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 the most important commercially grown fruit crops in India with greatest collection of varieties. Genotypes does not show same response in all locations due to their interactions with the surrounding environment. Presence of such interactions limits the breeding progress during selection of superior genotypes. Multi location trials are being carried out to study the behaviour of genotypes over different environments. Genotype environment interaction is a major problem in selecting and recommending superior genotypes for the cultivation of crops. This problem gets intensified, when we are dealing with perennial crops like Mango 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 a period of 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 biological concept of stability and the stability measures DZ and EV are based on agronomic concept of stability. Selection of mango genotypes based on agronomic concept of stability will be recommended in favourable environments, while in unfavourable environments, selection based on biological stability will be recommended.

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

1. INTRODUCTION

Mango (*Mangifera indica L.*) is the most important commercially grown perennial fruit crop in India. 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 huge collection of mango cultivars, and ranks first in the 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 the production around 24.75 million tonnes, which accounting 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 had been tested over different locations in each year, with an intention to identify the genotypes with not only high yield, but also 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 performance of genotype across different environments is known as stability, which is one of the most important characteristics for the superior cultivar. There are two stability concepts, viz., static and dynamic. In 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 being used predominantly for evaluating GEI and identifying superior genotypes [5, 6]. AMMI model was introduced in 1988 and basically, AMMI model is a combination of Analysis of Variance (ANOVA) and Principal Component Analysis (PCA) [7]. Bose et al., 2014 [8] utilized AMMI model and several AMMI based stability measures to quantify and rank the genotypes of rice. Hongyu et al., 2014 [9] studied the GEI and evaluated the adaptability & stability in the yield of nine maize genotypes tested over twenty environments by using AMMI models. Ajay et al., 2020 [10] performed AMMI analysis to study GEI in peanut. 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 huge 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 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 to facilitate growth in farmer's income by recommending superior genotypes prior planting.

2. MATERIALS AND METHODS

2.1. Source and description of data

This study was based on secondary data of mango fruit crop with common 16 genotypes grown in four locations over a period of 9 years, which have been 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 3 replications at each location. These four locations contain common data for 16 genotypes of mango tested over a period of 9 years (*i.e.,* 1997- 2005) with 3 replications 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 for evaluation of MLT data of mango.

2.2. Statistical Analysis

Data available on the yield variable was subjected to analysis of variance to estimate the variations among genotypes, environments and interactions. The analysis 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 is a mixture of additive and multiplicative effect analysis. AMMI uses Analysis of Variance (ANOVA) and

Principal component analysis (PCA) for analysing additive and multiplicative parts of GEI respectively.

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

For the purpose of attaining normality and homogeneity of error variances across environments, data was transformed using appropriate data transformation techniques. Yield variable data was transformed to normal using 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 crop improvement program is identifying superior varieties having high yield and stability across diverse locations. 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). This kind of results were observed by several other researchers [8, 24-28]. Such significant interaction effects suggest that fruit yield of mango genotypes varied across years and locations and the same enable us to study 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 are account for 6.95%, 37.78%, and 42.81% of the total sum of square respectively. Similar kind of results had been observed by [4]. Application of 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.

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

3.2. AMMI Stability Measures

Highest mean yield was observed for the genotypes G2 and G4; while, the genotype G6 exhibited 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 × 9 years) and the same were presented in the Table 4. Lower the value of stability measure higher will be 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 highly consistent genotype across all test environments. However, G3 was found to be highly inconsistent genotype by ASV, ASTAB, ASI, DA, DZ, EV, MASV and MASI. The stability measures SIPC and DA found G7 and G15 as most stable genotypes since they exhibited lowest values. However, SIPC and DA also found G16 and G3 as most unstable genotypes respectively. ASI and ASV found G10 followed by G8 as stable genotypes, while G3 and G16 as unstable genotypes. The genotypes G5 followed by G9 were recognized as stable genotypes by DZ and EV. MASV identified G15 followed by G7 as most consistent genotypes for all the test environment under study.

Spearman's rank correlation coefficients have been computed to describe the association among the stability measures [4, 8, 29, 30, 31] 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 shows significant correlations with yield variable. The stability measures MASV and DA have highly significant positive correlation (r = 0.94) with each other and has 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 has no correlation with DZ and EV. Non-significant correlations were observed between SIPC & ASI; SIPC & ASV; SIPC & AVAMGE.

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 different 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 separates the stability measures into two groups according to the two stability concepts, being similar to the findings of Flores et al., 1998 [30]. Fig.2 displays, the stability measures corresponding to the static concept on 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, and DZ and EV formed as Group B; ASV and ASI formed as Group D. However, all the remaining stability measures (SIPC, AVAMGE, ASTAB, DA, MASV, MASI, ZA) collectively forms as Group A, this group contains the 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 with the favourable 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 favourable and unfavourable 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

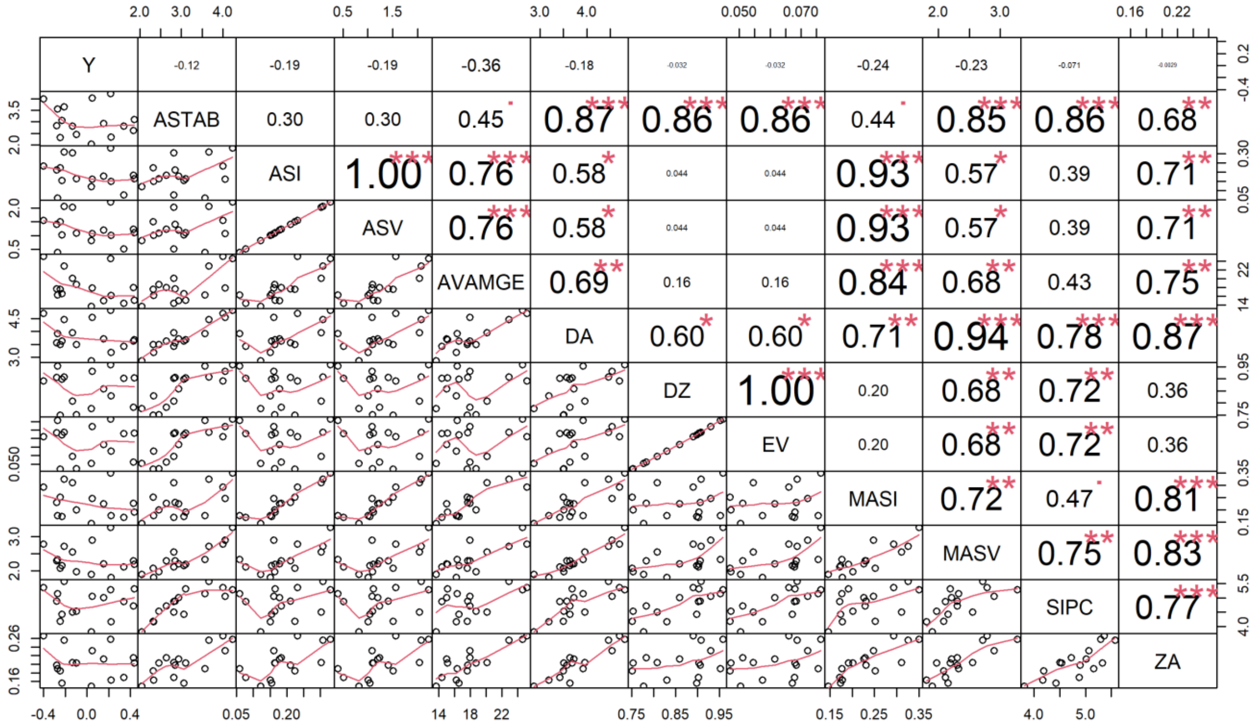
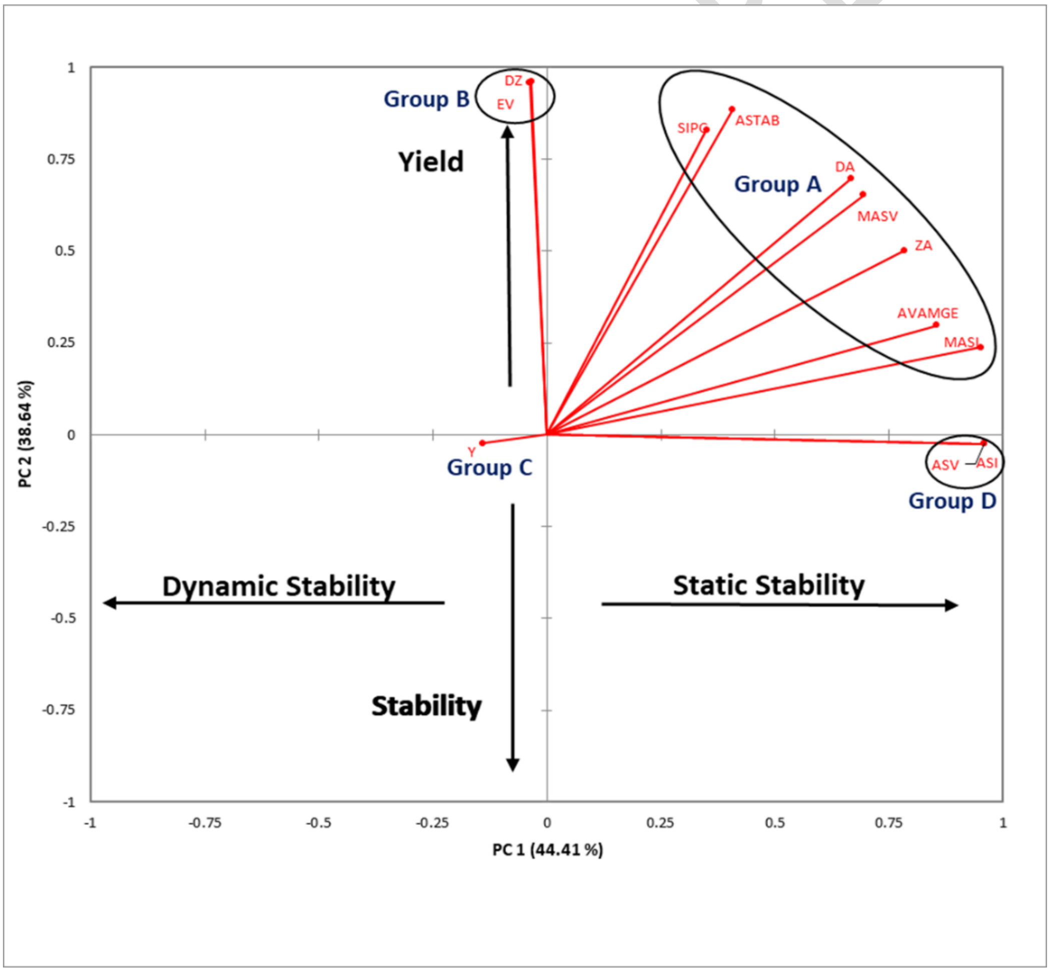


Fig.1. Spearman's rank correlation coefficients and scatter plots among AMMI Stability



Measures (*P <0.05, **P <0.01 and ***P <0.001)

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

4. CONCLUSION

Genotype environment interaction is a major 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 biological concept of stability and the stability measures DZ and EV are based on agronomic concept of stability. Selection of mango genotypes based on agronomic concept of stability will be recommended in favourable environments, while in unfavourable environments, selection based on biological stability will be recommended. This study also concludes that AMMI analysis and various AMMI stability measures more helpful in analysis of GEI and evaluation of genotypic performance of perennials especially in mango.

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