Indian J. Genet. Plant Breed., (2023); 83(3): 389-397
https://doi.org/10.31742/ISGPB.83.3.11
ISSN: 0975-6906
www.isgpb.org

RESEARCH ARTICLE

Multi environmental evaluation for selection of stable and high yielding sugarcane (*Saccharum officinarum* L.) clones based on AMMI and GGE biplot models

Arati Yadawad*, Sanjay B. Patil[1], B. Y. Kongawad, A. D. Kadlag and G. Hemaprabha[2]

Abstract

The present study was aimed to evaluate the G x E (genotype x environment) interaction using AMMI and GGE biplot analysis to identify sugarcane (*Saccharum officinarum* L.) genotypes that combine high yield and stability in multi-location trials. Twelve advanced clones generated in the sugarcane breeding programs along with three standards (Co 86032, CoC 671 and Co 09004) were evaluated for cane and sugar yield using randomized complete block design with three replicates over two plant crops and one ratoon during 2019 to 2021 across two years and locations. Data was collected on yield traits and sugar quality characters. Stability parameters were determined. The data was also investigated using GGE biplot and the AMMI models. The results of combined analyses of variance exhibited significant differences among genotypes at the three test environments and when locations were combined. The GE interaction was also significant for all the traits, indicating inconsistency of performance of the genotypes over the locations and seasons. Pooled data analysis of 15 genotypes indicated the superiority of Co 15017 and CoN 15071 for CCS yield across six environments. Two clones, Co 15017 and CoSnk 15102 recorded higher mean cane yield as compared with three standards across the six experimental conditions. Multivariate (AMMI and GGE biplot) statistical analysis indicated that CoSnk 15102 exhibited higher and more stable commercial cane sugar yield and cane yield per hectare, indicating this genotype's suitability across the test locations. The results of such multi-environmental trials with the elucidation of GE interaction using AMMI and GGE are of great significance in guiding the selection and recommendation of stable and superior varieties in sugarcane production zones.

Keywords: Sugarcane, AMMI, GGE, Cane yield, CCS yield

Introduction

Sugarcane *(Saccharum officinarum* L.*)* is India's and the world's important cash and sugar crop. India is the world's largest producer and consumer and the world's second-largest exporter of sugar in the world (Anonymous 2023). The sustainable supply of new sugarcane varieties adaptable to various agroclimatic conditions is vital to farmers and the sugar industry in the country. Breeders often use yield and its contributing traits as well as a phenotypic expression for selection of crop cultivars under mega environments. Temperature, humidity, soil texture and, fertility, precipitations play an important role in the yield fluctuation caused by genotypes in response to changing environments. Stability and adaptability are the main criteria for the selection of genotypes in any breeding program (Wolde et al. 2018). Estimation of stability of a new genotype for yield and quality traits is a pre-requisite in plant breeding program prior to its release for commercial planting. The stability of a genotype is greatly affected by the environment (E), genotype (G) and G x E interaction (GEI) that causes significant variation in cultivar performance across the different locations and seasons (Mohammad et al. 2007).

K. J. Somaiya Institute of Applied Agricultural Research, Sameerwadi 572 129, Karnataka, India.

[1]Agricultural Research Station, Sankeshwar, University of Agricultural Sciences, Dharwad 580 005, Karnataka, India.

[2]Division of Crop Improvement, ICAR-Sugarcane Breeding Institute, Coimbatore 641 003, Tamil Nadu, India.

***Corresponding Author:** Arati Yadawad, K. J. Somaiya Institute of Applied Agricultural Research (KIAAR), Sameerwadi 572 129, Karnataka, India, E-mail: aratiyadawad@gmail.com

How to cite this article: Yadawad A., Patil S.B., Kongawad B.Y., Kadlag A.D. and Hemaprabha G. 2023. Multi environmental evaluation for selection of stable and high yielding sugarcane clones based on AMMI and GGE biplot models. Indian J. Genet. Plant Breed., **83**(3): 389-397.

Source of support: Nil

Conflict of interest: None.

Received: Dec. 2022 **Revised:** July 2023 **Accepted:** Aug. 2023

The observation and analysis of GEI in multi environment trials are very important for evaluating, selecting and recommending crop varieties (Mattos et al. 2013; Regis et al. 2018).

Breeders invariably encounter GEI while evaluating varieties over several environments that complicates response of the selection. A significant GEI for a quantitative trait such as yield can seriously limit the efforts to select superior genotypes for crop production and improved cultivar development. It is important to quantify GEI to design selection methods that can accurately recognize superior cultivars in the final selection stages and predict their potential performance in numerous environments. To determine the presence of GEI in a multi-environmental yield trial, analysis of variance (ANOVA) is executed. The ANOVA procedures highlighted differentiation in fixed and random effects such as genotype, replication, location, and environment. Nevertheless, the major bottleneck of ANOVA are the failure to distinguish genotype variances in a non-additive manner as GEI (Yusuff et al. 2017). A group of stability statistical measures was settled to analyze genotype stability that divulges several GEI features, resultant in detecting stable genotypes across environments. To better understand genotypic stability patterns, two separate techniques, univariate and multivariate stability analysis, are used (Yusuff et al. 2017).

The cultivar superiority index and stability measurements (Huehn 1990; Lin and Binns 1988) are the indices used for identification of stable genotypes across multiple environments. Biplots are widely used to graphically show the interrelationships between genotypes (G), environments (E), and GEIs, as well as to demonstrate interaction patterns and identify comparably stable genotypes across environments (Yusuff et al. 2017). There are two widely used biplot models of multivariate approaches: AMMI biplot (Gauch et al. 2006; Gauch et al. 2008) and GGE biplot (Yan et al. 2000; Yan and Tinker 2006). The GGE-biplot and AMMI models support the stability and superiority indices in recognizing varieties with both specific and broad adaptation (Kaya 2006). AMMI can detect and display GEI in a multi-dimensional environment using a biplot. AMMI Biplot's graphic analysis provides relatively simple analysis for breeding researchers and allows conclusions to be drawn concerning phenotypic stability, genotype behavior, genetic divergence between genotypes, and environments with optimal performance.

GGE biplots analysis, on the other hand complements AMMI Biplot's environmental stratification and aid researchers in better understanding complicated GE interactions in multi-environment breeding line trials using mega environment analysis ("Which Won-Where" pattern), evaluation of genotype (ranking biplot) and environment (comparison biplot), which provides discriminating power and representation of the environments. GGE Biplot analysis is regarded as a useful statistical technique for producing phenotypically stable and superior cultivars, identifying stable genotypes across several environments, and achieving crop yield stability across multiple locations. Multi-environment trials are important for properly ranking candidate cultivars and recognizing representative selection or production environments (Yan et al. 2007). This could accelerate breeding efficiency (Yan and Holland 2010) and strengthen the competitiveness of yield production (Gauch and Zobel 1997). Therefore, the present study aimed to determine the productivity and stability of advanced sugarcane clones evaluated across six test environments and identify new stable genotypes with high cane and sugar yield using AMMI and GGE-biplot stability models.

Materials and methods

Experimental design and trials

The experimental material, comprising of 12 advanced sugarcane clones derived from different sugarcane research centers of All India Co-ordinated Research Project on Sugarcane for peninsular zone were evaluated along with three checks (Co 86032, CoC 671 and Co 09004) in two locations, Sameerwadi (*voluntary center)* and Sankeshwar (*regular center)* representing two different agro climatic zones, Northern dry zone and Northern transitional zone of Karnataka. This study was aimed for estimating GEI for various yield and quality traits. The experimental material was planted in a randomized, complete-block design with three replications in 2020-2021 and 2021-2022 plant crops and a ratoon crop in 2021-2022. The seed rate was 12 buds per meter in six rows of six-meter-long plots, with a row-to-row spacing of 120 cm and plot size of 43.2 m^2 under irrigated conditions.

Observations recorded

Data was collected on six quantitative traits viz., single cane weight (kg), brix (%), sucrose (%), Commercial Cane Sugar (CCS%), cane yield and CCS yield. A sample of five canes was randomly taken from each plot and weighed to calculate single cane weight and expressed as kgs. CCS (t/ha) was computed as per the standard formula. The clarified juice was analyzed with a polarimeter and refractometer for sucrose percent. Four rows were harvested at 12 months after planting for measuring cane yield in net plot across replications and were expressed as tons per hectare.

Statistical analysis

The data collected on six quantitative traits was subjected to analyses of variance (ANOVA) for yield and quality parameters to estimate the existence of variations among the genotypes, locations, seasons, and interactions using OPSTAT software for individual and pooled analysis across the seasons. The general mean for each genotype pooled across six environments is the trait value across the crop cycle. Treatment means were compared using the Fisher's protected least significant difference (LSD) test at 5% probability. The phenotypic stability was performed for CCS yield and cane yield as per method outlined by Eberhart and Russell (1966). In this model of analysis sum of square due to G×E were partitioned into individual genotypes (X-i) regression of environmental mean (bi) and deviation from regression (S^2di). The regression coefficient (bi) and mean square deviation from (S^2di) were used to define genotypic stability.

To explain the G×E interaction, the multivariate stability analysis was performed graphically using PBTools software (PBtools for windows 2014, Version 1.4, http://bbi.irri.org/products) and R (R CoreTeam, 2012), with a user-friendly graphical interface developed at IRRI (IRRI, 2002). The performance of clones was assessed using two stability models, Additive Main effects and Multiplicative Interaction (AMMI) (Gauch and Zobel 1997) and GGE Biplot or Site Regression model (Yan and Kang, 2003). In GGE biplot analysis both the genotypic effect (G) and its interaction with the environment (GEI) are used for the analysis, while in AMMI model only interaction component (GEI) is used. AMMI first analyzes the genotypes and environment's main effects (additive) using analysis of variance (ANOVA) and then analyzes the residual (namely the interaction) using principal components analysis (PCA). The GGE biplot which is based on the site regression linear (SREG) bilinear model (Crossa and Cornelius, 1997; Crossa et al. 2002) displays both genotype and genotype environment variation (Kang 1993). The graph generated is based on multi environment evaluation (which-won-where pattern), genotype evaluation (mean versus stability), and tested environment raking (discriminative versus representative). The ranking of genotypes was allocated in increasing order of each stability parameter. Performance consistency or stability of each genotype was determined after testing the significance of the genotype by environment interaction.

Results and discussion

Analysis of variance

Analysis of variance of 15 cultivars evaluated for single cane weight, brix, sucrose, CCS%, CCS yield and cane yield across two locations and three seasons (two plants and one ratoon crop) is presented in Table 1. The genotypic difference was found to be significant ($p < 0.01$) for each of the six environments. The differences among the environments were evident between years. The combined analysis of variance for cane and sugar yield revealed that genotypes and GEI contributed to significant variation for CCS yield and cane yield and genotype x environment interaction for all the traits except CCS yield (Table 1). The results indicated that genotypes responded differently across the six environments and the importance of testing genotypes in different locations rather than generations as against the current practice in order to maintain the high levels of genotype stability and wide adaptability.

The mean values of test genotypes and the checks for six traits across six environments indicate that the genotypes varied significantly for all the traits. CoN15071 and CoSnk 15102 genotypes recorded very high single cane weight compared to standards in all experiments except ratoon trial in Sankeshwar. On the contrary, PI 15131 recorded high single cane weight across the six experimental conditions except in ratoon crop of Sameerwadi. This indicated the superiority of these genotypes for single cane weight and differences in performance of genotypes in plant and ratoon crops over locations. For Brix% and Sucrose%, Co 11015 recorded highest values in each experiment and pooled across the six environments (24.53 and 22.48%) which was numerically higher than two best standards CoC 671 (24.27 and 22.26%) and Co 09004 (24.12 and 21.97%) indicating the potential of this variety for sugar quality. Similarly for CCS%, a derived parameter of brix and sucrose, Co 11015 recorded higher values in individual plant seasons over two locations and pooled across the seasons.

Mean performance of genotypes for CCS yield indicated that two varieties, Co 15017(17.50 t/ha) and CoN 15071 (17.14 t/ha) recorded very high pooled mean CCS yield across six environments. Co 15006 clone recorded high pooled mean CCS yield (16.70 t/ha). Mean CCS yield among two locations across three seasons revealed no much difference for genotypic performance between Sankeshwar and Sameerwadi. Co 15009 performed better in plant crops in both locations in individual experiments but recorded poor CCS yield in ratoon crop in both Sameerwadi and Sankeshwar. These results of poor performance in ratoon crop is in accordance with Mehareb et al. (2016) reporting general tendency of ratoon crops to yield 10–30% lesser than the plant crop of sugarcane that can be attributed to low and differential ratooning potential of genotypes, increased disease and insect infestation, poor crop husbandry practices and inherent genetic make-up of the cultivars. For cane yield, Co 15009 (125.46 t/ha) recorded highest mean cane yield values across six experiments, which is numerically higher when compared to all three standards. Two clones, namely, Co 15017 (122.96 t/ha) and CoSnk 15102 (122.59 t/ha) recorded higher mean cane yield as compared to three standards across the six experimental conditions. Mean cane yield of sugarcane was higher in Sameerwadi as compared with Sankeshwar, indicating that it is more suitable for the cultivation of sugarcane which could be attributed to soils, climate and many other factors contributing for higher yields in Sameerwadi region.

Stability parameters, regression coefficients, and deviation from regression indicated that CoSnk 15102 ranked first for CCS yield and was found to be highly stable across the six environments as revealed from regression values and deviation from the regression followed by Co 15009. For cane yield, Co 15009 found to be highly stable. Finlay and Wilkinson (1963) and Eberhart and Russell (1966) considered genotypes with high mean yield, coefficients of regression equivalent to unity (bi=1) and deviation from regression proximate zero (S^2di=0) to be stable. Although, Co 15017 and CoN 15071 have recorded very high CCS and cane yield across the six environments, they found to be unstable due to very high S^2di values. Similar results of poor stability of high yielding sugarcane genotypes have been reported earlier (Tahir et al. 2013; Guddadamath et al. 2014) for cane yield. This could be due to the wide differences in both edaphic and climatic conditions prevailed at two locations of the experiment. However, the unstable high yielding genotypes, Co 15017 and CoN 15071, have higher yields than the other stable genotypes at two locations. This indicates that stability analysis alone is insufficient to decide which genotypes to recommend in certain locations without considering the average performance of such genotypes (Ali et al. 2020).

Biplot analysis for Determination of Environmental Influence

AMMI incorporates ANOVA and PCA into a single model, enabling a simple visual interpretation of the GE interaction. It enables the clustering of genotypes based on the similarity of response characteristics and identifying potential trends across environments (Bocianowski et al. 2019). AMMI model for CCS yield and cane yield showing the means of genotypes (G) and environments (E) against their respective IPCA scores are presented in Table 2. The AMMI model for CCS yield and cane yield extracted six significant ($p<0.001$) IPCAs from the interaction component. These six IPCAs accounted a total 100 and 99.9% of the interaction sum

Table 1. Analysis of variance for cane yield and quality traits in different Seasons

Seasons	Source of Variation	DF	Mean Sum of Squares for different traits					
			Single cane weight	Brix	Sucrose%	CCS%	CCS yield	Cane yield
I Plant Sameerwadi	Replication	2	0.029	0.301	0.253	0.334	1.107	0.837
	Treatment	14	0.151**	2.746**	2.759**	2.719**	3.107**	2.378*
	Error	28	0.043	1.000	1.000	1.000	1.000	1.000
II Plant Sameerwadi	Replication	2	0.030	0.611	0.121	0.051	4.586	4.308
	Treatment	14	0.108**	254.238**	209.795**	141.885**	3.915**	4.048**
	Error	28	0.019	1.003	1.009	1.005	1.000	1.000
Ratoon Sameerwadi	Replication	2	0.014	0.060	0.054	0.080	0.574	0.489
	Treatment	14	0.127**	284.331**	363.674**	222.160**	5.280**	5.654**
	Error	28	0.018	0.999	1.003	0.996	1.000	1.000
I Plant Sankeshwar	Replication	2	0.043	4.422	4.410	3.153	0.933	0.315
	Treatment	14	0.235**	9.599**	10.291**	7.513**	3.299**	5.374**
	Error	28	0.036	1.000	1.000	1.000	1.000	1.000
II Plant Sankeshwar	Replication	2	0.004	0.371	2.657	3.298	1.676	0.230
	Treatment	14	0.214**	5.573	4.649**	4.168**	2.475*	2.373*
	Error	28	0.045	1.001	1.000	1.000	1.000	1.000
Ratoon Sankeshwar	Replication	2	0.080	0.704	3.743	7.860	6.697	12.449
	Treatment	14	0.183**	3.520**	4.664**	4.505**	10.993**	13.146**
	Error	28	0.028	0.999	1.000	1.000	1.000	1.000
Combined Analysis of Variance for pooled data	Seasons	5	1.301**	241,698**	196,512**	1,01,894**	356.12**	444.21**
	Replications within seasons	12	0.033	1.07	1.873	2.46	2.59	3.10
	Treatments	14	0.397**	213.77**	219.96**	146.15**	7.17**	11.07**
	Genotype x Environment	70	3.960**	69.24**	75.17**	47.35**	4.37^{NS}	4.38**
	Pooled error	168	0.031	1.000	1.002	1.000	1.000	1.000

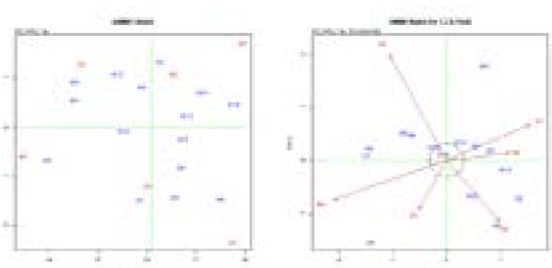
Table 2. AMMI model for CCS yield and Cane yield showing the means of genotypes (G) and environments (E) against their respective IPCA1 scores

S.No	Genotype	Mean CCS yield	AMMI PC scores for CCS yield		Mean Cane yield	AMMI PC scores for Cane yield	
			IPCAg1	IPCAg2		IPCAg1	IPCAg2
G1	Co 11015	15.86	-1.488	0.101	101.46	-3.233	0.442
G2	Co 14005	16.27	1.340	-0.712	113.52	1.961	-1.763
G3	Co 15005	14.53	0.931	-1.227	98.95	1.434	-3.226
G4	Co 15006	16.57	-1.427	-1.547	117.17	-2.233	-3.225
G5	Co 15007	15.89	0.815	0.200	107.11	2.321	0.314
G6	Co 15009	16.70	-0.812	0.523	125.46	-3.205	0.341
G7	Co 15010	14.53	0.543	0.280	109.13	1.692	0.179
G8	Co 15017	17.50	-1.448	0.226	122.96	-5.492	1.123
G9	Co 15021	13.96	-0.659	0.476	97.00	-0.821	1.750
G10	CoSNK 15102	16.75	-0.238	0.259	122.59	-0.727	0.887
G11	CoN 15071	17.14	0.713	1.785	121.98	2.872	5.257
G12	PI 15131	15.40	1.087	-0.174	111.72	2.174	-1.371
G13	Co 86032	16.82	0.243	0.353	118.73	1.455	0.416
G14	CoC 671	15.53	-0.068	0.121	99.55	0.533	0.918
G15	Co 09004	17.79	0.468	-0.664	115.44	1.269	-2.043
E1	I Plant (Sameerwadi)	13.49	-0.593	-1.032	106.65	-1.616	-2.429
E2	II Plant (Sameerwadi)	17.77	-2.337	-0.824	130.99	-7.000	-1.761
E3	Ratoon (Sameerwadi)	16.03	-1.189	2.228	116.55	-1.413	6.781
E4	I Plant (Sankeshwar)	17.97	1.726	0.755	113.34	4.175	0.966
E5	II Plant (Sankeshwar)	16.55	1.090	-1.283	114.52	3.076	-2.760
E6	Ratoon (Sankeshwar)	14.67	1.304	0.157	91.05	2.778	-0.797

of squares. The extracted IPCAs are capable of providing information on the interaction effect, although their degree decreases from the first to the last IPCAs. However, the first two IPCAs could best explain the interaction sum of squares (Zobel et al. 1988). Accordingly, the first two IPCA's (IPCA1 and IPCA2) were highly significant and accounted for 77.9% (53.1 and 24.8%) and 77.8% (50.9 and 26.9%) of variance. The AMMI methods are commonly used in a breeding program of sugarcane (Mehareb et al. 2022).

Genotype adaptability and stability

AMMI biplot for CCS yield drawn using PC Vs CCS yield (Fig. 1a) and PC1 Vs PC2 (Fig. 1b) indicated E4 and E5 as the favorable environments, whereas E1, E2, E3, and E4 as poor environments. Similarly, G11, G13 and G15 are rated as the better performer genotypes for the trait, while G14, G9 and G1 are rated as the poor performer genotypes. Genotypes G13, G14, and G10 are located near the origin in the PC1 Vs PC2 biplot and are stable performers for CCS yield. Hence they have better adaptation across the environments. AMMI biplot for cane yield using PC1 Vs cane yield (Fig. 2a) and PC1 Vs PC2 (Fig. 2b) indicated E2, E3, E4 and E5 as the favorable environments, whereas E1 and E6 as poor environments. G11, G13 and G15 are rated as the better performer genotypes for the cane yield, while G9 and G1 are rated as the poor performer genotypes. Genotypes G10, G14 and G13 are located near the origin in the PC1 Vs PC2 biplot and are stable performers with better adaptation across the environments for cane yield



(a) (b)

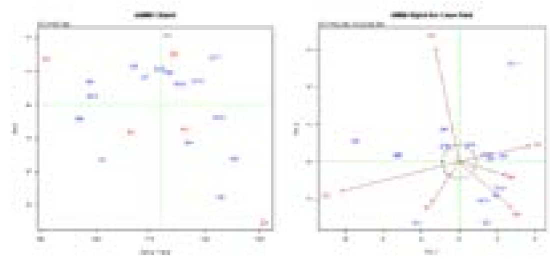
Fig. 1. (a) AMMI biplot PC1 Vs CCS yield); (b) AMMI Biplot PC1 Vs PC2 for CCS yield. G = Genotypes (1–15) and E = Environments (1–6). The genotypes are shown as G1-G15 and environments as E1-E6 and their full names are displayed in Table 3

GGE Biplot analysis for CCS yield and cane yield

The GGE biplot analysis is a very useful statistical tool in examining the aggression of the genotype by environment (GE) interaction as well as identifying mega environments and superior genotypes. GGE biplot tools (Yan and Tinker 2006) were used to evaluate the sugarcane MET for identifying the most promising candidate genotypes. It is a scatter plot that graphically shows both the genotypes and environments of two-way data for picturing the mega environments, ranking the genotypes, and identifying stable environments (Yan 2002). The main effect of genotype (G) and G×E interactions is the principal source of variation in the assessment of the genotypes under multi environment trials (MET) (Yan et al. 2000). GGE-biplot model for cane yield and CCS yield showing the means of genotypes (G) and environments (E) against their respective IPCA scores are presented in Table 3. GGE analysis for CCS yield revealed significant proportion of variation explained by first two principal components (41.91 and 24.7%) with accumulated variance of 66.61%. For cane yield, first (42.5%) and second (28.6%) principal components revealed major variation with an accumulated variance of 71.1%. These values indicate that the variability due to GEI is adequately represented, implying differential response of genotypes to environments (Elbasyoni 2018) and analysis of G × E interaction in different environments is very informative for selecting, evaluating, and recommending crop varieties.

GGE biplot Pattern of mean vs stability for ideal genotype assessment

The 'Mean vs. stability' view helps to simplify the genotype assessment based on the mean performance and stability



(a) (b)

Fig. 2. (a). AMMI biplot PC1 Vs cane yield; (b). AMMI Biplot PC1 Vs PC2 for cane yield (t ha^{-1}); Where G = Genotypes (G1-G15) and E = Environments (E1-E6).

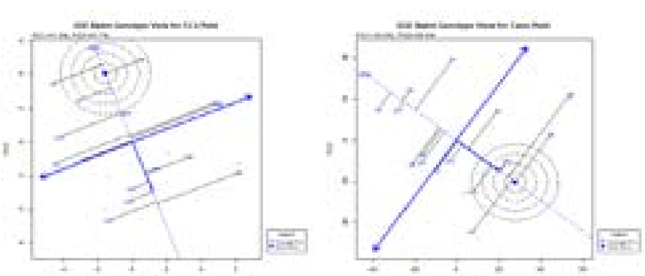
Table 3. GGE model for CCS yield and cane yield showing the means of genotypes (G) and environments (E) against their respective IPCA1 scores

S.No	Genotype	Mean CCS yield	GGE PC scores for CCS yield		Mean cane yield	GGE PC scores for Cane yield	
			IPCAg1	IPCAg1		IPCAg1	IPCAg2
G1	Co 11015	15.86	-4.846	-2.327	101.46	1.978	-39.215
G2	Co 14005	16.27	4.478	1.252	113.52	9.613	14.344
G3	Co 15005	14.53	4.601	-3.475	98.95	37.408	-14.830
G4	Co 15006	16.57	-5.086	-2.298	117.17	-19.489	-14.578
G5	Co 15007	15.89	2.852	1.047	107.11	21.567	11.803
G6	Co 15009	16.70	-3.328	0.860	125.46	-44.996	-2.934
G7	Co 15010	14.53	3.131	-2.461	109.13	16.539	7.020
G8	Co 15017	17.50	-6.183	1.795	122.96	-53.888	-22.361
G9	Co 15021	13.96	-0.513	-4.880	97.00	22.226	-24.524
G10	CoSNK 15102	16.75	-1.418	1.531	122.59	-23.752	9.750
G11	CoN 15071	17.14	1.403	4.656	121.98	-7.459	44.456
G12	PI 15131	15.40	4.270	-0.279	111.72	16.786	10.545
G13	Co 86032	16.82	0.061	2.775	118.73	-7.837	24.863
G14	CoC 671	15.53	0.339	-1.717	99.55	27.914	-14.538
G15	Co 09004	17.79	0.239	3.520	115.44	3.389	10.196
E1	I Plant (Sameerwadi)	13.49	-0.260	0.083	106.65	-0.271	-0.100
E2	II Plant (Sameerwadi)	17.77	-0.759	0.159	130.99	-0.816	-0.312
E3	Ratoon (Sameerwadi)	16.03	-0.458	0.421	116.55	-0.480	0.264
E4	I Plant (Sankeshwar)	17.97	0.279	0.699	113.34	-0.151	0.720
E5	II Plant (Sankeshwar)	16.55	0.171	0.251	114.52	-0.053	0.400
E6	Ratoon (Sankeshwar)	14.67	0.199	0.489	91.05	-0.065	0.381

under a wide range of environments. In present investigation, the 'mean vs. stability' pattern of GGE biplot for CCS yield (Fig. 3a) revealed that the Average Environment Co-ordinate (AEC) abscissa line directed the ranking of genotypes in increasing order with a greater value of traits evaluated. Co 15010 (G7) was identified as ideal genotype with higher mean and good stability followed by Co 15021 (G9) across the six locations for CCS yield. Co 15017 (G8) genotype with high mean grain yield falling out of the concentric circle and lengthy direction from the AEC abscissa found relatively unstable across locations. For cane yield (Fig. 3b) CoSnk 15102 (G10) was identified as stable genotype across six experimental conditions followed by standard variety Co 86032 (G13). However, Co 15017 (G8) with high cane yield found to be unstable across locations due to lengthier directions from AEC abscissa and falling out of concentric circle. Yan (2014) reported that high yielding but less stable genotypes may be mistakenly discarded if too much weight is given to instability during selection. Assessment of genotypes under different environments is essential to study the quantitative traits and to measure the stability and adaptability. Yield is a very complex trait which is highly influenced by environments. Further, to evaluate multi-environment data effective use of both models is recommended by Gauch and Zobel (1988). Although GGE biplot procedure has been used in stability studies of several annual crops, GGE the procedure has been used in stability studies of several annual crops including peanut (Lal et al. 2021) and pearl millet (Reddy et al. 2022), it has been used in limited occasions for perennials like sugarcane. The discrimination and representativeness view of the GGE biplot to show the discriminating ability and representativeness of the test environments has been studied in perennial crop like tea (Kottawa-Arachchi et al. 2022). Verma et al. (2023) carried out an experiment on 24 sugarcane (*Saccharum officinarum* L.) varieties to ascertain the Gene × Environment interaction (GEI), yield stability and adaptability of across three locations through AMMI and GGE biplot analysis. AMMI analyses revealed significant ($P < 0.01$) genotype and environmental effects as well as G × E with respect to cane yield. GGE-biplot model showed that the three environments belonged to three mega-environments as an obtuse angle was observed between the environments. The analysis facilitated the select the most productive varieties with stable yield from specific test environments. A good strategy to improve the selection is simultaneous selection for yield and stability (Orlando et al. 2023). Genotypes and Genotype x Environment interaction studies help to assess and make recommendations on potential new cultivars depending on their yield potential and stability (Luo et al. 2015).

GGE biplot ('which-won-where' pattern)

Which-won-where GGE-biplot polygon is an important component of GGE analysis. These figures are separated by an equality line into sectors in which dissimilar mega environments can be noticed (Yan and Tinker 2005; Yan and Tinker 2006). Fig. 4 illustrates the which-won-where' pattern of GGE biplot for CCS yield (4a) and cane yield per hectare (4b). The vertex clones are the extreme genotypes in GGE biplot, signifying the best performers in all or some of the environments (Tollo et al. 2020). The Which-won-where graph shown in Fig. 4a shows that the three locations fall into first mega environment (E1-E3) and next three locations fall into second mega environment (E4-E6). The genotype Co 15017(G8) on the vertex of the polygon containing first three environments of Sameerwadi performed best for CCS yield and was the winning genotype in Sameerwadi. While, CoN 15071 (G11) on the polygon vertex containing next three mega environments were the winning genotype at Sankeshwar across two plant and a ratoon crop. Similarly for cane yield, two clones Co 15017 (G8) and Co 15009 (G6) were winning genotypes for cane yield per hectare at Sameerwadi over two plant and ratoon crop. CoN 15071 (G11) was winning genotype at Sankeshwar for cane yield across two plant and one ratoon crop. Co 15005 (G3) genotype that is linked with polygon vertex where no environment indicator drops in the sector indicated that this genotype is poorly performed across the three crops in both Sameerwadi and Sankeshwar. The detection of different sugarcane genotype winners in



(a) (b)

Fig. 3. Mean versus stability assessment of GGE biplot showing the rank of 15 sugarcane genotypes for CCS yield (a) and cane yield (b). The genotypes are shown as G1-G15 and environments as E1-E6 and their full names are displayed in Table 3

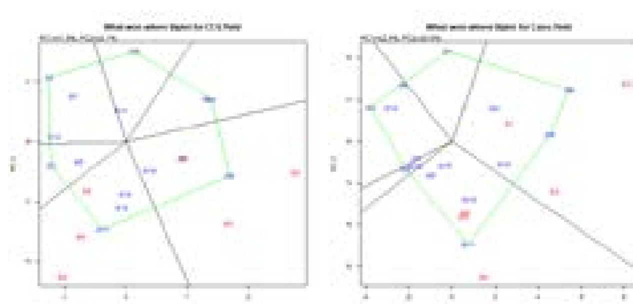


Fig. 4. Which-won-where view of 15 sugarcane genotypes for CCS yield (a) and cane yield (b) over two locations and three crop cycles. The genotypes are shown as G1-G15 and environments as E1-E6 and their full names are displayed in Table 3

the mega-environments indicated the presence of crossover as revealed by differential yield ranking and stability across environments (Mattos et al. 2013; Xu et al. 2014; Orlando et al. 2023). Hence, selection strategy to be firstly oriented toward selecting genotypes adapted to specifically targeted environments to enhance the mean productivity rather than selecting for broad adaptation (Xu et al. 2014; Akhter et al. 2015; Guilly et al. 2017; Muhammad et al. 2019).

Sugarcane clones, Co 15017 and CoN 15071 were highly productive with high CCS and cane yield but relatively unstable across six environments. AMMI and GGE biplot indicated that two clones, Co 15010 and Co 15021 were highly stable for CCS yield and CoSnk 15102 and Co 86032 were highly stable for cane yield across six experimental conditions. The results of these multi environmental trials with the elucidation of genotype and environmental interaction using AMMI and GGE are of significance in guiding the selection and recommendation of stable and superior sugarcane varieties in sugarcane production zones.

Authors' contributions

Conceptualization of research (AY); Designing of the experiments (AY); Contribution of experimental materials (HG); Execution of field/lab experiments and data collection (AY, BYK, SBP); Analysis of data and interpretation (AY, ADK); Preparation of the manuscript (AY).

References

Akter A., Hasan M. J., Kulsum U., Rahman M. H., Khatun M. and Islam M.R. 2015. GGE biplot analysis for yield stability in multi-environment trials of promising hybrid Rice (*Oryza sativa* L.). Bangladesh Rice J., **19**(1): 1-8.

Ali M. A., Hassan M. S., Mohamed B. D. and Ali M. H. 2020. Performance and stability analysis of some sugarcane genotypes across different environments. SVU Int. J. Agric. Sci., **2**(2): 192 -213, 2020.

Anonymous 2023. Press Information Bureau, Ministry of Consumer Affairs, Government of India.

Bocianowski J., Niemann J. and Nowosad K. 2019. Genotype-by-environment interaction for seed quality traits in interspecific cross derived *Brassica* lines using additive main effects and multiplicative interaction model. Euphytica, **215**: 7.

Crossa J. and Cornelius P. L. 1997. Sites regression and shifted multiplicative Model clustering of cultivar trials sites under heterogeneity of variances. Crop Sci., **37**: 406–415.

Crossa J., Cornelius P. L. and Yan W. 2002. Biplots of linear-bilinear models for studying cross over genotype × environment interaction. Crop Sci., **42**: 619–633.

Eberhart S. A. and Russel W. A. 1966. Stability parameters for comparing varieties. Crop Sci., **6**: 36-40.

Elbasvoni I. S. 2018. Performance and stability of commercial wheat cultivars under terminal heat stress. Agron., **8**(4):37.

Finlay K. W. and Wilkinson G. N. 1963. The analysis of adaptation in a plant-breeding program. Aust. J. Agri. Res., **14**: 742-754.

Gauch H. G., Piepho H. P. and Annicchiarico P. 2008. Statistical analysis of yield trials by AMMI and GGE: further considerations. Crop Sci., **48**: 866-889.

Gauch H. and Zobel R. 1988. Predictive and post dictive success of satistical analysis of yield trials. Theor. Appl. Genet., **76**: 1-10.

Gauch H. G. and Zobel R. W. 1997. Identifying mega-environments and targeting genotypes. Crop Sci., **37**: 311-326.

Gauch H. G. 2006. Statistical analysis of yield trials by AMMI and GGE. Crop Sci., **46**: 1488-1500.

Guddadamath S. S., Patil S. B. and Khadi B. M. 2014. Stability analysis of cane and jaggery yield in elite sugarcane genotypes (Saccharum spp.). Indian J. Genet. Plant Breed., **74**(2): 261-264.

Guilly S., Dumont T., Thong-Chane A. Barau L. and Hoarau Y. 2017. Analysis of multi-environment trials (MET) in the sugarcane breeding program of Reunion Island. Euphytica, **213**(9): 213.

Huehn M. 1990. Nonparametric measures of phenotypic stability. Part 1: theory. Euphytica, **47**: 189-194.

Kang M. S. 1993. Simultaneous selection for yield and stability in crop performance trials: consequences for growers. Agron. J., **85**: 754–757.

Kaya Y., Akcura M. and Taner S. 2006. GGE biplot analysis of multi-environment yield trials in bread wheat. Turk. J. Agric., **30**: 325-337.

Kottawa-Arachchi, J.D., Ranatunga, M.A.B., Abeysiriw ardena D.S. de Z. 2022. Utilization of within location non-replicated multi-locational yield trials and GGE biplot methods for testing adaptability of tea [(*Camellia sinensis* (L.) O. Kuntze)] over diverse environments. Indian J. Genet. Plant Breed., **82**(3): 342-349. doi: 10.31742/ISGPB.82.3.9

Lal C., Ajay B. C. and Rupapara K. V. 2021. AMMI and GGE models indicating seasonal variations as major source of variations for nodulation related characters in peanut. Indian J. Genet. Plant Breed., **81**(2): 277–288. DOI: 10.31742/IJGPB.81.2.10.

Lin C. S. and Binns M. R. 1988. A superiority measure of cultivar performance for cultivar 9 location data. Can. J. Plant Sci., 68: 193-198.

Luo J., Pan Y. B., Xu L., Grisham M. P., Zhang H. and Que Y. 2015. Rational regional distribution of sugarcane cultivars in China. Scientific Reports, **5**(1): 1-10.

Mattos P. H. C., Oliveira1 R. A. J., Filho C. B., Daros E. and Veríssimo M. A. A. 2013. Evaluation of sugarcane genotypes and production environments in Paraná by GGE biplot and AMMI analysis. Crop Breed. Appl. Biotechnol., **13**: 83-90.

Mehareb E. M., Salah F., Elwafa A. and Mohamed O. A. G. 2016. Mean performance and ratooning ability of sugarcane promising genotypes at early clonal selection. Amer. Eur. J. Agric. Environ. Sci., **16** (1): 20-27.

Mehareb E. M., Osman M. A. M., Attia A. E., Bekheet M.A., Fouz F. M., Abo Elenen. 2022. Stability assessment for selection of elite sugarcane clones across multi-environment based on AMMI and GGE-biplot models. Euphytica, **218**: 115.

Muhammad K. and Khan F. A. 2007. Genetic Divergence in sugarcane (Saccharum officinarum L.) based on yield and yield qualities. Pakistan J. Bot. **39**(5): 1559-1563.

Orlando C. A., Aliya M., Hardev S. S., Sushma S., Wayne D., Miguel B. and Duli Z. 2023. Selection of New Sugarcane Genotypes for Sandy Soils in Florida with Enhanced Sucrose Content. Agriculture, **13**(5): 1-21.

PB Tools, version 1.4. 2014. Biometrics and Breeding Informatics, California, CA, USA, PBGB Division, International Rice Research Institute.

R Core Team. 2012. R: A Language and Environment for Statistical Computing. Vienna: R Foundation for Statistical Computing.

Reddy P. S., Satyavathi C. T., Khandelwal Patil H. T., Narasimhulu R., Bhadarge H. H., Iyanar K., Talwar A. M., Sravanthi K. and Athoni B. K. 2022. GGE biplot analysis for identification of ideal cultivars and testing locations of pearl millet (*Pennisetum glaucum* L.R. Br.) for peninsular India. Indian J. Genet. Plant Breed., 82(2): 167–176. DOI: 10.31742/IJGPB.82.2.5.

Regis J. A. V. B., Andrade J. A. C., Santos A., Moraes A., Trindade R. W. R., Henriques H. J. R., and Oliveira L. C. 2018. Adaptability and phenotypic stability of sugarcane clones. Pesquisa Agropecuária Brasileira, **53**(1): 42-52.

Tahir M., Rahman H., Amjad A., Anwar S. and Khalid M. 2013. Assessment of genotype × environment interaction and stability of promising sugarcane genotypes for different agronomic characters in Peshawar valley. Amer. J. Exp. Agric., **3**(1): 142-151.

Tollo J. A., Okwiri P. P. O., Karimi R., Mafurah J. J. and Nzioki H. S. 2020. Genotype-by-environment interaction and stability of resistance in mungbean landraces against common bacterial blight across semi-arid environments. Euphytica, **216**: 175.

Verma O.N., Rastogi N.K., Sinha S.K., Salam J.L., Singh P.K. 2023. Genotype × Environment interaction for cane yield of sugarcane varieties (*Saccharum officinarum* L.) in the three agro-climatic zones of Chhattisgarh. Indian J. Genet. Plant Breed., **83**(1): 114-121. doi: 10.31742/ISGPB.83.1.14

Wolde L., Keno T., Tadesse B., Bogale G. and Abebe B. 2018. Megaenvironment targeting of maize varieties using AMMI and GGE-biplot analysis in Ethiopia. Eth. J. Agric. Sci., **28**: 65–84.

Xu F., Tang F., Shao Y., Chen Y., Tong C. and Bao J. 2014. Genotype × Environment interaction for agronomic traits of rice revealed by Association Mapping. Rice Sci., **21**(3): 133-141.

Yan W. and Kang. M. S. 2003. GGE Biplot Analysis: a Graphical Tool for Breeders, Geneticists and Agronomists. Boca Raton, FL: CRC Press.

Yan W. and Holland J. B. 2010. A heritability-adjusted GGE biplot for test environment evaluation. Euphytica, **171**: 355–369.

Yan W. and Tinker N. A. 2005. An integrated biplot analysis system for displaying, interpreting, and exploring genotype and environment interaction. Crop Sci., **45**: 1004–1106.

Yan W. and Tinker N. A. 2006. Biplot analysis of multi-environment trial data: principles and applications. Can. J. Plant Sci., **86**(3): 623-645.

Yan W., Hunt L., Sheng Q. and Szlavnics Z. 2000. Cultivar evaluation and mega-environment investigation based on the GGE-biplot. Crop Sci., **40**: 597-605.

Yan W., Kang M. S., Ma B., Woods S. and Cornelius P. L. 2007.GGE biplot vs. AMMI analysis of genotype-by-environment data. Crop Sci., **47**: 643-655.

Yan, W. Singular-Value Partitioning in Biplot Analysis of Multi environment Trial Data. 2002. Agron. J., **94**: 990–996.

Yusuff O., Mohd Y. R., Norhani A., Usman M., Gous M., Ghazali H. and Asfaliza R. 2017. Genotype × Environment interaction and stability analyses of yield and yield components of established and mutant rice genotypes tested in multiple locations in Malaysia, Acta Agric. Scand. B Soil Plant Sci., **67**(7): 590-606,

Zobel R.W., Wright M.J. and Gauch H.G. 1988. Statistical analysis of a yield trial. Agron. J., **80**: 388-393.