effect through NMC, sucrose% and brix %. Stalk diameter was found to have negative effect on cane yield indirectly through millable cane number as also recorded previously (Tena et al. 2016). The SCW recorded positive indirect effect on cane yield through cane length, purity %, CCS % and HR brix %. The positive indirect effect of sucrose % on cane yield was recorded through NMC, cane diameter and brix %, and negative indirect effect by cane length, SCW, purity %, CCS % and HR brix %. The brix at different crop age was recorded as positive indirect effect for cane yield through stalk diameter, stalk length, and stalk weight, on the other hand negative indirect effect through number of shoots and number of millable canes (Kumar and Kumar 2014). From the study it was found that number of millable cane, single cane weight and cane diameter were highly correlated hence, most essential trait for improvement of cane yield in sugarcane. Selection based on these traits could increase both cane yield and CCS yield. Further, the importance needs to be given to the indirect effects of cane diameter and cane length through single cane weight along with NMC during selection of suitable genotypes.

Understanding the adaptation pattern and stability of newly developing genotypes, multi location trials are essential in sugarcane breeding. Based on mean performance and stability, the genotypes namely, Co 11015, Co 09004, Co 0240, Co 13014, and Co 14016 were found to be highly adapted and more stable over all the environments for cane yield and CCS yield, and for sucrose % five genotypes *viz*., Co 15021, Co 11015, Co 15007, Co 13001 and Co 16001 displayed more stability. Number of millable cane, single cane weight and cane diameter highly correlated and essential for improvement of cane yield. The selection done considering the above traits could increase both cane yield and the CCS yield.

Authors' Contribution

Conceptualization of research (BR, GH, CA, PG); Designing of the experiments (PG, KE, AP, VR); Contribution of experimental materials (BR, GH, CA, PG); Execution of field/ lab experiments and data collection (KE, PG, AP, VR); Analysis of data and interpretation (KE, PG, HKM, CA); Preparation of the manuscript (KE, PG, HKM, CA).

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