Indian Journal of Agricultural Sciences **81** (5): 438–44, May 2011

Application GGE biplot and AMMI model to evaluate sweet sorghum (*Sorghum bicolor*) hybrids for genotype × environment interaction and seasonal adaptation

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Received: 14 May 2010; Revised accepted: 11 March 2011

ABSTRACT

The genotype × environment interaction influences greatly the success of breeding strategy in a multipurpose crop like sweet sorghum [*Sorghum bicolor* (L.) Moench]. Eleven improved sweet sorghum hybrids were evaluated in both seasons for three years and genotype main effects and genotype × environment interaction (GGE) biplot analysis revealed that the hybrids that performed well in rainy season are: 'ICSSH 24' and 'ICSSH 39' and post rainy season are: 'ICSSH 57' and 'ICSSH 28'. The stable hybrid, based on additive main effects and multiplicative interaction (AMMI) and GGE biplot analysis that performed well across seasons and over the years for grain yield and stalk sugar yield is: 'ICSSH 28'.

Key words: AMMI model and sugar yield, Genotype × environment interaction, GGE biplot, Sweet sorghum

Sweet sorghum (*Sorghum bicolor* (L.) Moench) is similar to the traditionally grown grain sorghum except for the thick, juicy stalks containing fermentable sugars. Sweet sorghum is considered to be a smart biofuel feedstock that provides food, feed, fodder and fuel (Reddy *et al*. 2008 and Srinivasarao *et al*. 2009) and has tremendous potential in tropics and sub-tropics to augment ethanol production for use in transport sector. The success of genetic enhancement programme hinges on identification of genotypes adapted to specific season with stable performance for harnessing maximum gains from the selection.

The measured yield of each cultivar in each test environment is a measure of an environment main effect (E), a genotype main effect (G), and the genotype × environment (GE) interaction (Yan and Tinker 2005). Typically, E explains 80% or higher of the total yield variation; however, it is G and GE that are relevant to cultivar evaluation (Yan *et al*. 2002). The GE interaction reduces the correlation between phenotype and genotype and selection progress. The GE interaction has been studied by different researchers extensively, and several methods have been proposed to analyze it, eg univariate methods such as Francis and Kannenberg's coefficient of variability, Plaisted and Peterson's mean variance component for pair-wise GE interactions, Wricke's ecovalence, Shukla's stability variance, Finlay and Wilkinson's regression coefficient, Perkins and Jinks's regression coefficient, and Eberhart and Russell's sum of squared deviations from regression.

Usually a large number of genotypes are tested across a number of sites, seasons and years, and it is often difficult to determine the pattern of genotypic response across locations or seasons without the help of graphical display of the data (Yan *et al*. 2001). Biplot analysis, provides solution to the above problem as it displays the two-way data and allows visualization of the interrelationship among environments, genotypes, and interactions between genotypes and environments. Two types of biplots, the AMMI biplot (Gauch, 1988; Gauch and Zobel 1997) and the GGE biplot (Yan *et al*. 2000; Ma 2004) have been used widely to visualize genotype × environment interaction.

Compared to the methods of joint regression and type B genetic correlation, AMMI as well as GGE biplot analysis integrates some features from all of them. The differences of the two methods, GGE biplot analysis is based on environment-centered principal component analysis (PCA), whereas AMMI analysis is referred to double centered PCA. However, if the purpose for "which-won-where", AMMI could be misleading (Yan *et al*. 2007). In addition, comparing with different AMMI family models (AMMI0 to AMMIk, Dias *et al*. 2003), GGE biplot is always close to the best AMMI models in most cases (Ma *et al*. 2004). Moreover,

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GGE biplot is more logical and biological for practice than AMMI in terms of explanation of PC1 score, which represents genotypic effect rather than additive main effect (Yan *et al*. 2000 and Yan 2002).

The purpose of this paper is to do a case study to estimate the pattern of genotype×season interaction for few prominent sweet sorghum hybrids and varieties and to take a decision on their potential and adaptability for two seasons namely rainy (*kharif*) or postrainy (*rabi*) and also to do a comparative study of popular multivariate analysis models, ie AMMI and GGE.

MATERIALS AND METHODS

A total of 9 improved sweet sorghum hybrids along with checks 'CSH 22SS' (a nationally released sweet sorghum hybrid) and 'SSV 84' (a popular sweet sorghum variety) were evaluated at International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Andhra Pradesh, India in both rainy (*kharif*) and post rainy (*rabi*) seasons during 2005–07 in randomized complete block design (RCBD) with three replications (Table 1). Plots were 3m wide and 4m long. Grain yield was obtained from a sample of 6 m^2 from the centre of each plot in each year and season. Sugar yield is calculated as the product of Brix% and juice weight. Data on Brix%, juice volume and stalk weight were collected following standard procedure and analyzed using SAS/STAT software, Version 9.2 of the SAS Systems for Windows (2008). In terms of effects basic model for a multi-environment trial can be written (omitting random error) as

$$Y_{ij} = \mu + \alpha_i + \beta_j + \phi_{ij} \quad \text{... [1]}$$

Where Y_{ij} is the measured mean of *i*th genotype in *j*th environment, μ is the grand mean, α_i is the main effect of *i*th genotype, β_j is the main effect of *j*th environment, ϕ_{ij} is interaction between *i*th genotype and *j*th environment.

In GGE biplots genotype plus genotype × environment (G+GE) interaction is studied together and to achieve this G+GE effect is separated out from the observed mean and eventually model becomes as

$$Y_{ij} - \mu - \beta_j = \alpha_i + \phi_{ij} \quad \text{... [2]}$$

However in case of AMMI effect of genotypes is also separated out and only genotype×environment (GE) interaction is studied for biplot, and eventually model becomes as

$$Y_{ij} - \mu - \beta_j - \alpha_i = \phi_{ij} \quad \text{... [3]}$$

In further text we shall only give mathematical expressions for partitioning of G+GE model, as mathematical partitioning of GE is similar except difference in model. The G+GE (for GGE and GE for AMMI) effect is partitioned into multiplicative terms by using SVD as

$$Y_{ij} - \mu - \beta_j = \lambda_1 \xi_{i1} \eta_{j1} + \lambda_2 \xi_{i2} \eta_{j2} + \varepsilon_{ij} \quad \text{... [4]}$$

Where λ_1 and λ_2 are the singular values (SV) for the first and second principal component (PC1 and PC2), ξ_{i1} and ξ_{i2} are eigenvectors of genotype *i* for PC1 and PC2, η_{1j} and η_{2j} are eigenvectors of environment *j* for PC1 and PC2 and ε_{ij} is the residual not explained by PC1 and PC2 for genotype *i* in environment *j*. PC1and PC2 eigenvectors cannot be plotted directly to construct a meaniningful biplot before the singular values are partitioned into the genotype and environment eigenvectors. Singular-value partitioning is implemented by,

$$g_{il} = \lambda_l^{f} \xi_{il} \text{ and } e_{lj} = \lambda_l^{1-f} \eta_{lj} \quad \text{... [5]}$$

Where *f* is the partition factor and theoretically it can take any value between 0 and 1. In this paper we have used a value of 0.5 to give equal importance to both genotypes and environments. A simplification of [4] gives following

$$Y_{ij} - \mu - \beta_j = \lambda_1 \xi_{i1} \eta_{j1} + \lambda_2 \xi_{i2} \eta_{j2} + \varepsilon_{ij} = g_{i1} e_{1j} + g_{i2} e_{2j} + \varepsilon_{ij} \quad \text{... [6]}$$

Equation [6] is used to construct biplots by using scores derived from first two PCs, said as primary (g_{i1} and e_{1j}) and secondary (g_{i2} and e_{2j}) scores for genotype *i* and environment *j*, respectively.

Table 1 The parentage of sweet sorghum hybrids used in the study

Hybrid	ICSSH* No.
'ICSA 38' × 'NTJ2'	'ICSSH 21'
'ICSA 474' × 'ICSR 93034'	'ICSSH 57'
'ICSA 474' × 'SSV 74'	'ICSSH 28'
'ICSA 516' × 'SPV 422'	'ICSSH 27'
'ICSA 675' × 'SPV 422'	'ICSSH 24'
'ICSA 702' × 'SPV 422'	'ICSSH 16'
'ICSA 702' × 'SSV 74'	'ICSSH 39'
'ICSA 724' × 'SSV 74'	'ICSSH 30'
'ICSA 749' × 'SSV 74'	'ICSSH 26'
'CSH 22SS' (hybrid, check)	'CSH 22SS'
'SSV 84' (variety, check)	'SSV 84'

*ICSSH: ICRISAT sweet sorghum hybrid

RESULTS AND DISCUSSION

There are obvious differences in the trait means of the improved sweet sorghum hybrids among themselves and the vast variability of all the traits studied within the genotype with respect to the season of evaluation (Table 2). Data shown in Table 3 clearly show that there is significant interaction of genotypes with seasons and years for Brix%, sugar yield and grain yield in hybrids. Mean squares due to genotype × year × season interaction for the three traits showed differential behaviour of genotypes in different seasons and years except for sugar yield. In GGE, the first two PCs explain 85.87% of the GGE variation for stalk weight (tonnes/ha), 81.81% for juice volume (KL/ha), 68.41% for Brix%, 80.07% for sugar yield (tonnes/ha) and 80.1% for grain yield (tonnes/ha). In AMMI, the first two PCs explain 79.87% of the AMMI variation for stalk weight (tonnes/ha), 69.89% for juice volume (KL/ha), 76.73% for Brix%, 79.15% for sugar yield (tonnes/ha) and 80.54% for grain yield (tonnes/ha). The GGE variation, as explained by PC1 and PC2 for Brix% content was surprisingly low compared to the other traits analyzed in this study much lower than that of AMMI (Table 4). The

Table 2 Season-wise character means from the trials conducted of sweet sorghum hybrids evaluated over two seasons (rainy and post-rainy) and three years (2005–07)

Genotype	Days to 50% flowering		Plant height (m)		Stalk weight (tonnes/ha)		Juice volume (KL/ha)		Brix (%)		Sugar yield (tonnes/ha)		Grain yield (tonnes/ha)	
	Rainy	Post-rainy	Rainy	Post-rainy	Rainy	Post-rainy	Rainy	Post-rainy	Rainy	Post-rainy	Rainy	Post-rainy	Rainy	Post-rainy
'ICSSH 21'	81.78	73.00	3.38	2.33	76.84	21.93	37.62	10.31	15.44	9.72	6.04	0.98	5.86	7.91
'ICSSH 57'	77.67	72.22	3.66	2.14	78.60	27.92	37.65	12.04	15.50	12.78	5.89	1.55	7.16	6.06
'ICSSH 28'	76.11	71.44	3.70	2.18	78.78	28.17	36.25	12.21	15.17	12.33	5.79	1.55	7.26	7.39
'ICSSH 27'	79.44	78.11	3.09	1.94	67.88	22.15	31.99	6.58	17.11	11.28	5.76	1.04	4.95	7.94
'ICSSH 24'	82.56	80.78	2.98	1.87	77.08	23.54	38.05	9.86	17.33	12.89	6.74	1.31	4.68	7.05
'ICSSH 16'	77.44	75.89	3.25	2.03	67.09	24.16	30.27	10.24	16.67	14.33	5.40	1.47	4.91	5.50
'ICSSH 39'	78.00	74.11	3.34	2.11	72.64	26.58	36.67	11.06	16.56	12.33	6.26	1.40	5.96	6.36
'ICSSH 30'	78.67	76.11	3.49	2.18	74.90	26.55	35.42	11.00	16.33	9.33	6.01	1.08	7.00	9.84
'ICSSH 26'	77.56	76.56	3.62	2.36	75.79	28.23	36.41	12.89	15.17	11.61	5.60	1.66	6.31	6.94
'CSH 22SS'	83.78	75.67	3.52	2.38	70.94	26.60	31.58	10.67	18.33	11.61	5.82	1.28	3.03	9.01
'SSV 84'	87.11	77.00	2.98	1.77	48.04	17.51	18.51	6.32	19.11	11.28	3.59	0.72	2.76	7.18
Grand mean	80.01	75.54	3.36	2.12	71.69	24.85	33.67	10.29	16.61	11.77	5.72	1.28	5.44	7.38
CV (%)	2.36		7.19		19.78		24.56		10.37		26.33		20.42	
LSD	1.21		0.13		6.30		3.56		0.97		0.61		0.87	

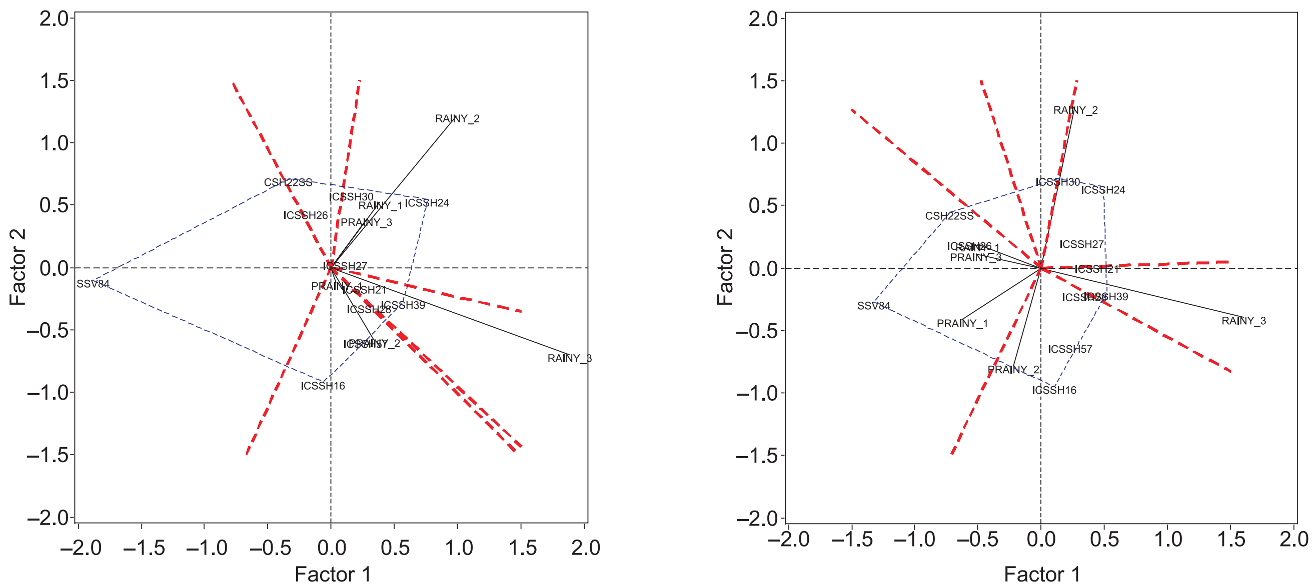

Fig 1 Plots showing the results of analysis by (*a*) genotype + genotype × environment interaction (GGE) and (*b*) additive main effects and multiplicative interaction (AMMI) of sweet sorghum hybrids performance for sugar yield (tonnes/ha) in each season (2005–07)

correlation coefficients among the six test environments are presented in Table 5. The differences are not pronounced among the environments tested, except for postrainy seasons 1 and 3.

The polygon view of the GGE biplot and AMMI model for sugar yield (Fig 1) indicates the best genotype(s) for each season(s) (Yan 2002). The polygon is formed by connecting the markers of the genotypes that are farthest away from the biplot origin such that all other genotypes are contained in the polygon. The hybrids 'ICSSH 24', 'ICSSH 30' and 'ICSSH 39' are found to be promising for sugar yield during rainy season while 'ICSSH 57' and 'ICSSH 28' are better adapted to post rainy season as they are located either on the vertex of the polygon or near the periphery. The rays/equality lines are lines that are perpendicular to the sides of the polygon, that facilitates visual comparison of the genotypes (Yan 2002). These six rays divide the biplot into six sections, and six seasons fall into three of them. The vertex families for each quadrant are the one that gave the highest yield for the season that fall within that quadrant. The variety 'SSV84' is the poorest performer for sugar yield and located outside the limits of any season. In case of AMMI model, the six

Table 3 Combined analysis of variance of sweet sorghum hybrids evaluated over two seasons (rainy and post-rainy) and three years (2005–07) for Brix%, sugar and grain yield

Source of variation	Hybrid		
	Brix%	Sugar yield (tonnes/ha)	Grain yield (tonnes/ha)
Year	175.29**	55.35**	140.72**
Residual	4.93	1.27	0.74
Season	1077.70**	957.97**	163.91**
Year × season	77.29**	12.45**	178.74**
Residual	2.18	0.59	5.33
Genotype	17.06**	3.98**	16.72**
Year × genotype	8.13**	1.18	10.65**
Season × genotype	18.83**	2.21**	21.26**
Year × season × genotype	8.53**	1.41	8.34**
Residual	2.29	0.9	1.99

** (*P*=0.01)

rays are wide spread 'ICSSH 24', 'ICSSH 39' and 'ICSSH 21' are found to be best for rainy season while no hybrid was good for post rainy season. The genotype 'ICSSH 24' was marginally superior over 'ICSSH 39' in terms of mean (4.02 tonnes/ha over 3.83 tonnes/ha). Fig 1 also gives the vector view of the GGE biplot, in which the environments are connected with the biplot origin via lines. This view of the biplot aids understanding of the interrelationships among the environments. The cosine of the angle between the vectors of two environments approximates the correlation coefficient between them. Therefore, the correlation coefficients are no-significant among the six seasons as indicated by acute angles. However, the results from rainy season 3 and post rainy season 3 are indifferent; consequently the rays are closure to the other group. Seasons with small angles between them were highly positively correlated, and they provided similar information on genotypes.

The polygon view of the GGE biplot and AMMI model for grain yield (Fig 2) indicates the best genotype(s) for each season(s). The hybrids 'ICSSH 24', 'ICSSH 30' and 'ICSSH 39' are found to be promising during rainy season, while 'ICSSH 21' and 'ICSSH 28' are better adapted to post rainy season as they are located between the lines of post rainy season 1, 2 and 3. Based on the vertex position and location between the lines of post rainy season and rainy season, it can be inferred that 'ICSSH 30' is adapted to both the seasons. In AMMI model (shown in figure 3 b), 'CSH 22SS', 'ICSSH 27' and 'SSV84' were found to be best adapted to postrainy season, but based on the means it was 'ICSSH 30', that performed equally well in both the seasons (rainy-7.00 tonnes/ha and postrainy season- 9.84 tonnes/ha).

The GGE biplot for stalk yield (shown in Fig 3 a) indicates that 'ICSSH 57' and 'ICSSH 26' are suitable for cultivation in rainy season while 'ICSSH 28' is adapted for both the seasons and relatively stable owing to it's proximity to origin.

Table 4 Trait-wise principal component 1 and 2 variance (PC1 and PC2) of total GGE variation in sweet sorghum hybrids evaluated over two seasons (rainy and postrainy) and three years (2005–07)

Trait	GGE			AMMI		
	PC1	PC2	Sum	PC1	PC2	Sum
Stalk weight (tonnes/ha)	65.74	20.13	85.87	60.82	19.05	79.87
Juice volume (KL/ha)	70.06	11.75	81.81	49.22	20.67	69.89
Brix%	39.21	29.20	68.41	47.40	29.33	76.73
Sugar yield (tonnes/ha)	60.78	19.29	80.07	51.15	27.99	79.15
Grain yield (tonnes/ha)	47.77	32.33	80.1	61.96	18.57	80.54

*Non-significant

GGE, Genotype main effects and genotype × environment interaction model; AMMI, additive main effects and multiplicative interaction model

Table 5 Correlation coefficients among the six test environments in sweet sorghum hybrids evaluated over two seasons (rainy and post-rainy) and three years (2005–07)

	Postrainy 1	Postrainy 2	Postrainy 3	Rainy1	Rainy 2	Rainy 3
Post-rainy 1	1.00					
Post-rainy 2	–0.01	1.00				
Post-rainy 3	0.82*	0.08	1.00			
Rainy 1	0.15	–0.11	0.30	1.00		
Rainy 2	0.25	–0.40	0.03	0.62	1.00	
Rainy 3	0.26	–0.37	0.11	0.09	0.55	1.00

**P*=0.05

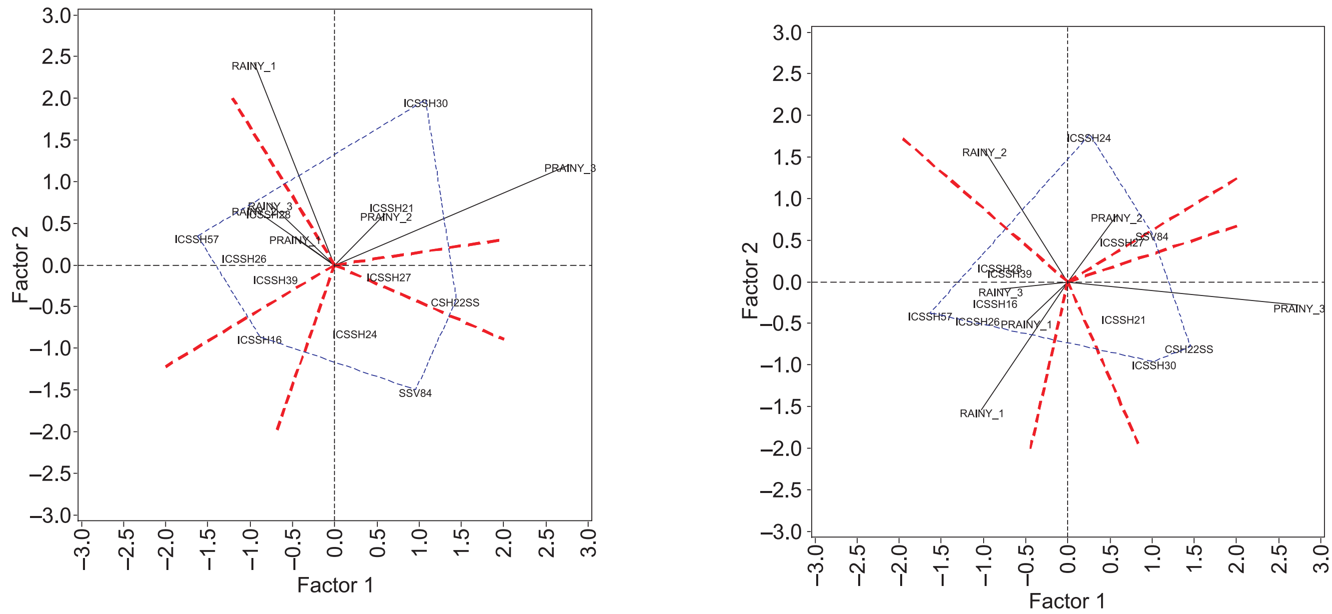

Fig 2 Plots showing the results of analysis by (*a*) genotype + genotype × environment interaction (GGE) and (*b*) additive main effects and multiplicative interaction (AMMI) of sweet sorghum hybrids performance for grain yield (Tonnes/ha) in each season (2005–07)

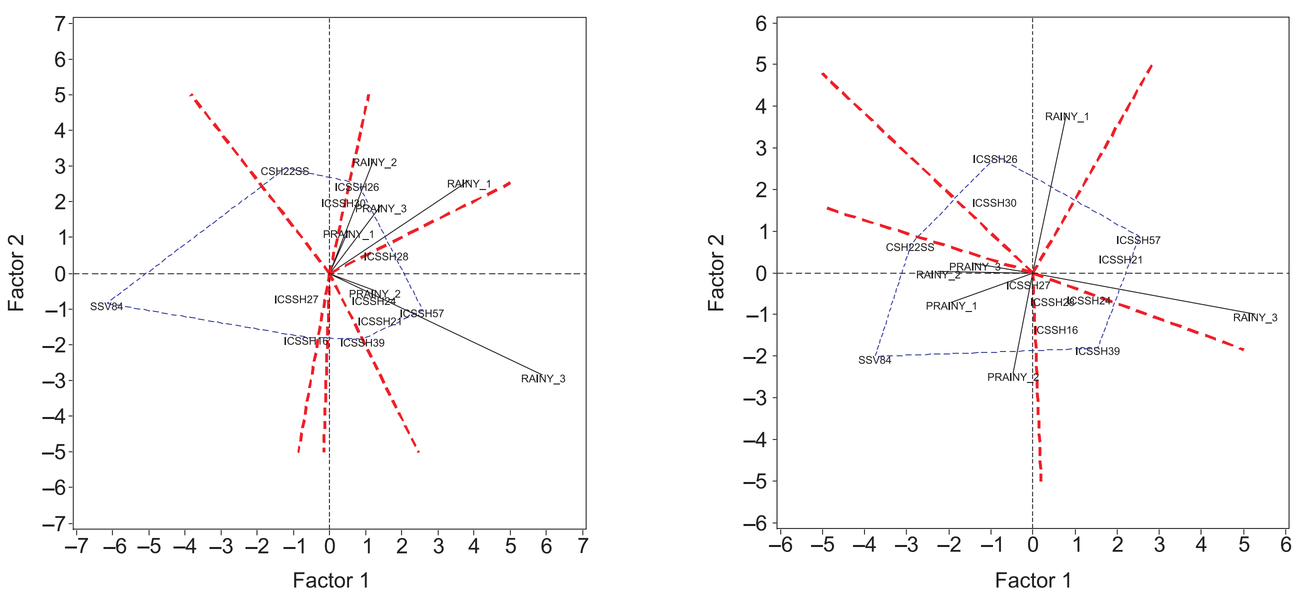

Fig 3 Plots showing the results of analysis by (*a*) genotype + genotype × environment interaction (GGE) and (*b*) additive main effects and multiplicative interaction (AMMI) of sweet sorghum hybrids performance for stalk yield (tonnes/ha) in each season (2005–07)

The polygon also reflects that 'SSV 84', 'ICSSH 16' and 'ICSSH 27' are poor stalk yielding genotypes not suited for neither of the seasons. AMMI model indicates (shown in Fig 3b) that 'ICSSH 57' and 'ICSSH 21' were best adapted hybrids for rainy season while none of the tested entries are found to be best for postrainy season contrary to the results of GGE biplot. The mean values (Table 2) favour the results of GGE biplot.

The GGE interaction for the Brix% or total soluble solids (shown in Fig 4a) indicates that the variety 'SSV 84' has the highest Brix% during rainy season while 'ICSSH 16' recorded the highest Brix% for postrainy season. In case of AMMI model also 'SSV 84' was best for Brix% in rainy season and 'ICSSH 16' and 'ICSSH 57' were best performing sweet sorghum hybrids for Brix% in postrainy season.

The limitations of the GGE biplot are that, seldom it may explain only a small proportion of the total GGE as happened in this study with Brix% (68.41%). This could be due to when the genotype main effect is considerably smaller than the G×E interaction and when the G×E interaction pattern is

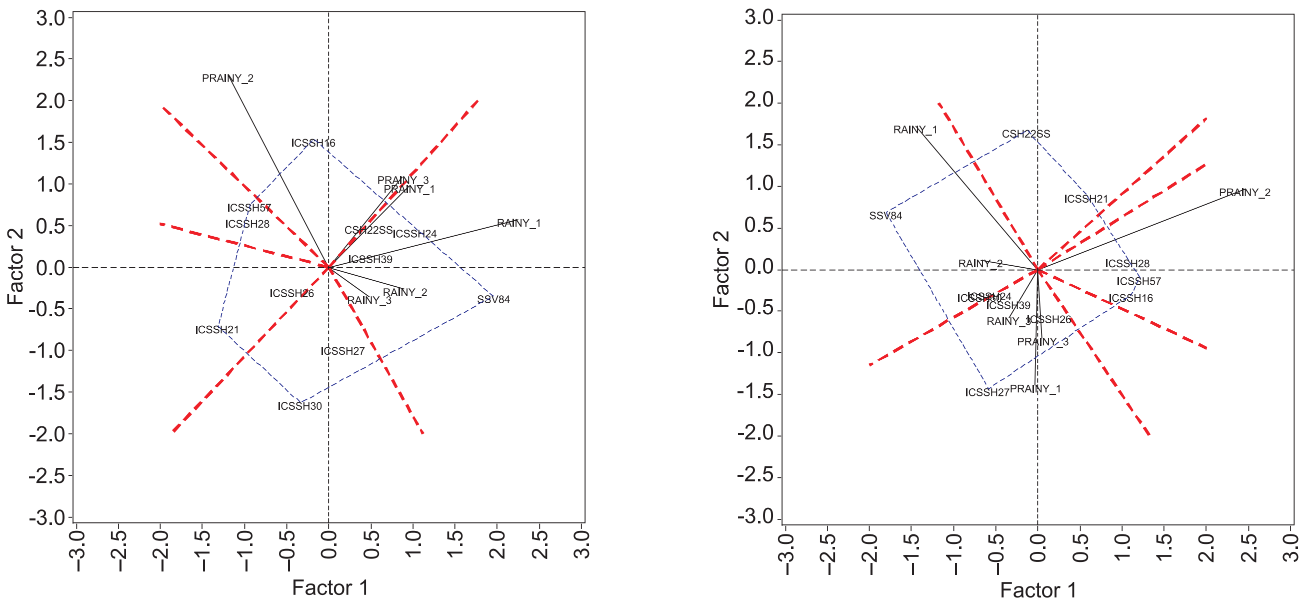

Fig 4 Plots showing the results of analysis by (*a*) genotype + genotype × environment interaction (GGE) and (*b*) additive main effects and multiplicative interaction (AMMI) of sweet sorghum hybrids performance for Brix% (tonnes/ha) in each season (2005–07)

complex. In such cases, the GGE biplot consisting of PC1 and PC2 may be insufficient to explain the GGE (Yan 2002). For Brix%, AMMI model explained significantly higher variation 76.73%. Hence, there is a need for use of confidence regions for individual genotype and environment scores in biplots to make critical decisions on genotype selection or cultivar recommendation based on a statistical test(s) as suggested by Yang *et al*. 2009.

Nevertheless, in short this study indicates the possibility of identifying suitable and stable improved sweet sorghum hybrids under diverse seasonal conditions by applying a GGE biplot as well as AMMI model. Based on the conclusions drawn earlier, it is advised to use both methods to improve efficiency of identifying the season specific genotypes, though GGE biplot resembles more *vis a vis* respective trait means. In this study, there is good correspondence between the results of both the models of stability analysis as discrimination among tested entries in different seasons is reasonable. Considering the grain and stalk sugar yields, the hybrids that performed well in rainy season are: 'ICSSH 24' and 'ICSSH 39' and post rainy season are: 'ICSSH 57' and 'ICSSH 28'. The stable hybrid that performed well across seasons and over the years for grain yield and stalk sugar yield is: 'ICSSH 28'; but its sugar yield is lower by 16.4% compared to the best rainy season hybrid, and 7.1% lower compared to the highest yielding post rainy season hybrid. Similarly, its grain yield is surprisingly stable in both the seasons at about 7.3 tonnes/ha. Therefore, 'ICSSH 28' ('ICSA 474' × 'SSV 74') can be recommended for cultivation in both the rainy and post rainy seasons. Compared to the variety, 'SSV 84', which recorded the highest Brix%, but low grain yield, the best performing rainy season hybrid, 'ICSSH 24' had 87.74% high sugar yield, the best performing post rainy season hybrids, 'ICSSH 57' and 'ICSSH 28' has exhibited 115.2% superiority.

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