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Genotypes x environment interactions and stability analysis of sugarcane clones (*Saccharum* spp.) by AMMI model in sub-tropical regions of India

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Abstract

Fifteen elite sugarcane clones along with five zonal standard varieties were evaluated under four production environments in the sub-tropical climate. AMMI model was employed to assess the magnitude of Genotype x environment (GE) interaction and the stability of sugarcane clones across environments. AMMI analysis revealed the significant difference among tested clones and environments. It has shown 43.17% of the variation in cane yield which could be attributed to environmental effects. The genotypic effects accounted for 45.76% variation with 11.06% of GEI effects. The early maturing high sugar varieties, Co 0238 and Co 0118 gave 89.27 t/ha and 80.11 t/ha cane yield, respectively and thus considered as widely adapted genotypes across the environments and can be recommended for commercial cultivation in sub-tropical region. Co 98014 and Co 05011 exhibited better adaptability in ratoon trials and appeared to be suitable for multiple ratoon. Considering IPCA score, CoS 767 was most stable standard (check) across the environments. With regards to the environments, E2 (spring season plant crop) and E1 (autumn season plant crop) placed on the upper right half of perpendicular axis of AMMI biplot due to the positive interactions and hence both E2 and E1 are the favourable environments for obtaining higher cane yield.

Key words: *Saccharum* spp., AMMI biplot, adaptability, stability, sub-tropical India.

Introduction

Sugarcane (*Saccharum* spp.) is one of the most important cash crop, cultivated both in the tropical- and sub-tropical states of India. It plays a significant role in Indian economy, contributing 346.72 mt of sugarcane production and 25.2 mt of crystal sugar production in the country during 2015-16 from the cropped area of 4.96 mha (DAC, 2016). Generally, sugarcane is cultivated widely through vegetative means (stem cutting) with great diversity among the cultivated species clones. In sub-tropical India, the production of sugarcane is lower than the tropical India due to the vagaries of climatic conditions prevailing in subtropical India, where the temperature ranges from 0 to 47^{o}C, photoperiod range from 4 to 8 h and humidity ranges from 8 to 100 per cent. The variations in climate are wide from crop growth to maturity stage. In the extreme weather conditions, the active growth of sugarcane restricted to 4-5 months only. Sugarcane breeders are aware of different performance of sugarcane cultivars in terms of cane yield which vary from region to region and diverse environments. It raises concern about the cultivars of sugarcane grown in different regions regarding their suitability for an ideal environment. Considering genotype x environment interaction (GEI), the genotypes should be planted in different environments (locations and years) in order to identify the best genotypes based on phenotypic performance for cane yield and quality. For the breeders' understanding, the factors that affect GEI are essential to implement an efficient selection process and sites for evaluation need to be selected. The identification of widely adaptive and high yielding genotypes require more time and resources due to the strong presence of genotype x environment interaction. The complexity of GEI makes difficult for breeders to recommend superior genotypes. Therefore, the identification and selection of location specific adaptive sugarcane genotypes are expected to

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maximize the sugarcane production. If G x E accounts for a significant portion of variation in yield trials (Khan et al. 2013), proper statistical tool should be employed while recommending and release of varieties for commercial cultivation. Further, estimation of GE is an important and essential component in breeding for varietal development. Several statistical models such as linear regression analysis, non-regression analysis, multivariate analysis, etc. are available to estimate the effects of G x E interaction for selection of varieties and prediction of phenotypic response to environmental changes. But the additive main effects and multiplicative interaction effects (AMMI) model, which integrates analysis of variance to study the main effect of genotypes and environment and principal component analysis for residual multiplicative interaction among genotypes and environments is considered an efficient model. These stabilized models quantify the contribution of each genotype and environment to $SS_{G \times E}$ and provide an easy graphical representation of results by biplot technique to simultaneously classify genotype and environments (Zobel et al. 1988; Crossa et al. 1990; Gauch and Zobel 1996). In recent past, the quantification of G × E interactions and yield stability investigation involving sugarcane clones have been done through multivariate procedures, *i.e.*, principal component analysis, (Kumar et al. 2009; Guerra et al. 2009; Rea et al. 2011), two-table coupling method (Rea et al. 2016) and using non-parametric methods (Rae et al. 2015). Farmers in the sub-tropical region of India needs a high sugared and high yielding sugarcane variety which exhibits wider geographic adaptation under different planting environments. In view of the above, the study was conducted with the objective to evaluate the phenotypic adaptability and stability of elite sugarcane genotypes in the sub-tropical region of India by using AMMI model.

Material and methods

Experimental material and site

The experimental material comprised of seven elite sugarcane clones developed at ICAR-Sugarcane Breeding Institute, Regional Centre, Karnal, namely, Co 0241, Co 0121, Co 07023, Co 07024, Co 07025, Co 07026, Co 07027, eight newly released varieties of North Western Zone (NWZ) namely, Co 98014, Co 0118, Co 0124, Co 0237, Co 0238, Co 05010, Co 05009, Co 05011 and five zonal standards, namely, CoJ 64, Co 89003, CoS 8436, Co 1148 and CoS 767. These varieties were evaluated in randomized complete block design with three replications at the institute's research farm under four environments *viz*., plant autumn (Oct 2009-10), plant spring (March 2010-11), ratoon autumn (2010-11) and ratoon spring (2011-12). The plot size per clone was 10.8 sqm *i.e*., 2 rows x 6 m length x 0.9 m between rows. The cultural practices as recommended for NWZ were adopted to raise good crop.

Data recording and statistical analysis

The plant crops were harvested 12 month after planting and its ratoon *i.e.*, autumn initiated ratoon (from Oct. 2010 harvested crop) and spring initiated ratoon (from Feb. 2011 harvest) were allowed to grow. The ratoon crop was harvested at the age of 10^{th} month. Data on cane yield (t/ha), number of millable canes (NMC), single cane weight (SCW) was recorded. Five randomly selected canes from each entry were initially weighed for recording SCW (kg). The juice was extracted in the crusher and was clarified using lead sub acetate. Juice quality parameters such as brix % in the clarified raw juice, sucrose % in juice, purity % in juice were estimated at 10^{th} and 12^{th} month using the standard procedures (Chen 1985). From the above data, commercial cane sugar% (CCS%) at 10^{th} and 12^{th} month and commercial cane sugar yield (CCS yield-t/ha) at $10^{th}/12^{th}$ month were computed as per Chen and Chou (1993). The data of two plant crop and two ratoon were treated as four environments and the effect of sugarcane clones in each environment and their interaction were assessed.

AMMI analysis

An initial analysis of variance was performed for each environment to verify the existence of differences between varieties. After these analyses, the homogeneity between residual variances was determined, and a joint analysis of variance was performed to test the effects of genotype (clones), environments (season, crop type), and the magnitude of the G x E interaction. AMMI analysis as described by Zobel et al. (1988) was used to estimate the main or additive effects of genotypes and environments by analysis of variance and multiplicative effects for the G x E interaction through principal component analysis (PCA).

The sum of squares of the G × E interaction was divided into an *n* singular axis or interaction principal component axis (IPCA), which reflects the standard portion in which each axis corresponded to a particular AMMI model. The AMMI model that best describes the G x E interaction was chosen based on the FR test given by Cornelius et al. (1992). After selecting the best fit AMMI model, the adaptability and phenotypic stability was investigated using biplot graphs. Biplot graph interpretation is based on the variation of the additive main effects (genotype and environment) and the multiplier effects of the G x E interaction. The abscissa represents the main effects (average of clones evaluated), and the ordinate represents the interaction among the axes (IPCA). In this case, the lower IPCA value (absolute value) represents the lower the contribution of the G × E interaction and greater genotype stability. An ideal genotype is the one with a high yield and IPCA values close to zero. An undesirable genotype would have low stability associated with low productivity (Ferreira et al. 2006). Finally, the predictive averages were estimated according to the selected model. All statistical analyses were conducted using SAS Software version 9.0.

Results and discussion

Analysis of variance

Analysis of variance for cane yield revealed highly significant differences among genotypes, environment and their interactions. Mean square differences were also significant for genotypes showing that the differences among the genotypes were persistent over the environments. The significant effect of the G x E interaction showed that genotypes had high variable performance in the tested environment. The change in relative ranking of genotypes resulted from GEI (Genotype Environment Interaction), implying that genotypes responded differently to the environmental conditions justifying the conduction of more refined analysis in multi-environment trial to understand the stability of these genotypes. Tahir et al. (2013) and (Queme et al. 2005) analyzing sugarcane genotypes for stability under different environments reported that genotypes responded differently due to G x E interaction. The AMMI analysis showed that the variation in cane yield could be almost equally attributed by the genotypes effects (45.76%) and environmental effects (43.17%), whereas the GEI effects contributed 11.06% effect on cane yield (Table 1). This response to environmental and genotypic effects coincides with those found by Rea et al. (2011). A large sum of square for environments indicated that environment were diverse and caused large variation in the cane yield. Rea et al. (2017) also found that in sugarcane the genetic variation for cane yield is largely attributed by genotypic and environmental effects.

The G x E Interaction variance (11.06%) was further partitioned into Interaction Principal Component Axes (IPCAs). Four IPCA axes were found to be adequate to explain the entire G x E variance. The IPCA-1 has accounted for 53.62% and IPCA-2 for 36.72%, both together accounted for 90.34% of the total variance. The value explained by these first two IPCAs presents the same magnitude as those found by Guerra et al. (2009). In view of this, the IPCA I and IPCA II axes of AMMI-I model were selected for drawing AMMI I biplot. Similarly, biplots of AMMI models for yield variable was generated using genotypic and environmental scores of the first two AMMI components (Rea et al. 2011). In the above AMMI I biplot (Fig. 1), the IPCA scores of 20 sugarcane clones and four different crop environments were plotted against their respective means. In the biplot-I display, clones and environment that falls on horizontal line are presumed to have similar mean yields and those that falls along the perpendicular line have similar interactions as reported by Crossa et al. (1990). Clones

Table 1. Combined ANOVA through AMMI model for cane yield of 20 sugarcane clones tested in 4 environments

Source	Df	SS	MS	AMMI	
				% Explained	% Accumulated
Environment (E)	3	21862.2	7287.39**	43.17	
Genotypes (G)	19	20625.0	1085.5**	45.76	
G x E	57	5280.23	92.63*	11.06	
IPCA 1	21	2831.75	134.84*	53.62	53.62
IPCA 2	19	1939.02	102.0	36.72	90.34
Residual	17	509.45	29.96	9.64	99.9
Error	160	9143.08	57.14		

NS, **,* non-significant and significant at P > 0.005 and P > 0.001 by F test, respectively

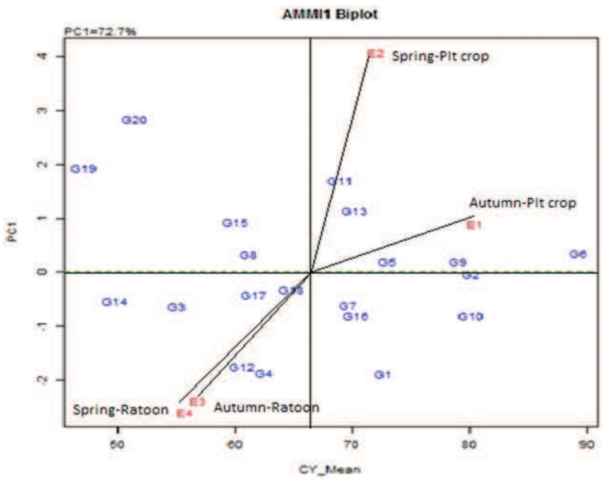

Fig. 1. AMMI I biplot (IPCA 1 x mean cane yield) showing the main effects of 20 sugarcane clones and 4 environments

or environment found on the right side of the midpoint of the perpendicular line have higher yield or mean than those on the left side. Further Zobel et al. (1988) also reported that the expected yield of any genotype and environment combination can be visualized in AMMI I biplot.

Out of 20 sugarcane clones, 10 clones have exhibited higher cane yield than that of average yield (65.23 t/ha) and falls on the right side of the midpoint of the perpendicular line. These clones in their increasing order of cane yield were: Co 0238 (G6-89.27 t/ha), Co 0118 (G2-80.11 t/ha), Co 05011 (G10-80.11 t/ha), Co 05009 (G9-78.96 t/ha), Co 0237 (G5-73.01 t/ ha), Co 98014 (G1-72.65 t/ha), Co 1148 (G16-70.24 t/ ha), and Co 07025 (G13-70.20 t/ha) as shown in Table 2. Value closer to the origin of the axis (IPCA1) provides a smaller contribution to the interaction than

Table 2. Average production of cane yield (tons/ha = TPH) of the 20 Sugarcane genotypes in each of four tested environments and overall average mean predicted by AMMI model

Label	Genotypes	Environments				Mean
		E[1]	E[2]	E[3]	E[4]	
G1	Co 98014	83.14	71.63	70.58	65.24	72.65
G2	Co 0118	94.28	83.65	70.33	68.16	80.11
G3	Co 0121	64.77	60.17	47.26	47.65	54.96
G4	Co 0124	76.26	59.92	57.76	55.99	62.48
G5	Co 0237	91.04	77.56	65.66	57.79	73.01
G6	Co 0238	104.75	95.89	80.69	75.77	89.27
G7	Co 05010	82.77	73.16	60.91	61.73	69.64
G8	Co 0241	74.16	69.00	50.92	50.29	61.09
G9	Co 05009	96.17	84.05	69.06	66.55	78.96
G10	Co 05011	88.87	84.98	72.94	73.64	80.11
G11	Co 07023	88.65	79.63	55.92	51.66	68.97
G12	Co 07024	77.13	57.20	52.66	55.24	60.56
G13	Co 07025	79.71	83.55	59.72	57.83	70.20
G14	Co 07026	62.51	53.77	41.90	40.71	49.72
G15	Co 07027	76.37	68.84	46.71	47.96	59.97
G16	Co 1148	84.80	72.17	62.27	61.70	70.24
G17	Co 89003	77.31	64.64	51.61	52.62	61.55
G18	CoS 767	73.61	71.98	54.56	59.21	64.84
G19	CoS 8436	64.09	60.17	31.99	31.99	47.06
G20	CoJ 64	66.06	70.05	35.00	34.78	51.47
	Mean	80.32	72.10	56.92	54.62	65.23

The underlined values indicates the genotypes with highest cane yield (t/ha) in the corresponding environment, E1-Autumn Plant crop, E2-spring plant crop, E3-Autumn ratoon and E4-Spring ratoon those are further away from the origin. Of these 10 entries exhibiting cane yield above the overall mean yield, Co 0237, Co 05009 and Co 0238 had low positive interaction with environments whereas, Co 05010, Co 1148, Co 0118 and Co 05011 had low negative interaction as evident from their low IPCA 1 scores. These clones were less influenced by environments hence they may be treated as having high adaptability to different environments or seasons.

Clones such as Co 98014, Co 07025 and Co 07023 had larger interaction effects because they falls almost on same perpendicular line and away from IPCA-1 axis origin. Nonetheless, their interactions were different. The plant crop of Co 07023 and Co 07025 have appeared to have positive interactions with autumn (E1) and spring (E2) seasons and resulted in high cane yield in comparison to their ratoon crop yield in E3 and E4. On the other hand Co 98014 had large negative interactions in E1 and E2 (plant crop) hence its plant crop was lower or its ratoon cane yield in E3 and E4 were on-par with that of plant crop yield (E1 and E2). Clones such as CoS 767, Co 89003, Co 0121, Co 07026, Co 07024, Co 0124, Co 0241, Co 07027, CoS 8436 and CoJ 64 were distributed on the left half of AMMI biplot I because of their lower mean yield. The IPCA score of CoS 767 was close to zero hence it was plotted near the origin of IPCA 1 axis. It shows that this variety had little interaction with environments and can be adjudged as the most stable variety, although its yield was slightly lower than the improved Co canes. CoS 767 is being cultivated on wide range of environment in subtropical states like Uttar Pradesh, Haryana, Punjab, Uttarakhand and Bihar, which could be attributed to its stability as evident from the results of present study. Varieties such as CoJ 64 and CoS 8436 larger interaction with environments and positioned far away from the IPCA origin point. They may give high cane yield only under selected environments/season and where the inputs are not limiting. Farmers who have access to high dose of fertilizers, other inputs and good growing environments may opt for these varieties.

With regards to environments (seasons and crop type), E2 *i.e.*, spring season plant crop and E1 *i.e.* autumn season plant crop have placed on the upper right half of the perpendicular axis due to its positive interactions and hence they are the favourable environments for higher cane yield. This might be one of the reason for higher cane yield of plant crop of spring and autumn planted sugarcane varieties comparison to the yield of ratoon. Similarly, the significant family and environment interaction was also observed for cane yield by Naing et al. (2016). In the present study, the environments E3 (autumn harvested ratoon) and E4 (spring harvested ratoon) had negative IPCA 1 scores and found to be limiting environment for achieving higher cane yield.

AMMI biplot analysis

To demonstrate the stability of genotype as well as the relative magnitude of interaction effects of each genotype and environment, AMMI II biplot were drawn using IPCA 1 and IPCA 2 scores (Fig. 2). Unlike

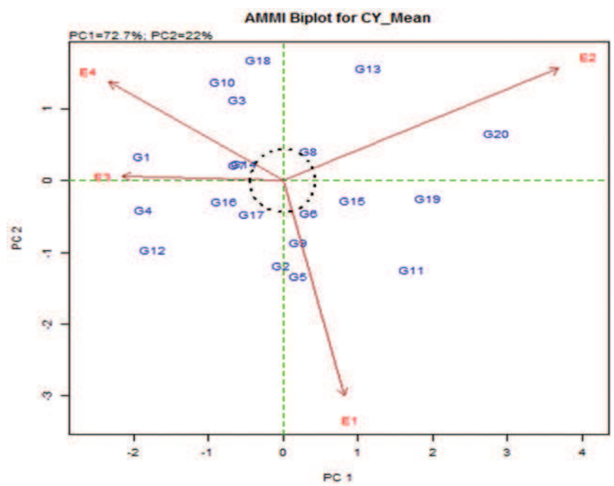

Fig. 2. AMMI II biplot (IPCA 1 x IPCA 2) depicting the genotype x environment interaction and stability of 20 sugarcane clones evaluated in 4 environments at Karnal

AMMI I, in AMMI II biplot the IPCA 1 and 2 scores were regarded as more stable when they are positioned at close proximity of the origin of AMMI II than genotypes located far away from the centre. According to the principle, the clones Co 0118 (G2), Co 0238 (G6), Co 0241 (G8), Co 05009 (G9), Co 05010 (G7), Co 07026 (G16), Co 07027 (G15), Co 89003 (G17) and Co 1148 (G16) confined closer to the origin point of AMMI II biplot have less interaction with environments. These clones may be regarded as stable one also identified stable clones through similar analysis. Silveira et al. (2012) and Dubey et al. (2017). However, cane yield of Co 07026 (49.72 t/ha), Co 07027 (59.97 t/ha), Co 0241 (61.09 t/ha) and Co 89003 (61.55 t/ha) were lower than the average yield of tested clones and therefore, do not qualify as high yielding stable clones. Barring these clones, other high yielding stable clones like Co 0118 (80.11 t/ha), Co 0238 (89.27 t/

ha), Co 05009 (78.96 t/ha), Co 05010 (69.64 t/ha) and Co 1148 (70.24 t/ha) may be recommended for cultivation in different seasons and environments in sub-tropical states. The clones were evolved by crossing tropical and subtropical parental pool and perhaps the wider parental diversity might have contributed for their adaptability (Aitken et al. 2010).

In the AMMI II biplot, the angle between the vectors of two environments or between genotypes and environment also throw lights on the relationship between the two (Gauch 2006, Yan and Kang 2003). The line that connect to test environments to the biplot origin are called environmental vectors and the vector length which indicate the discriminating ability of testing environments. Hence, Environments E1 (Autumn-plant crop) and E2 (spring-plant crop) were positively correlated and have the power to discriminate genotypes efficiently as evident from the longest vector distance of these environment from the IPCA axes origin point. The distance between two environments (locations) measured by the cosine of the angle between the vectors indicate their similarity or dissimilarity in discriminating the genotypes (Yan and Tinker 2006), whereas, E3 and E4 were negatively correlated with their short vector distance. Only the environments E2 (spring plant crop) have recorded highest and positive IPCA 1 and 2 scores thereby indicating that this season is the more favorable environments for obtaining higher cane yield. It may be due to crop get more duration for active growth compared to other season, as also reported (Annicchiarico et al. 1997) in wheat. The angle between E1 and E2 (plant crop of autumn and spring season) and E2 and E4 (Plant vs ratoon crops) were wide or obtuse which implies strong crossover of GE. Hence, the response of these two sets of environments were in opposite direction and thereby they have different requirements for genotypes. The angle between the vectors of environment E3 and E4 (autumn and spring ratoon) was acute and it shows similarity or close relationship of the two environments. The mean cane yield of autumn ratoon (56.92 t/ha) and spring ratoon (54.62 t/ha) also justify the interpretation made as above.

The specific adaptability of a clone to a particular environment may be judged by analyzing the position of the clones with reference to environment vectors in AMMI II biplot graph. The clone Co 0237 was aligned proximity to E1 vector. So it can be treated as having greater adaptability for autumn planting in comparison to spring planting. Similarly Co 98014 and Co 05011 exhibited better adaptability in E3 and E4 hence these clones are suited for allowing multiple ratoons after autumn or spring harvest. CoJ 64 showed better adaptability towards spring season planting than autumn planting.

Authors' contribution

Conceptualization of research (BR, RK, MRM); Designing of the experiments (BR, RK, MRM); Contribution of experimental materials (BR, RK, NK, RK); Execution of field/lab experiments and data collection (BR, RK, MRM); Analysis of data and interpretation (MRM, RK); Preparation of manuscript (MRM, RK, BR, RK, NK).

Declaration

The authors declare no conflict of interest.

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