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Evaluation of Genotype × Environment Interaction and Yield Stability Analysis in Peanut Under Phosphorus Stress Condition Using Stability Parameters of AMMI Model

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Abstract Development of new genotypes with high yield and acceptable level of stability is an important breeding programme. The genotype × environment interaction (GEI) was studied to find out stable high yielders in a field experiment conducted with 52 peanut genotypes for 2 years under two phosphorus levels. Combined analysis of variance showed that environment effect was a predominant source of variation followed by GEI and genotype effect. Study of the AMMI model for GEI indicated that the first three interaction principal components (IPCA1–IPCA3) were highly significant ($P < 0.01$). Using these significant IPCAs, 12 AMMI stability parameters and simultaneous selection for yield and stability (SSI) were computed. SSI identified genotypes PBS-22080, PBS-22083 and Somnath as the most stable high yielders and PBS-29172 as the least stable low yield. Stability measures such as SIPC, MASI and MASV could be used to identify stable high-yielding genotypes.

Keywords AMMI · Genotype × environment interaction · Peanut · Stability measures · SSI

Introduction

Yearly variations in the yield and phenotypic trait of a genotype are due to environmental variations and GEI. GEI is the most common feature resulting from the differential expression of genotypes over the environments which complicate the selection of a genotype for a target trait as various genotypes respond in a different way under varied environmental conditions. Under such conditions, stability analysis provides the best solution for the relative performance of genotypes over the environments. Several parametric and nonparametric statistical tools are available to study GEI [23, 24] such as coefficients of determination (Ri^2) [26], coefficient of variability (CVi) [14] and the genotypic variances across environments (S^2i) [31], regression coefficient (*bi*) [13] and Shukla's [36] stability variance (σi^2), regression coefficient (*bi*) and deviation from regression (S^2di) [9, 25], Wricke's ecovalence [40] and cultivar performance measure [21]. Main problem with these stability indices is that they are univariate, but the genotypic response to an environment is multivariate [6, 15]. Hence, stability statistics also should be a multivariate to give the correct picture of GEI on genotype and one such multivariate technique is the Additive Main Effect and Multiplicative Interaction (AMMI) model [15]. Gauch et al. [16] claimed the AMMI model performs much better than linear regression models and other multivariate procedures such as GGE biplot [41] in deciphering GEI.

In multilocational yield trials aimed at developing superior genotypes, researchers are faced with two kinds of problems, i.e. genotypes are different and environments/target sites are varying. Hence, there are two options

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to the problem: one aimed at genotype, and other aimed at environment. One option is to develop the high-yielding widely adapted genotype which can be grown throughout the environments. If this option fails, the other option is to group environments into relatively homogenous macro-environment and then recommend genotypes for each [27]. The AMMI model addresses both of these challenges of genotype and environment together and assists in investigating the above-mentioned options [17]. The AMMI model is comprised of additive main effects of genotype and environment, and the multiplicative effect of GE interaction, and thus can explain more information compared to other methods [35]. AMMI models are generally called AMMI (1), AMMI (2), … AMMI (*n*), depending on the number of principal components used to study the interaction.

The AMMI model does not make provision for a quantitative stability measure, which is essential in order to quantify and rank genotypes according to their yield stability. AMMI stability parameters permit to evaluate yield stability after reduction of the noise from the GE interaction effects [33]. In order to quantify the AMMI model, several stability measures are available in literature and are listed in Table 1 with an objective to use different AMMI model stability parameters to estimate yield stability of improved peanut genotypes and to explore the advantages and disadvantages of different AMMI stability parameters in selecting stable peanut genotypes.

Materials and Methods

A total of 52 groundnut genotypes comprising 47 advanced breeding lines; two cultivated varieties of different seed sizes (BAU 13, Somnath); two P-efficient lines (ICGV 86590, SP250A); and a P-inefficient (NRCG 7320) line

Table 1 AMMI stability parameters

AMMI stability parameter		Description	References
AMGE	Sum across environments of GEI modelled by AMMI	$\mathrm{AMGE} = \sum_{j=1}^{E}\sum_{n=1}^{N'} \lambda_n \gamma_{in} \delta_{jn}$	Sneller et al. [38]
ASI	AMMI stability index	$\mathrm{ASI} = \sqrt{[PC_1^2 \times \theta_1^2] + [PC_2^2 \times \theta_2^2]}$	Jambhulkar et al. [20]
ASV	AMMI stability value	$\mathrm{ASV} = \sqrt{\left(\frac{\mathrm{SSIPC}_1}{\mathrm{SSIPC}_2} \times \mathrm{PC}_1\right)^2 + (\mathrm{PC}_2)^2}$	Purchase [27]
ASTAB	AMMI-based stability parameter	$\mathrm{ASTAB} = \sum_{n=1}^{N'} \lambda_n \gamma_{in}^2$	Rao and Prabhakaran [30]
AVAMGE	Sum across environments of absolute value of genotype × environment interaction modelled by AMMI	$\mathrm{AV}_{(\mathrm{AMGE})} = \sum_{j=1}^{E}\sum_{n=1}^{N'} \lvert \lambda_n \gamma_{in} \delta_{jn} \rvert$	Zali et al. [43]
DA	Annicchiarico's D parameter	$D_a = \sqrt{\sum_{n=1}^{N'} (\lambda_n \gamma_{in})^2}$	Annicchiarico [4]
DZ	Zhang's D parameter or AMMI statistic coefficient or AMMI distance or AMMI stability index	$D_z = \sqrt{\sum_{n=1}^{N'} \gamma_{in}^2}$	Zhang et al. [44]
EV	Averages of the squared eigenvector values	$\mathrm{EV} = \sum_{n=1}^{N'} \frac{\gamma_{in}^2}{N'}$	Zobel [45]
FA	Stability measure based on fitted AMMI model	$\mathrm{FA} = \sum_{n=1}^{N'} \lambda_n^2 \gamma_{in}^2$	Raju [29] and Zali et al. [43]
MASI	Modified AMMI stability Index	$\mathrm{MASI} = \sqrt{\sum_{n=1}^{N'} PC_n^2 \times \theta_n^2}$	[2]
MASV	Modified AMMI stability value	$\mathrm{MASV} = \sqrt{\sum_{n=1}^{N'-1} \left(\frac{\mathrm{SSIPC}_n}{\mathrm{SSIPC}_{n+1}} \times \mathrm{PC}_n\right)^2 + (\mathrm{PC}_{N'})^2}$	Zali et al. [43]
SIPC	Sums of the absolute value of the IPC scores	$\mathrm{SIPC} = \sum_{n=1}^{N'} \lvert \lambda_n^{0.5} \gamma_{in} \rvert$	Sneller et al. [38]
Za	Absolute value of the relative contribution of IPCs to the interaction	$\mathrm{Za} = \sum_{i=1}^{N'} \lvert \theta_n \gamma_{in} \rvert$	Zali et al. [43]

[3, 37] were evaluated during 2013 and 2014 rainy seasons under two levels of P, i.e. without P application of 0 kg/ha (LP) and with application of 50 kg/ha P_2O_5 (as single superphosphate) (MP). Nitrogen (as urea) and potash (as muriate of potash) were applied at 50 kg/ha N and 60 kg/ha K_2O equally for both the treatments. The recommended crop management practices were adopted for raising a healthy crop. Field screening was conducted at ICAR-Directorate of Groundnut Research, Junagadh (lat 21° 31′ N, long 70° 36′ E), India, in a medium black calcareous (17% $CaCO_3$) clayey, Vertic Ustochrept soil having moderate available phosphorus (15 kg/ha P), 7.5 pH, 0.7% organic C, 268 kg/ha N, 300–400 kg/ha K, 5 kg/ha available S and 1.6, 15, and 0.78 kg/ha DTPA extractable Fe, Mn, and Zn, respectively.

All the statistical analyses involving the AMMI model were performed in R [28] using package 'agricolae' [7]. Twelve stability parameters of the AMMI model were computed, and further genotypes were ranked on the basis of simultaneous selection index for yield and stability (SSI) as suggested by Farshadfar et al. [11] using the package 'ammistability' [1]. The details about AMMI stability parameters/indices used in the present manuscript are listed in Table 1. AMMI stability values were subjected to PCA, and a plot of the first two PCs scores was drawn and correlation among these stability values was calculated using PAST software [18].

Results and Discussion

The AMMI analysis of variance on peanut pod yield with and without phosphorus application (Table 2) showed that peanut yields were significantly ($p < 0.01$) affected by environment (E), genotypes (G) and GE interaction. Environment significantly explained about 59.9% of the total sum of squares due to treatments indicating that diverse environments caused most of the variations in yield. Up to 80% contribution of environment towards overall variation in MLT data has been reported in various crops [8, 39].

Table 2 AMMI analysis of variance for pod yield under with and without phosphorus treatments

	Df	Sum Sq	MSS	*F* value	% ss
Environment (E)	3	3871.2	1290.4**	366.0	59.9
Rep	4	14.1	3.5	2.3	0.2
Genotype (G)	51	998.4	19.6**	12.6	15.5
E*G	153	1259.7	8.2**	5.3	19.5
PC1	53	628.4	11.9	7.7	49.9
PC2	51	364.3	7.1	4.6	28.9
PC3	49	267.0	5.4	3.5	21.2
Residuals	204	316.1	1.55		4.9

Genotypes explained 15.5% of total sum of squares, whereas GEI explained 19.5% of treatment variation in pod yield. The larger magnitude of GEI (sum of squares) than genotypes indicated the presence of genotypic differences across environments and complex GE interaction for pod yield in groundnut. High GEI effects over genotype are reported in several studies [5, 11, 32], thus making selection of stable genotype difficult.

Though E contributed about 60% of the total variability in the present study as compared to 80% in other studies, only G and GEI are relevant to the evaluation of genotypes in multi-environment trials [42]. The multivariate procedures such as AMMI model can display several aspects of multidimensionality of GE interaction phenomenon [19]. The partitioning of GEI through the AMMI model revealed that the first three multiplicative terms (IPCA1, IPCA2 and IPCA3) of AMMI were significant and explained 49.9%, 28.9% and 21.2% of GEI sum of squares, respectively. The remaining 4.9% is the residual or noise, which is not interpretable and thus discarded [27]. Significant proportion of GEI warrants the estimation of phenotypic stability [12] of genotypes over environments.

AMMI Stability Measure

The AMMI model does not make provision for a quantitative stability measure, which is essential to quantify and rank the genotypes according. Twelve such stability measures from the AMMI model (formulas presented in Table 1) were compared with mean yield for each genotype over all environments, and results are presented in Table 3. Further, simultaneous selection index for yield and stability (SSI) was computed for each of the twelve measures of stability as per the formula suggested by Farshadfar et al. [11]. The 52 genotypes were then ranked based on SSI for each of the twelve measures of stability from the AMMI model such that genotype with high yield and stability gets top rank, whereas low-yielding and unstable genotype gets the least rank. The SSI rank orders displayed by these twelve measures of stability from AMMI model are presented in Table 4.

According to averages of the squared eigenvector values (EV) stability statistic, a genotype is considered to be more stable if EV is low. Accordingly, the genotype PBS-22083 followed by PBS-29145 and PBS-29017 had high stability and genotype PBS-29148 had the least stability. Since EV does not provide any advantage in favourable environments, genotypes screened by this measure can be recommended for less favourable environments or where farmers do not have advanced technology.

The AMMI stability index (ASI), AMMI stability value (ASV), Modified AMMI stability value (MASV) and

Table 3 Mean yield (Y, g/plant) and stability parameter estimates (ASI, ASTAB, AVAMGE, DA, DZ, EV, FA, MASI, MASV, SIPC, Za) and their ranks of 52 peanut advanced breeding lines tested in 4 environments

Genotype	Y	ASI	ASV	ASTAB	AVAMGE	DA	DZ	EV	FA	MASI	MASV	SIPC	Za
BAU-13	2606.13	5.8 (37)	19.9 (37)	213.1 (33)	1406 (32)	853 (32)	0.25 (31)	0.021 (32)	727,608 (32)	5.9 (37)	22.2 (34)	24.5 (40)	0.151 (40)
ICGV-86590	3218.85	5.7 (36)	19.8 (36)	376.5 (49)	1747 (41)	1065.8 (48)	0.35 (49)	0.042 (49)	1,135,915 (48)	5.7 (36)	26.6 (46)	22.4 (35)	0.125 (32)
M-13	2957.48	7.1 (45)	24.7 (47)	452.2 (51)	1915 (49)	1197.4 (51)	0.38 (51)	0.049 (51)	1,433,789 (51)	7.4 (46)	30.1 (51)	35.6 (51)	0.208 (51)
NRCG-7320	2212.00	1.6 (5)	5.7 (5)	180.7 (29)	1127 (23)	691.1 (26)	0.26 (34)	0.023 (34)	477,665 (26)	3.1 (15)	14.4 (19)	18.4 (26)	0.085 (17)
PBS-22075	2265.33	2.1 (10)	7.2 (10)	149.9 (25)	1036 (18)	639 (23)	0.24 (30)	0.019 (30)	408,332 (23)	3.1 (15)	13.7 (18)	18.7 (27)	0.095 (21)
PBS-22076	2858.05	2.2 (11)	7.7 (11)	63.5 (8)	730 (9)	436.7 (7)	0.15 (9)	0.007 (7)	190,695 (7)	2.6 (5)	10.2 (6)	11.5 (7)	0.065 (8)
PBS-22077	3185.52	6.8 (42)	23.4 (42)	292.6 (43)	1904 (48)	999.8 (44)	0.3 (42)	0.029 (41)	999,619 (44)	6.8 (42)	26.2 (43)	27 (45)	0.17 (47)
PBS-22080	3424.94	2.6 (13)	9.1 (13)	62.9 (7)	690 (7)	445 (8)	0.14 (6)	0.007 (7)	198,054 (8)	2.7 (9)	11.2 (9)	12.8 (12)	0.074 (10)
PBS-22081	2920.82	1.7 (6)	5.9 (7)	125.8 (21)	1113 (22)	581.4 (16)	0.22 (23)	0.016 (23)	338,071 (16)	2.7 (9)	12.5 (13)	16.4 (21)	0.079 (15)
PBS-22082	2327.82	3.3 (18)	11.5 (18)	46.4 (5)	696 (8)	424.5 (6)	0.11 (3)	0.004 (3)	180,234 (6)	3.3 (18)	11.6 (10)	8.8 (2)	0.063 (6)
PBS-22083	2890.54	1 (1)	3.4 (1)	4.3 (1)	216 (1)	127.5 (1)	0.03 (1)	0 (1)	16,258 (1)	1 (1)	3.4 (1)	2.9 (1)	0.02 (1)
PBS-22084	3316.89	8.2 (51)	28.5 (51)	319.8 (47)	2018 (51)	1093.3 (49)	0.3 (42)	0.029 (41)	1,195,257 (49)	8.4 (51)	29.3 (50)	23.9 (38)	0.163 (45)
PBS-22086	3540.48	7.6 (48)	26.4 (48)	236.5 (35)	1795 (42)	963.3 (41)	0.25 (31)	0.02 (31)	927,911 (41)	7.6 (47)	26.4 (45)	17.7 (25)	0.133 (35)
PBS-22088	2103.40	1.1 (2)	3.8 (2)	41.9 (3)	543 (2)	337.8 (2)	0.12 (5)	0.005 (5)	114,107 (2)	1.6 (2)	7.3 (2)	9.9 (4)	0.05 (2)
PBS-22091	2615.02	6.8 (42)	23.4 (42)	243.5 (36)	1862 (47)	935.6 (38)	0.26 (34)	0.023 (34)	875,283 (38)	6.8 (42)	24.9 (40)	24.6 (41)	0.16 (44)
PBS-29017	2538.64	2.9 (16)	10.1 (16)	42.1 (4)	666 (5)	393.8 (5)	0.11 (3)	0.004 (3)	155,051 (5)	2.9 (14)	10.6 (7)	9.9 (4)	0.066 (9)
PBS-29035	3006.64	4 (24)	13.7 (24)	136.5 (23)	1216 (29)	660.2 (25)	0.21 (21)	0.015 (21)	435,901 (25)	4.2 (22)	16.4 (23)	20.2 (31)	0.118 (28)
PBS-29067	2730.56	6.8 (42)	23.5 (44)	186.2 (31)	1497 (35)	855.5 (33)	0.22 (23)	0.016 (23)	731,822 (33)	6.8 (42)	23.5 (38)	15.3 (18)	0.116 (27)
PBS-29077	2367.26	5 (34)	17.2 (34)	256 (38)	1576 (38)	889.9 (36)	0.29 (40)	0.029 (41)	791,976 (36)	5.5 (35)	21.6 (32)	27.5 (46)	0.157 (43)
PBS-29080	2686.68	7.8 (49)	26.9 (49)	283.1 (42)	2051 (52)	1029.5 (47)	0.28 (38)	0.026 (38)	1,059,931 (47)	7.8 (49)	27.8 (48)	25 (42)	0.169 (46)
PBS-29083	2974.98	6.1 (39)	21.1 (39)	254.7 (37)	1508 (36)	924 (37)	0.28 (38)	0.026 (38)	853,689 (37)	6.1 (38)	24.1 (39)	23.3 (36)	0.148 (38)
PBS-29087	2677.51	2.7 (14)	9.5 (14)	71.5 (11)	682 (6)	472.4 (10)	0.15 (9)	0.008 (11)	223,131 (10)	2.8 (11)	11.9 (11)	12.7 (11)	0.074 (10)
PBS-29098	2556.41	1.2 (3)	4.3 (3)	52.8 (6)	626 (3)	379.3 (4)	0.14 (6)	0.007 (7)	143,874 (4)	1.9 (3)	8.1 (3)	10.9 (6)	0.056 (3)
PBS-29115	2999.42	4.9 (32)	17 (32)	151.4 (26)	1133 (24)	722 (29)	0.21 (21)	0.015 (21)	521,223 (29)	5.1 (33)	18.5 (30)	18.9 (28)	0.118 (28)
PBS-29124	3542.42	4.3 (27)	14.7 (26)	313.4 (46)	1847 (45)	948.8 (40)	0.33 (47)	0.037 (47)	900,307 (40)	5 (32)	22 (33)	29.2 (50)	0.155 (42)
PBS-29125	2841.38	4.1 (25)	14 (25)	157.3 (28)	1212 (28)	702.5 (27)	0.23 (28)	0.017 (28)	493,510 (28)	4.4 (25)	17.2 (26)	21.6 (33)	0.125 (32)
PBS-29137	2659.46	2.9 (16)	10.1 (16)	69.2 (10)	830 (11)	473.1 (11)	0.15 (9)	0.007 (7)	223,866 (11)	3.1 (15)	11.9 (11)	14.4 (16)	0.085 (17)
PBS-29138	2835.27	5.2 (35)	18.1 (35)	351.8 (48)	1857 (46)	1022 (46)	0.34 (48)	0.04 (48)	1,044,478 (46)	5.3 (34)	25.2 (42)	24 (39)	0.124 (31)
PBS-29143	2510.03	4.7 (29)	16.1 (29)	297 (44)	1535 (37)	935.7 (39)	0.32 (45)	0.034 (45)	875,543 (39)	4.9 (30)	22.8 (36)	25 (42)	0.131 (34)
PBS-29145	2750.56	2.5 (12)	8.8 (12)	33.5 (2)	635 (4)	348.3 (3)	0.1 (2)	0.003 (2)	121,320 (3)	2.6 (5)	9.3 (4)	9.1 (3)	0.059 (5)
PBS-29148	3090.52	8.4 (52)	29.1 (52)	531.9 (52)	1929 (50)	1324.8 (52)	0.41 (52)	0.056 (52)	1,754,994 (52)	9 (52)	33.2 (52)	37.9 (52)	0.228 (52)
PBS-29149	2267.00	1.7 (6)	5.8 (6)	126.6 (22)	1049 (19)	582.8 (17)	0.22 (23)	0.016 (23)	339,670 (17)	2.6 (5)	12.5 (13)	15.8 (19)	0.074 (10)
PBS-29150	2541.97	6 (38)	20.9 (38)	303.3 (45)	1582 (39)	987.2 (42)	0.31 (44)	0.032 (44)	974,494 (42)	6.2 (39)	25.1 (41)	28.9 (49)	0.171 (48)
PBS-29151	2837.22	3.6 (22)	12.5 (22)	123 (20)	1031 (17)	622.3 (21)	0.2 (20)	0.014 (20)	387,268 (21)	4 (20)	15.1 (21)	17.6 (24)	0.103 (23)
PBS-29152	2751.67	2 (9)	6.8 (9)	137.5 (24)	1112 (21)	610.6 (19)	0.23 (28)	0.017 (28)	372,794 (19)	2.8 (11)	13.3 (17)	16.4 (21)	0.076 (14)

Table 3 (continued)

Genotype	Y	ASI	ASV	ASTAB	AVAMGE	DA	DZ	EV	FA	MASI	MASV	SIPC	Za
PBS-29153	2793.05	4.7 (29)	16.1 (29)	96.7 (16)	1020 (16)	606.8 (18)	0.16 (12)	0.009 (12)	368,224 (18)	4.7 (28)	16.4 (23)	13.2 (13)	0.092 (19)
PBS-29157	2339.49	4.7 (29)	16.3 (31)	110.2 (19)	1156 (25)	636.6 (22)	0.18 (16)	0.01 (15)	405,212 (22)	4.8 (29)	16.9 (25)	14 (14)	0.094 (20)
PBS-29158	2932.76	4.9 (32)	17 (32)	108.7 (18)	1076 (20)	642.3 (24)	0.17 (13)	0.01 (15)	412,594 (24)	4.9 (30)	17.4 (28)	15 (17)	0.103 (23)
PBS-29159	2849.16	3.5 (20)	12.3 (21)	197.1 (32)	1250 (30)	758.3 (30)	0.26 (34)	0.023 (34)	575,040 (30)	4.3 (23)	17.3 (27)	22.1 (34)	0.122 (30)
PBS-29160	2514.47	6.4 (41)	22.1 (41)	183.8 (30)	1402 (31)	834.2 (31)	0.22 (23)	0.016 (23)	695,861 (31)	6.4 (41)	22.6 (35)	19.6 (30)	0.134 (36)
PBS-29161	2335.60	4.4 (28)	15.1 (28)	107.4 (17)	1203 (27)	616.8 (20)	0.18 (16)	0.01 (15)	380,483 (20)	4.5 (26)	16.1 (22)	16.6 (23)	0.105 (25)
PBS-29162	2581.13	4.2 (26)	14.7 (26)	154.9 (27)	1192 (26)	702.5 (27)	0.22 (23)	0.016 (23)	493,469 (27)	4.3 (23)	17.9 (29)	19.5 (29)	0.115 (26)
PBS-29164	2684.73	7.1 (45)	24.5 (46)	395.6 (50)	1835 (44)	1137.1 (50)	0.36 (50)	0.042 (49)	1,293,012 (50)	7.7 (48)	28.2 (49)	28.6 (48)	0.174 (49)
PBS-29165	2734.17	3.4 (19)	11.6 (19)	279.9 (40)	1462 (33)	883 (35)	0.32 (45)	0.034 (45)	779,697 (35)	4.6 (27)	19.4 (31)	25.9 (44)	0.137 (37)
PBS-29166	2491.42	3.5 (20)	11.9 (20)	64.6 (9)	821 (10)	480.5 (12)	0.14 (6)	0.006 (6)	230,899 (12)	3.5 (19)	12.8 (15)	12.1 (9)	0.08 (16)
PBS-29168	2466.98	3.9 (23)	13.5 (23)	94.4 (15)	947 (15)	569.9 (15)	0.17 (13)	0.009 (12)	324,829 (15)	4 (20)	14.9 (20)	16.2 (20)	0.101 (22)
PBS-29169	2935.82	7.8 (49)	27 (50)	270.1 (39)	1818 (43)	1014.9 (45)	0.27 (37)	0.024 (37)	1,030,070 (45)	7.9 (50)	27.5 (47)	21.4 (32)	0.15 (39)
PBS-29170	2434.76	1.9 (8)	6.5 (8)	90.5 (13)	848 (13)	501.6 (13)	0.18 (16)	0.011 (19)	251,635 (13)	2.6 (5)	10.9 (8)	14.1 (15)	0.075 (13)
PBS-29171	2182.28	2.8 (15)	9.6 (15)	92 (14)	899 (14)	525.1 (14)	0.18 (16)	0.01 (15)	275,728 (14)	2.8 (11)	13 (16)	11.8 (8)	0.063 (6)
PBS-29172	2180.06	6.2 (40)	21.4 (40)	213.5 (34)	1480 (34)	870.6 (34)	0.25 (31)	0.021 (32)	757,909 (34)	6.3 (40)	23 (37)	23.6 (37)	0.151 (40)
Somnath	3159.96	1.3 (4)	4.6 (4)	75.8 (12)	832 (12)	451.6 (9)	0.17 (13)	0.009 (12)	203,915 (9)	2.1 (4)	9.7 (5)	12.1 (9)	0.056 (3)
SP-250A	2621.405	7.1 (45)	24.4 (45)	281.6 (41)	1641 (40)	997.7 (43)	0.29 (40)	0.027 (40)	995,449 (43)	7.2 (45)	26.2 (43)	27.6 (47)	0.174 (49)

Values in the parenthesis indicate their ranks

Table 4 Ranking of genotypes based on simultaneous selection index considering stability and yield (SSI) [11]

Genotype	ASI	ASV	ASTAB	AVAMGE	DA	DZ	EV	FA	MASI	MASV	SIPC	Za
BAU-13	70	70	66	65	65	66	66	65	70	67	73	74
ICGV-86590	41	41	54	46	53	54	54	53	41	51	40	38
M-13	59	59	63	61	63	63	63	63	58	63	63	63
NRCG-7320	54	54	78	72	75	83	83	75	65	68	75	67
PBS-22075	58	58	73	66	71	78	78	71	65	66	75	69
PBS-22076	28	28	25	26	24	27	27	24	24	23	24	25
PBS-22077	49	49	49	54	50	48	48	50	50	49	51	53
PBS-22080	16	16	10	10	11	11	11	11	13	12	15	15
PBS-22081	22	22	36	37	31	38	38	31	24	28	36	30
PBS-22082	64	64	51	54	52	50	50	52	64	56	48	53
PBS-22083	17	17	17	17	17	17	17	17	17	17	17	17
PBS-22084	55	55	51	55	53	47	47	53	55	54	42	49
PBS-22086	50	50	37	44	43	33	33	43	49	47	27	37
PBS-22088	54	54	55	54	54	57	57	54	54	54	57	54
PBS-22091	74	74	68	79	70	67	67	70	75	72	73	76
PBS-29017	54	54	41	42	42	40	40	42	51	44	41	46
PBS-29035	33	33	32	38	34	30	30	34	31	33	40	38
PBS-29067	70	70	57	61	59	51	51	59	68	64	44	53
PBS-29077	77	77	81	81	79	84	84	79	78	75	89	86
PBS-29080	76	76	69	79	74	65	65	74	76	75	69	73
PBS-29083	50	50	48	47	48	50	50	48	49	50	47	49
PBS-29087	43	43	40	35	39	40	40	39	40	41	40	40
PBS-29098	38	38	41	38	39	42	42	39	38	38	41	38
PBS-29115	42	42	36	34	39	32	32	39	43	40	38	38
PBS-29124	28	28	47	46	41	48	48	41	33	34	51	43
PBS-29125	44	44	47	47	47	48	48	47	44	45	52	51
PBS-29137	46	46	40	41	41	39	39	41	45	41	46	47
PBS-29138	56	56	69	67	67	69	69	67	55	63	60	52
PBS-29143	68	68	83	76	78	84	84	78	69	75	82	73
PBS-29145	36	36	26	28	27	26	26	27	29	28	27	29
PBS-29148	60	60	60	58	60	60	60	60	60	60	60	60
PBS-29149	53	53	69	66	64	71	71	64	55	61	66	57
PBS-29150	74	74	81	75	78	80	80	78	75	77	85	84
PBS-29151	42	42	40	37	41	40	40	41	41	41	44	43
PBS-29152	32	32	47	44	42	51	51	42	36	40	45	37
PBS-29153	52	52	38	38	40	34	34	40	50	45	35	41
PBS-29157	75	75	63	69	66	61	61	66	73	69	58	64
PBS-29158	47	47	32	34	38	29	29	38	45	42	31	38
PBS-29159	39	39	50	48	48	54	54	48	42	45	52	48
PBS-29160	79	79	68	69	69	64	64	69	79	73	68	74
PBS-29161	73	73	62	72	65	63	63	65	71	67	68	70
PBS-29162	60	60	61	60	61	61	61	61	57	63	63	60
PBS-29164	74	74	78	72	78	78	78	78	76	77	76	77
PBS-29165	44	44	65	58	60	71	71	60	52	56	69	62
PBS-29166	60	60	49	50	52	46	46	52	59	55	49	56
PBS-29168	64	64	56	56	56	54	54	56	61	61	61	63
PBS-29169	63	63	52	56	58	50	50	58	63	60	45	52

Table 4 (continued)

Genotype	ASI	ASV	ASTAB	AVAMGE	DA	DZ	EV	FA	MASI	MASV	SIPC	Za
PBS-29170	50	50	55	55	55	61	61	55	48	50	57	55
PBS-29171	65	65	64	64	64	66	66	64	62	66	58	56
PBS-29172	91	91	85	85	85	83	83	85	91	88	88	91
Somnath	11	11	19	19	16	21	21	16	11	12	17	11
SP-250A	76	76	72	71	74	71	71	74	76	75	78	81

modified AMMI stability index (MASI) are comparable with other AMMI stability parameters to study GEI. Results of ASI and ASV showed that genotype, PBS-22083, PBS-22088 and PBS-29098 were most stable and PBS-29148 the least stable. Parameters ASI and ASV are useful when the proportion of variation explained by the first two IPCAs is high, but when three or more IPCAs are significant total variation explained by these parameters is low. The values of MASI and MASV which consider all significant IPCAs also showed that the genotypes PBS-22083, PBS-22088 and PBS-29098 are most stable and again PBS-29148 was found the least stabile one. ASI and ASV measures are equivalent to drawing a biplot with the first two PCA axes, whereas MASI and MASV measures are equivalent to plot with all significant PCA axes for ranking of genotypes, while comparing ASV and MASV [43] also was of similar opinion.

The sum across environments of absolute value of GEI modelled by AMMI (AVAMGE) parameters are sum of absolute value of eigenvectors across all environments. The largest absolute value of AVAMGE was for the genotype PBS-22080 making it least stable one, whereas most stable genotypes were PBS-22083, PBS-22088 and PBS-29098. Annicchiarico's D parameter (DA) was similar to Zhang's D parameter (DZ), AMMI-based stability parameter (ASTAB) and fitted AMMI model (FA) as all these parameters identified genotypes PBS-22083 PBS-29145 and PBS-22088 as most stable and genotype PBS-29148 was least stable in this study.

The sums of the absolute value of the IPC scores (SIPC) identified PBS-22083 followed by PBS-22082 and PBS-29145 as the most stable genotypes, whereas PBS-29148 as the least stable one. Absolute value of the relative contribution of IPCs to the interaction (Za) revealed PBS-22083, PBS-22088 and PBS-29098 genotypes as most stable in descending order of stability, whereas PBS-29148 genotype with the least stability.

Simultaneous Selection of Genotypes for Yield and Stability (SSI)

The stability alone by itself is not a desirable selection criterion as these stable genotypes may not be a high yielders, for which simultaneous consideration of grain yield and stability in a single nonparametric index is essential [11, 22, 23]. Thus, it is necessary to include both phenotypic trait and stability in a single selection index. SSI proposed by Farshadfar [10] also referred to as genotype stability index (GSI) or yield stability index (YSI) [11] was computed by adding the ranks of stability index/parameter and mean yields. The least SSI is considered as most stable with high yield, whereas high SSI is considered as least stable with low yield. In the present study, SSI computed using all stability measures identified genotypes PBS-22080, PBS-22083 and Somnath as most stable and high yielders, whereas genotype PBS-29172 is least stable with low yield.

Association Among Different Stability Parameters

Spearman's rank correlation was computed for each pair of yield and AMMI stability measures and are presented in Table 5. Mean yield showed a highly significant positive correlation with all AMMI stability measures except SIPC, Za and DZ. ASI and ASV revealed a positive correlation with other stability measures, and comparisons based on these methods will be equivalent to comparisons based on first two PCA axes. The FA was highly correlated with the measures SIPC, EV, AVAMGE, ASV, MASV, ASI, MASI, DZ, Za, DA and mean yield. The ASI and ASV were highly correlated with all other stability measures and mean yield. Sneller et al. [38] stability statistics (SIPC), Zhang's stability statistic (DZ) and Za showed the highest positive correlation with other methods and non-significant correlation with mean yield.

To better understand the relationships among stability measures from AMMI model, principal component analysis (PCA) based on the rank correlation matrix (Fig. 1) was used. The first two PCAs explained 99.8% of variation. The relationships among the different AMMI stability parameters are graphically displayed by plotting the first two PCs scores (Fig. 1). The PC1 and PC2 axes distinguish stability measures into different groups. SIPC, ASI, MASI, ASV and MASV; DZ and Za and DA and AVAMGE were grouped together. Stability measures EV, ASTAB and FA formed separate groups. Sabaghnia et al.

Table 5 Spearman's rank correlation among 11 stability parameter estimates and simultaneous selection indices estimated for pod yield (Y, g/plant) using data from 52 peanut genotypes grown under 4 environments

	Y	ASI	ASV	ASTAB	AVAMGE	DA	DZ	EV	FA	MASI	MASV	SIPC
Y												
ASI	0.32*											
ASV	0.32*	1.00**										
ASTAB	0.33*	0.76**	0.76**									
AVAMGE	0.34*	0.86**	0.86**	0.91**								
DA	0.31*	0.87**	0.87**	0.97**	0.97**							
DZ	0.27	0.67**	0.67**	0.97**	0.91**	0.95**						
EV	0.32*	0.63**	0.63**	0.96**	0.84**	0.90**	0.95**					
FA	0.35*	0.86**	0.86**	0.98**	0.94**	0.98**	0.93**	0.92**				
MASI	0.31*	0.99**	0.99**	0.83**	0.91**	0.92**	0.76**	0.71**	0.91**			
MASV	0.32*	0.94**	0.94**	0.92**	0.96**	0.98**	0.88**	0.83**	0.97**	0.97**		
SIPC	0.24	0.71**	0.71**	0.93**	0.88**	0.93**	0.95**	0.91**	0.91**	0.79**	0.87**	
Za	0.27	0.87**	0.87**	0.90**	0.91**	0.94**	0.87**	0.84**	0.93**	0.91**	0.94**	0.96**

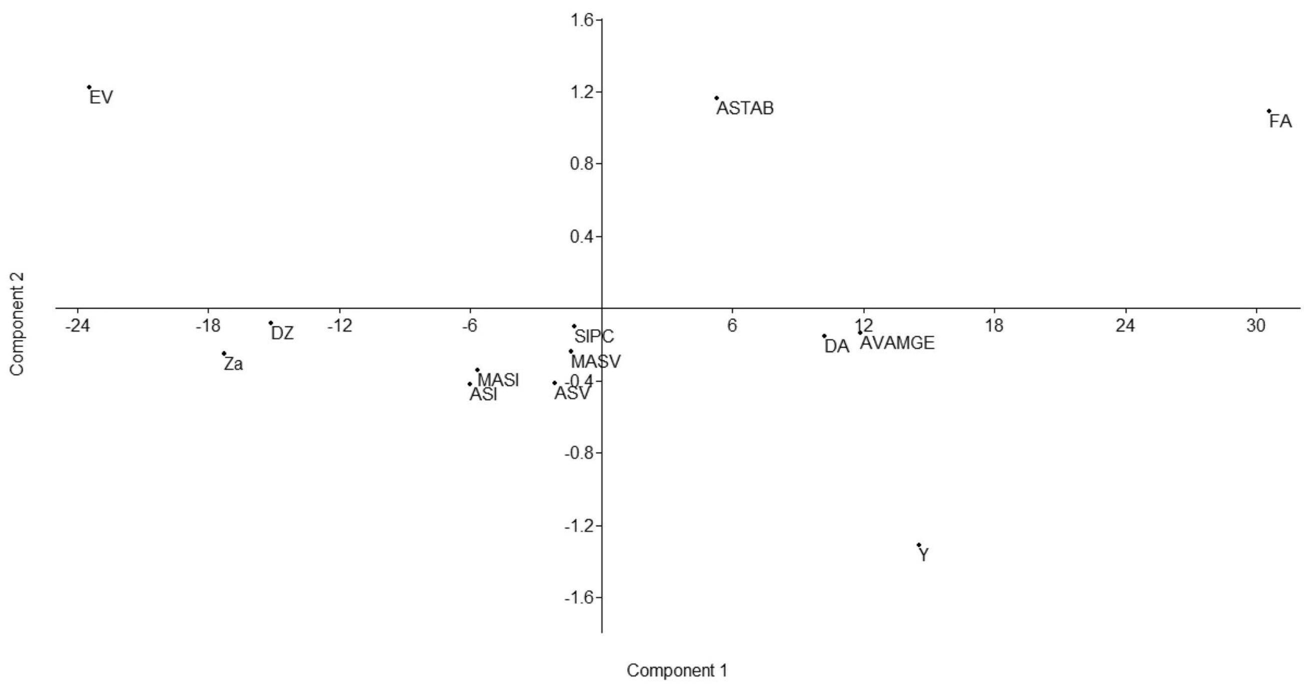

Fig. 1 Plot of the first two principal components (PC1 v. PC2) of standard values of stability of yield, estimated by 11 methods using yield data from 52 peanut genotypes grown in 4 environments

[34] while studying stability of wheat genotypes compared with different AMMI stability parameters have indicated that AMGE-based parameters can detect highly seed yield genotypes with good stability as most of the AMGE parameters were located near to zero on PC2 axis. In the present study, AMMI parameters namely SIPC, ASI, MASI, ASV and MASV were closer to zero on PC2 axis. MASI and MASV are modified versions of ASI and ASV, respectively. Hence, parameters MASI, MASV and SIPC could be used to identify stable high-yielding genotypes.

Conclusions

Thus, it is concluded that the AMMI model is an effective tool to study GEI in multi-environment yield trials in peanut. All the stability measures found to be correlated well with each other, and nine out of twelve such measures also exhibited a significant positive correlation with peanut yield. Parameters MASI, MASV and SIPC could be used to identify stable high-yielding genotypes. The present study also identified genotypes PBS-22080, PBS-22083 and Somnath as most stable and high yielders and PBS-29172 as least stable with low yield.

Authors' Contribution ABC, SKB and ALS were involved in conceptualization of research; ABC and NK were involved in designing of the experiments; NK and MCD were involved in contribution of experimental materials; ABC and NK were involved in execution of field/laboratory experiments and data collection; ABC, GK and PK were involved in analysis of data and interpretation; ABC, SKB, and PK were involved in preparation of the manuscript.

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Compliance with Ethical Standards

Conflict of interest All the authors declare that they have no conflict of interest.

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