Original Research Article

DECIPHERING THE GENOTYPE × ENVIRONMENT INTERACTION FOR IDENTIFICATION OF SUPERIOR GENOTYPES OF MANGO (*Mangifera indica L.*) USING AMMI STABILITY MEASURES

ABSTRACT

Mango is one of India's most important commercially grown fruit crops with the greatest collection of varieties. Genotypes do not show the same response in all locations due to their interactions with the surrounding environment. Such interactions limit the breeding progress during the selection of superior genotypes. Multi-location trials are being carried out to study the behavior of genotypes in different environments. Genotype environment interaction is a major problem in selecting and recommending superior genotypes to cultivate crops. When we are dealing with perennial crops like Mango, this problem gets intensified because choosing unstable cultivars to plant in an orchard puts the farmers in a risky income situation for many years. In the present investigation, an attempt has been made to identify the high-yielding and stable genotypes of Mango by using AMMI stability measures. Data on sixteen genotypes of Mango tested across four locations viz., Rewa, Sabour, Sangareddy, and Vengurla in India over nine years is considered for the study. The present study concludes that the AMMI stability measures SIPC, AVAMGE, ASTAB, DA, MASV, MASI, ZA, ASV, and ASI are based on the biological concept of stability, and the stability measures DZ and EV are based on the agronomic concept of stability. Selection of mango genotypes based on the agronomic concept of stability will be recommended in favorable environments, while selection based on biological stability will be advised in unfavorable environments.

Keywords: *AMMI; Genotype environment interaction; Mango; Multi-location trials; Stability*

1. INTRODUCTION

Mango (*Mangifera indica L.*) is India's most important commercially grown perennial fruit crop. Mango belongs to the family Anacardiaceae, and it is known as the *"King of fruits"* because of its versatile uses and taste. Mangoes can be used to prepare pickles, amchur, chutney, jams, jellies, and squashes. Consumption of mangoes helps in boosting immunity, lowering cholesterol, and promoting eye health. India has a vast collection of mango cultivars and ranks first in production in the world, followed by China, Thailand, Indonesia, Mexico, Pakistan, Brazil, Philippines, Nigeria, and Sudan [1]. Mango (including Guava and Mangosteen) is cultivated in a vast area of 2,578 thousand hectares with around 24.75 million tonnes, accounting for about 45.13% of total world mango production and 46.68% of world mango cultivated area [1]. The increasing population leads to the rise in demand for agricultural produce, and it is expected to enhance agricultural production per unit area.

To encounter this requirement, various crop improvement programs have been initiated all over the world. In any crop improvement program, the performance of promising genotypes has been tested over different locations each year to identify the genotypes with high yield and wider adaptability over different environmental conditions. In Multi-location trials (MLTs), most frequently, it is noticed that the genotypes respond differently to the diverse environmental conditions; this differential response of genotypes is known as Genotype environment interaction (GEI) [2]. Yet, there is no single method developed so far that equally satisfies plant breeders for the study of GEI. However, there are various statistical analyses in use today, including parametric and non-parametric methods to study the nature of interactions of genotypes with environments [3]. Consistency in genotype performance across different environments is known as stability, which is one of the most important characteristics of the superior cultivar. There are two stability concepts, viz., static and dynamic. In the static concept, the genotypic performance is stable across different environments, and it is also known as the biological concept of stability. However, in the case of dynamic stability, the performance of the genotype is stable, but for each environment, its performance corresponds to the predicted level. This concept of stability is also known as the agronomic concept [4].

Among various statistical techniques, Additive Main Effects and Multiplicative Interaction (AMMI) models are predominantly used to evaluate GEI and identify superior genotypes [5, 6]. AMMI model was introduced in 1988, and basically, the AMMI model is a combination of Analysis of Variance (ANOVA) and Principal Component Analysis (PCA) [7]. Bose et al., 2014 [8] utilized the AMMI model and several AMMI-based stability measures to quantify and rank rice genotypes. Hongyu et al., 2014 [9] studied the GEI and evaluated the adaptability & stability in the yield of nine maize genotypes tested over twenty environments using AMMI models. Ajay et al., 2020 [10] performed an AMMI analysis to study GEI in peanuts. Sholihin, 2021 [11] evaluated the phenotypic stability of cassava promising clones in acidic regions of Lampung, Indonesia, based on AMMI stability

Although the usefulness of AMMI models and their stability measures in determining superior genotypes is tremendous in annual crops, their application in perennial fruit crops, especially in Mango, is scanty. Genotype environment interaction is a major constraint in selecting and recommending superior genotypes for the cultivation of crops, which further intensifies while dealing with perennial crops like Mango because the selection of unstable cultivars puts the farmers in a long-term risky income situation. In this connection, the present study has been taken up to avoid such circumstances and facilitate growth in farmers' income by recommending superior genotypes prior to planting.

2. MATERIALS AND METHODS

2.1. Source and description of data

This study was based on secondary data of mango fruit crop with sixteen common genotypes grown in four locations over nine years, collected from MLTs of All India Co-Ordinated Research Project on Sub-Tropical Fruits (AICRP-STF), Central Institute for Subtropical Horticulture (CISH), Lucknow, India. Mango genotypes were tested over four locations, namely, Rewa (Madhya Pradesh), Vengurla (Maharashtra), Sangareddy (Telangana), and Sabour (Bihar), over different years in India. Multi-location trials (MLT) were conducted in a randomized complete block design with three replications at each location. These four locations contain common data for 16 genotypes of Mango tested over nine years (*i.e.,* 1997- 2005) with three repetitions, and the same data were considered for the study. For the present investigation, the yield variable, *i.e.,* the number of fruits per tree, has been considered to evaluate MLT data on Mango.

2.2. Statistical Analysis

Data on the yield variable was subjected to analysis of variance to estimate the variations among genotypes, environments, and interactions. The study will be continued to determine the stability level of the sixteen genotypes across thirty-six environments if there is a significant interaction between the environment and the genotype. Additive Main Effects and Multiplicative Interaction (AMMI) analysis combines additive and multiplicative effect analysis. AMMI uses Analysis of Variance (ANOVA) and Principal component analysis (PCA) to analyze GEI's additive and multiplicative parts. The AMMI model for T genotypes and S environments is given below,

$$Y_{ij} = \mu + g_i + e_j + \sum_{n=1}^{N'} \lambda_n \gamma_{in} \delta_{jn} + \phi_{ij}$$

$\phi_{ij} \sim N(0, \sigma^2)$; i = (1, 2, 3, 4……...T); j = (1,2, 3……. S), Y_{ij} = Average yield of i^{th} genotype in j^{th} environment; μ= Grand Man; g_i = i^{th} genotypic main effect; e_j= j^{th} environmental main effect; λ_n= Eigen value of n^{th} IPCA; γ_{in} and δ_{jn} = i^{th} genotype and j^{th} environment PCA scores for the axis n; ϕ_{ij}= Residual; N'= Number of PCA axes retained in the model.

The AMMI model does not provide for a quantitative stability measure, and such a measure is essential to quantify and rank genotypes in terms of yield stability [22]. Therefore, various AMMI-based stability measures were proposed by different scientists, and some of these measures (Table 1) have been utilized in the present study to describe the yield stability of mango genotypes. These AMMI-based stability measures were calculated using the package *Metan* of R studio [23].

2.3. Data Transformation

Data were transformed using appropriate data transformation techniques to attain normality and homogeneity of error variances across environments. Yield variable data were transformed to normal using the Ordered quantile (ORQ) normalization technique suggested by Pham & Kang, 1988 [2]. R-package *"bestNormalize"* has been employed for data transformation.

Table 1. Various AMMI Stability measures utilized in the study

Stability measure	**Formula**
Absolute Value of the Relative Contribution of IPCs to the Interaction (ZA) [12]	$ZA = \sum_{n=1}^{N'} \lvert\theta_n \gamma_{in}\rvert$
AMMI Based Stability Parameter (ASTAB) [13]	$ASTAB_i = \sum_{n=1}^{N'} \lambda_n \gamma_{in}^2$
AMMI Stability Index (ASI) [14]	$ASI = \sqrt{[PC_1^2 \times \theta_1^2] + [PC_2^2 \times \theta_2^2]}$
AMMI-stability value (ASV) [15]	$ASV = \sqrt{\left[\frac{IPCA1 sum\ of\ squares}{IPCA2 sum\ of\ squares}\right](IPCA1)^2 + [IPCA2]^2}$
Annicchiarico's D Parameter values (DA) [16]	$DA = \sqrt{\sum_{n=1}^{N'} (\lambda_n \gamma_{in})^2}$
Modified AMMI Stability Index (MASI) [17]	$MASI = \sqrt{\sum_{n=1}^{N'} PC_n^2 \times \theta_n^2}$
Modified AMMI Stability Value (MASV) [18]	$MASV = \sqrt{\sum_{n=1}^{N'-1} \left(\frac{SSIPC_n}{SSIPC_{n+1}}\right) \times (PC_n)^2 + (PC_{N'})^2}$
Sum Across Environments of Absolute Value of GEI Modelled by AMMI (AVAMGE) [12]	$AV_{(AMGE)} = \sum_{j=1}^{E} \sum_{n=1}^{N'} \lvert\lambda_n \gamma_{in} \delta_{jn}\rvert$
Sums of the Absolute Value of the IPC Scores (SIPC) [19]	$SIPC = \sum_{n=1}^{N'} \lvert{\lambda_n}^{0.5} \gamma_{in}\rvert$
Sums of the Averages of the Squared Eigenvector Values (EV) [20]	$EV = \sum_{n=1}^{N'} \frac{(\gamma_{in})^2}{N'}$
Zhang's D Parameter (DZ) [21]	$DZ = \sqrt{\sum_{n=1}^{N'} (\gamma_{in})^2}$

3. RESULTS AND DISCUSSION

3.1. Combined Analysis of Variance

One of the vital objectives of a crop improvement program is to identify superior varieties with high yield and stability across diverse locations. A combined analysis of variance (CANOVA) has been performed on mango fruit yield data to describe the main effects and quantify the interactions among and within the sources of variation. CANOVA revealed, highly significant ($P < 0.001$) temporal (years), spatial (locations), genotypic main effects and interaction effects (G×L; G×Y; G×L×Y) (Table 2). These kinds of results were observed by several other researchers [8, 24-28]. Such significant interaction effects suggest that the fruit yield of mango genotypes varied across years and locations. The same enables us to study the yield stability of genotypes across diverse locations [8]. As CANOVA confirms the presence of significant GEI, additional statistical techniques such as AMMI analysis can be more helpful in unfolding and understanding the GEI [6]. For the present study combination of years and locations are treated as environments. The mean squares of genotypes, environments and their interactions (*i.e.,* GEI) showed significant differences ($P<0.001$) for the yield variable. Genotypes, environments, and GEI effect account for 6.95%, 37.78%, and 42.81% of the total sum of squares, respectively. Similar kinds of results were observed by [4]. Application of the AMMI model for the apportioning of GEI revealed 12 significant interaction principal component axes (IPCA). IPCA1 and IPCA2 collectively account for 40.80% of GEI (Table 3).

Table 2. Analysis of Variance for sixteen genotypes of Mango across four locations over nine years

Source of Variation	Df	Sum. Sq.	MSS	F - Value
Year (Y)	8	178.64	22.33	116.91**
Location (L)	3	169.55	56.52	295.90**
L × Y	24	303.59	12.65	66.23**
Replication in (L× Y)	72	19.4	0.27	1.41*
Genotype (G)	15	120.03	8	41.90**
L × G	45	310.69	6.9	36.15**
Y × G	120	107.86	0.9	4.71**
L × Y × G	360	309.17	0.86	4.50**
Error	1080	206.27	0.19	
Total	1727	1725.19		

Df: Degrees of freedom; Sum Sq.: Sum of squares; MSS: Mean sum of squares; *P <0.05, **P <0.01 and ***P <0.001.

3.2. AMMI Stability Measures

The highest mean yield was observed for the genotypes G2 and G4, while the genotype G6 exhibited the lowest mean yield across all test environments. Various AMMI-based stability measures have been computed to ascertain the consistency of genotypes across 36 environments (4 locations × nine years), and the same were presented in Table 4. The lower the value of the stability measure, the higher the yield consistency of the genotype. Ranks of mango genotypes based on these stability measures are given in Table 5. Most of the stability measures (ASTAB, AVAMGE, DA, MASI, SIPC, ZA) identified G7 as a highly consistent genotype across all test environments. However, G3 was found to be a highly inconsistent genotype by ASV, ASTAB, ASI, DA, DZ, EV, MASV, and MASI. The stability measures SIPC and DA found G7 and G15 the most stable genotypes since they exhibited the lowest values. However, SIPC and DA also found G16 and G3 the most unstable genotypes, respectively. ASI and ASV found G10 followed by G8 as stable genotypes, while G3 and G16 were unstable. The genotypes G5 followed by G9 were recognized as stable genotypes by DZ and EV. MASV identified G15 followed by G7 as the most consistent genotypes for all the test environments under study.

Spearman's rank correlation coefficients have been computed to describe the association among the stability measures [4, 8, 29, 30, 31, 32, 33], and the same was presented through the correlation matrix shown in Table 6 Fig.1. From the correlation matrix, it was clear that none of the stability measures showed significant correlations with the yield variable. The stability measures MASV and DA have a highly significant positive correlation ($r = 0.94$) and significant positive correlations with all the remaining stability measures. ASTAB exhibits significant positive correlations with all the stability measures except ASI and ASV. The pairs DZ & EV; ASV & ASI exhibited strong positive correlation ($r = 1$). The stability measures ASV, ASI, AVAMGE, ZA, and MASI, do not correlate with DZ and EV. Non-significant correlations were observed between SIPC & ASI; SIPC & ASV; SIPC & AVAMGE.

Table 3. AMMI Analysis of Variance for sixteen genotypes of Mango over 36 environments

Source of Variation	Df	Sum. Sq.	MSS	F value
Environment (E)	35	651.77	18.62	69.10**
Replication within E	72	19.40	0.27	1.41*
Genotype (G)	15	120.03	8.00	41.90**
G * E interaction	525	727.72	1.39	7.26**
PC1	49	188.00	3.84	20.09**
PC2	47	108.65	2.31	12.10**
PC3	45	99.56	2.21	11.58**
PC4	43	88.67	2.06	10.80**
PC5	41	59.36	1.45	7.58**
PC6	39	47.30	1.21	6.35**
PC7	37	32.93	0.89	4.66**
PC8	35	31.80	0.91	4.76**
PC9	33	18.26	0.55	2.90**
PC10	31	16.61	0.54	2.81**
PC11	29	12.23	0.42	2.21**
PC12	27	10.69	0.40	2.07**
PC13	25	6.65	0.27	1.39^{NS}
PC14	23	5.26	0.23	1.20^{NS}
PC15	21	1.74	0.08	0.43^{NS}
Residuals	1080	206.27	0.19	

Df: Degrees of freedom; Sum Sq.: Sum of squares; MSS: Mean sum of squares; *P <0.05, **P <0.01 and ***P <0.001; ^{NS}Non Significant

3.3. ***Visualization of Association among stability measures***

Principal component analysis (PCA) has been carried out on the correlation matrix of stability measures. These AMMI stability measures have been compared, and two different concepts of stability (static and dynamic) have been suggested. The first two Principal components (PC1 and PC2) of various stability measures accounted for 83.05% (PC1: 44.41% and PC2: 38.64%) of the variance of the original variables. Fig. 2 shows that the PC1 separates the stability measures DZ, EV, and mean yield (Y) from the remaining stability measures. Thus, the PC1 divides the stability measures into two groups according to the two stability concepts, similar to Flores et al., 1998 [30]. Fig.2 displays the stability measures corresponding to the static concept on the right and stability measures based on the dynamic concept of stability on the left. The PC2 splits the biplot into four groups. The mean yield (Y) is included in Group C. The stability measures DZ and EV formed Group B. ASV, and ASI were found in Group D. However, all the remaining stability measures (SIPC, AVAMGE, ASTAB, DA, MASV, MASI, ZA) collectively form Group A. This group contains stability measures, which are simultaneously influenced by yield and stability [4]. Superior mango genotypes based on Group B stability measures (EV, DZ) are G5 followed by G9, and their performance will be increased in favorable environments. However, Superior mango genotypes based on Group D stability measures (ASI, ASV) are G10 followed by G8, and their performance will be stable in favorable and unfavorable environments.

Table 4. Quantitative values of AMMI Stability measures

Genotype	Code	Mean Yield	ASTAB	ASI	ASV	AVAMGE	DA	DZ	EV	MASI	MASV	SIPC	ZA
Banganpalli	G1	210.18 (-0.40)	4.00	0.23	1.55	25.15	4.69	0.89	0.07	0.29	2.79	5.36	0.27
Suvarnarekha	G2	328.79 (0.43)	2.63	0.18	1.23	17.97	3.64	0.78	0.05	0.23	2.30	4.72	0.21
Neelum	G3	280.53 (0.22)	4.23	0.33	2.22	24.62	4.81	0.96	0.08	0.35	3.28	5.30	0.26
Totapari	G4	311.90 (0.44)	3.10	0.17	1.11	15.10	3.68	0.90	0.07	0.19	2.19	5.32	0.20
Fazli	G5	183.36 (-0.25)	2.32	0.22	1.50	17.58	3.50	0.75	0.05	0.25	2.08	4.19	0.18
Chousa	G6	166.01 (-0.28)	2.84	0.21	1.41	17.66	3.57	0.91	0.07	0.23	2.30	4.89	0.20
Mallika	G7	223.37 (0.04)	2.04	0.12	0.82	13.64	2.87	0.78	0.05	0.15	1.90	3.82	0.15
Zardalu	G8	297.93 (0.34)	2.82	0.08	0.51	14.42	3.43	0.90	0.07	0.17	2.11	4.88	0.17
Bombai	G9	187.13 (-0.10)	2.46	0.16	1.09	18.73	3.50	0.75	0.05	0.20	1.97	4.54	0.20
Bombay Green	G10	172.74 (-0.27)	3.57	0.06	0.40	16.34	3.92	0.95	0.08	0.18	2.33	5.16	0.19
Himsagar	G11	224.19 (0.05)	4.05	0.16	1.08	17.94	4.54	0.93	0.07	0.25	2.90	5.06	0.23
Kishan Bogh	G12	169.19 (-0.23)	3.06	0.15	1.04	16.54	3.63	0.90	0.07	0.17	2.15	4.43	0.16
Alphanso	G13	194.30 (-0.13)	2.81	0.30	2.03	20.14	3.95	0.81	0.05	0.31	2.56	4.51	0.20
Kesar	G14	258.89 (0.15)	2.93	0.18	1.20	15.01	3.72	0.86	0.06	0.23	2.21	5.02	0.21
Mankurad	G15	274.42 (0.22)	2.33	0.15	1.01	16.20	3.19	0.83	0.06	0.18	1.80	4.17	0.16
Vanraj	G16	200.26 (-0.21)	3.66	0.31	2.07	22.92	4.46	0.91	0.07	0.33	2.72	5.58	0.26

Numerical in the parenthesis are transformed values of yield variable

Table 5. Ranks of mango genotypes based on AMMI Stability measures

Genotype	Y	ASTAB	ASI	ASV	AVAMGE	DA	DZ	EV	MASI	MASV	SIPC	ZA
G1	16	14	13	13	16	15	8	8	13	14	15	16
G2	2	5	10	10	11	8	4	4	9	9	7	12
G3	5	16	16	16	15	16	16	16	16	16	13	15
G4	1	11	8	8	4	9	11	11	6	7	14	9
G5	13	2	12	12	8	4	1	1	12	4	3	5
G6	15	8	11	11	9	6	12	12	10	10	9	7
G7	8	1	3	3	1	1	3	3	1	2	1	1
G8	3	7	2	2	2	3	10	10	2	5	8	4
G9	9	4	7	7	12	5	2	2	7	3	6	8
G10	14	12	1	1	6	11	15	15	4	11	12	6
G11	7	15	6	6	10	14	14	14	11	15	11	13
G12	12	10	5	5	7	7	9	9	3	6	4	2
G13	10	6	14	14	13	12	5	5	14	12	5	10
G14	6	9	9	9	3	10	7	7	8	8	10	11
G15	4	3	4	4	5	2	6	6	5	1	2	3
G16	11	13	15	15	14	13	13	13	15	13	16	14

Table 6 Spearman's rank correlation coefficients among AMMI stability measures and Mean yield

	Y	ASTAB	ASI	ASV	AVAMGE	DA	DZ	EV	MASI	MASV	SIPC	ZA
Y	1.00	-0.12	-0.19	-0.19	-0.36	-0.18	-0.03	-0.03	-0.24	-0.23	-0.07	0.00
ASTAB		1.00	0.30	0.30	0.45	0.87	0.86	0.86	0.44	0.85	0.86	0.68
ASI			1.00	1.00	0.76	0.58	0.04	0.04	0.93	0.57	0.39	0.71
ASV				1.00	0.76	0.58	0.04	0.04	0.93	0.57	0.39	0.71
AVAMGE					1.00	0.69	0.16	0.16	0.84	0.68	0.43	0.75
DA						1.00	0.60	0.60	0.71	0.94	0.78	0.87
DZ							1.00	1.00	0.20	0.68	0.72	0.36
EV								1.00	0.20	0.68	0.72	0.36
MASI									1.00	0.72	0.47	0.81
MASV										1.00	0.75	0.83
SIPC											1.00	0.77
ZA												1.00

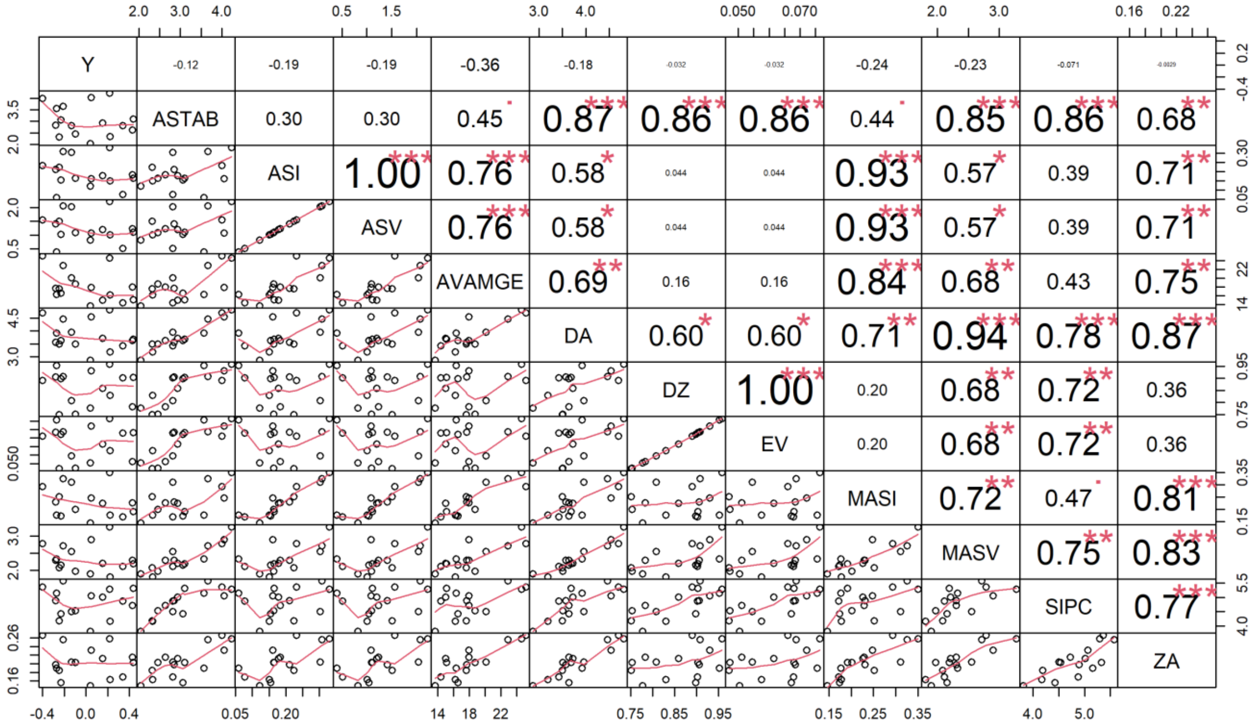

Fig.1. Spearman's rank correlation coefficients and scatter plots among AMMI Stability Measures (*P <0.05, **P <0.01 and ***P <0.001)

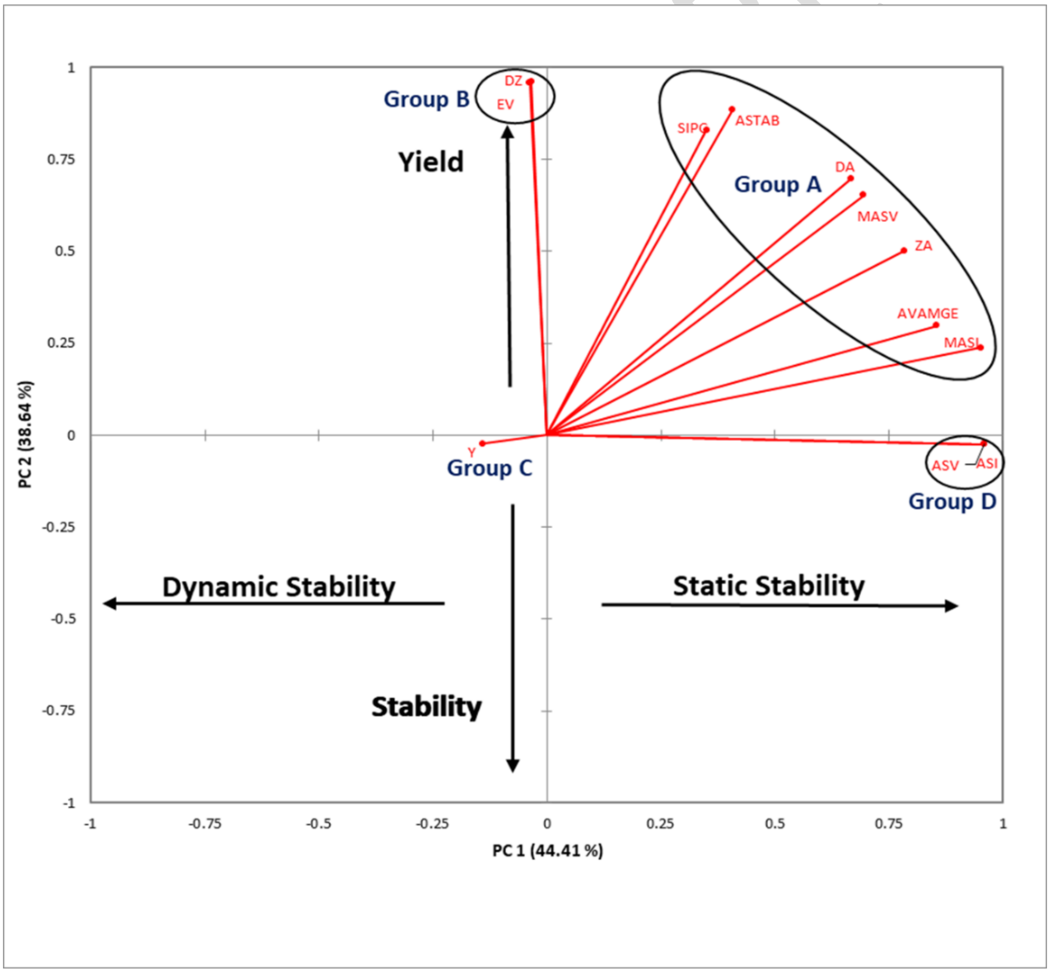

Fig. 2. PCA biplot (PC1 v/s PC2) based on AMMI Stability Measures correlation matrix.

4. CONCLUSION

Genotype environment interaction is a significant constraint in selecting and recommending superior genotypes for cultivation. The present study concludes that the AMMI stability measures SIPC, AVAMGE, ASTAB, DA, MASV, MASI, ZA, ASV, and ASI are based on the biological concept of stability, and the stability measures DZ and EV are based on the agronomic concept of stability. Selection of mango genotypes based on the agronomic concept of stability will be recommended in favorable environments, while selection based on biological stability will be advised in unfavorable environments. This study also concludes that AMMI analysis and various AMMI stability measures are more helpful in analyzing GEI and evaluating the genotypic performance of perennials, especially in Mango.

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