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Research article

G X E interaction and stability analysis for phosphorus use efficiency in fodder cowpea [*Vigna unguiculata* L. Walp] using AMMI-based stability measures

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Abstract

Forty-five fodder cowpea genotypes were evaluated under eight different levels of phosphorus fertilization over two seasons, *i.e., Rabi* 2022-23 and *Kharif* 2023,, to determine their phosphorus use efficiency. Combined ANOVA revealed the existence of a significant G×E interaction for this trait. AMMI analysis of variance indicated significant variation (p <0.01) among the genotypes (25.11%) and environments (17.25%). The genotype by environment interactions explained 57.35% of total variation, wherein PC1 and PC2 together accounted for 81% of the interaction component. Twelve AMMI-based stability measures were employed to identify stable genotypes. Statistical analysis, such as Spearman's rank correlation and PCA, suggested absolute value of the AMMI GEI scores (AVAMGE) and the absolute value of AMMI scores for a genotype (Za) could be useful to select phosphorus-efficient genotypes. Comparison of different methods (SI, GSI, SSI) indicated that the genotype selection index (GSI) method of ranking was the best. Genotypes, FD-1161, UPC-801, UPC-2001, EC-107120, UPC-2002, MFC-09-1 and UPC-618 were identified as stable genotypes with high phosphorus use efficiency using GSI & SI approaches.

Keywords: AMMI, Fodder cowpea, G ´ E interaction, GSI, Phosphorus use efficiency

Introduction

Cowpea (*Vigna unguiculata* L. Walp), a multipurpose legume crop that holds immense potential in ensuring three-fold security in terms of food, fodder, and nutrient cycling. This protein-rich pulse faces the concern of phosphorus unavailability that can affect its growth, development and yield. Cowpea is a significant annual legume, with nearly every part of the plant contributing to nutrition (Timko and Singh, 2008). The edible leaves, pods, and processed grains are consumed by humans, while the haulm is used as fodder. Even the roots play a crucial role in nutrient cycling, helping to maintain soil fertility and fostering a sustainable agriculture system. In legumes, a symbiotic relationship with certain bacteria in soil enables them to enhance nitrogen (N) levels through biological nitrogen fixation (BNF). However, to optimize this process, cowpea requires more phosphorus (P), as it is essential for energy conversion in the nodules. Additionally, phosphorus plays a crucial role in root development, nutrient absorption, and overall growth of legume crops (Vance *et al*., 2003). Due to such a high value for phosphorus, its deficiency leads to a significant limitation for the production of fodder cowpea. This limitation sets a major challenge for its cultivation, especially in the degraded soils found in many tropical areas (Adekiya, 2022). To tackle this problem, the breeders today aim mainly at developing varieties that have greater efficiency for the macronutrient (Lynch, 2007). The genotype's adaptability to lower phosphorus levels through certain morphological or physiological modifications is one of the few strategies to note.

Breeders encounter variations in trait expression for the same genotype across environments due to their interaction with environmental factors. Hence, selecting a stable genotype that performs well in different sets of environments or has relatively similar performance towards the fluctuations of the environment becomes a crucial strategy of crop improvement. In order to select stable genotypes for such multi-environment trials, several methods have been developed, of which the

AMMI model (Purchase, 1997) is able to break down the genotype by environment interaction (GEI) component further into principal components that give it an edge above the linear regression models. While the AMMI1 helps identify genotypes having high trait expression as predicted by a single principal component, the AMMI2 more accurately predicts genotypes adapted to a particular environment (Gauch *et al.*, 2008). The model itself is not able to quantify the extent and degree of stability of the genotypes which leads to use other AMMI-based stability parameters and selection indices that can provide an estimate to judge the different genotypes are AMMI stability value (ASV; Purchase, 1997), AMMI-based stability parameter (ASTAB; Rao and Prabhakaran, 2005), AMMI stability index (ASI; Jambhulkar *et al.*, 2014), Sum across environments of the absolute value of GEI modelled by AMMI (AVAMGE; Zali *et al.*, 2012), Annicchiarico's D parameter (DA; Annicchiarico *et al.*, 1997), Zhang's D parameter (DZ; Zhang *et al.*, 1998), Averages of the squared eigen vector values (EV; Zobel *et al.*, 1994, Stability measure based on fitted AMMI model (FA; Raju, 2002), Modified AMMI stability Index (MASI; Ajay *et al.*, 2018), Modified AMMI stability value (MASV; Zali *et al.*, 2012), Sums of the absolute value of IPC scores (SIPC; Sneller *et al.*, 1997) and Absolute value of the relative contribution of IPCs to the interaction (Za; Zali *et al.*, 2012). In this study, we aimed to identify high and stable phosphorus-use efficient fodder cowpea genotypes using AMMI-derived stability parameters

Materials and Methods

Study site and experimental design: Field trials were conducted on 45 fodder cowpea genotypes collected from ICAR-IGFRI Jhansi, including five nationally released varieties such as MFC 9-1, Sweta, TNFC 926, UPC 625 and UPC 4200. The genotypes were subjected to four different phosphorus fertilization levels (0, 20, 40 & 60 kg P_2O_5/ha), keeping the other two macronutrient (N and K) constant over two seasons, *i.e., Rabi* 2022-23 and *Kharif* 2023, constituting eight environments. The denotation for the environments created were E1 (RP0), E2 (RP20), E3 (RP40) and E4 (RP60) for *Rabi* and E5 (KhP0), E6 (KhP20), E7 (KhP40) and E8 (KhP60) for *Kharif.* The experiment was conducted at AICRP on Forage Crops and Utilisation, OUAT, Bhubaneswar. Entries were planted in a randomized block design with three replications in each environment. The soil of the experimental site was sandy loam with pH of 4.78; Available soil phosphorus content was 33.52 kg/ha as per Bray's method. Single super phosphate was applied @ 0, 125, 250 and 375 kg /ha to obtain 0 kg P_2O_5/ha, 20 kg P_2O_5/ha, 40 kg P_2O_5/ha and 60 kg P_2O_5/ha, respectively. Proper package of practices was followed such as the application of a recommended dose of fertilizers (N and K @ 20:40 kg/ha) and FYM (@10 t/ha) was applied. All the other recommended agronomical operations were followed to conduct the experiment as per the schedule. Phosphorus use efficiency was estimated using the formula of Dobermann (2007).

Observations and statistical analyses: The phosphorus use efficiency (PUE) of the genotypes in different environments was further subjected to single-environment and combined ANOVA. AMMI analysis was used to assess G ´ E interaction following R-Studio software (Olivoto and Lucio, 2020). The G ´ E interaction was analysed in an additive main and multiplicative interaction (AMMI) model (Zobel *et al.*, 1988; Gauch, 1992) with a view to identifying fodder cowpea genotypes better adapted to varying phosphorus levels. The mathematical function of the AMMI model is:

$$Y_{ij} = \mu + \alpha_i + \beta_j + \sum_{k=1}^{n} \lambda_k \gamma_{ik} \delta_{jk} + \theta_{ij}$$

Where, Y_{ij} = mean yield of i^{th} genotype (i=1, 2, ..., 45) in j^{th} environment (j= 1,2,...,8); μ = grand mean; α_i = mean deviation/effect of i^{th} genotype; β_j = mean deviation/effect of j^{th} environment; λ_k = eigen value of k^{th} IPCA axis; γ_{ik} = genotypic score of i^{th} genotypes on k^{th} IPCA; δ_{jk} = environment score of j^{th} environment on k^{th} IPCA; θ_{ij} = residual of G × E interaction effect in Y_{ij}; n = number of IPC axes retained in the model.

The principal component scores for genotypes and environments were calculated using the AMMI model. AMMI analysis of variance was performed to evaluate the contributions of different IPCAs to the G × E interaction, and their statistical significance was assessed using the F-test. Twelve stability parameters (ASV, ASTAB, ASI, AVAMGE, DA, DZ, EV, FA, MASI, MASV, SPIC, Za) based on the AMMI model were computed following the authors as quoted in the introduction part and further genotype selection index was estimated (Farshadfar 2008). Simultaneous selection index was calculated (Rao and Prabhakaran, 2005) to rank the genotypes. Correlation among the twelve stability parameters was assessed using the GRAPES software (Gopinath *et al.*, 2020) and a PCA analysis was carried out using PAST software (Hammer and Harper, 2001) to plot them against the first two principal components to understand the relationship among them and identify the most suitable stability parameter for further estimation.

Results and Discussion

Phosphorus use efficiency (PUE): PUE of the genotypes was estimated agronomically at P-deficient (P20), P-optimum (P40) and P-sufficient conditions (P60) during *Rabi* 2022-23 and *Kharif* 2023 (Table 1; Fig 1a-1c**)**. In phosphorus-deficient condition (P20), PUE of the genotypes ranged from 113.45 to 483.88 kg GFY per kg P

Table 1. Environment-wise mean and range in phosphorus use efficiency (kg GFY per kg P applied) of forty-five fodder cowpea genotypes

Environment	Mean PUE	Range in PUE	
		Minimum	Maximum
RPUE20	278.93	113.45	483.88
RPUE40	266.66	150.88	439.08
RPUE60	213.88	89.17	303.25
KhPUE20	287.67	88.88	759.75
KhPUE40	302.49	115.54	483.46
KhPUE60	201.66	77.03	322.31

PUE: Phosphorus use efficiency; GFY: Green fodder yield

applied, where the maximum PUE (483.88) was observed in genotype G21 (N-311) during the *Rabi* season. During the *Kharif* season, PUE varied from 88.88 to 759.75 kg GFY per kg P applied with G19 (UPC-2001), recording the maximum PUE.

In phosphorus optimum condition, PUE ranged from 150.88 to 439.08 (kg GFY per kg P applied) with a mean value of 266.66 kg GFY per kg P and G5 (MFC-18-10) accounted for the maximum PUE during the rabi season. During kharif season, PUE under optimum conditions varied from 115.54 to 483.46 kg GFY per kg P and G19 (UPC-2001) recorded the maximum PUE. Under sufficient phosphorus conditions, PUE varied from 89.17 to 303.25 kg GFY per kg P with G5 (MFC-18-10) exhibiting the highest PUE in *Rabi,* while in the *Kharif* season, PUE varied from 77.03 to 322.31 kg GFY per kg P applied, with G19 (UPC-2001) recording the maximum PUE. The present study indicates variation in the PUE of the fodder cowpea genotypes. While evaluating groundnut genotypes under different doses of phosphorus, Kumar *et al.* (2014) observed variation in their PUE ranging from 0.09 to 0.21 kg grain/kg P_2O_5 applied. Singh *et al.* (2015) evaluated groundnut genotypes at different levels of phosphorus and observed that the PUE varied from 4.1 to 29.0 kg grain/kg P_2O_5. However, Everest *et al.* (2022) in their investigation on groundnut genotypes observed that with increased doses of phosphorus fertilisation, the agronomic phosphorus use efficiency (APUE) was found to increase. But Oluleye and Akinrinde (2010) found that PUE reduced with increased doses of phosphorus in the case of maize/ egusi-melon/cassava mixtures.

***AMMI model*:** It was observed that the environment-wise analysis of variance for PUE (Table 2) exhibited significant differences at 1% probability level. Hence, the cowpea genotypes were adequately different for their PUE under different conditions. Following the individual environment analysis, the homogeneity of variances was checked using Bartlett's chi-square test (p >0.05). The combined ANOVA (Table 3) revealed that significant genotype by environment interactions existed for the studied trait. Fageria and Baligar (1999) in their study on wheat genotypes found significant variation among the genotypes for the PUE trait.

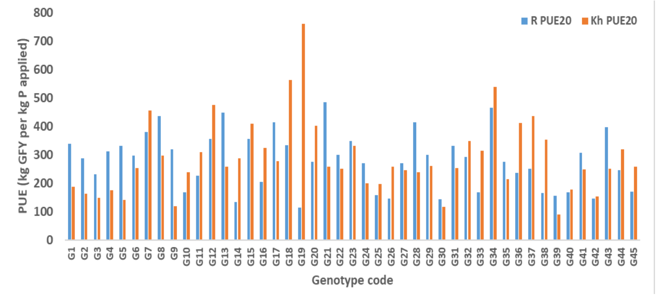

Fig 1a. PUE of fodder cowpea genotypes in phosphorus deficient condition (P20)

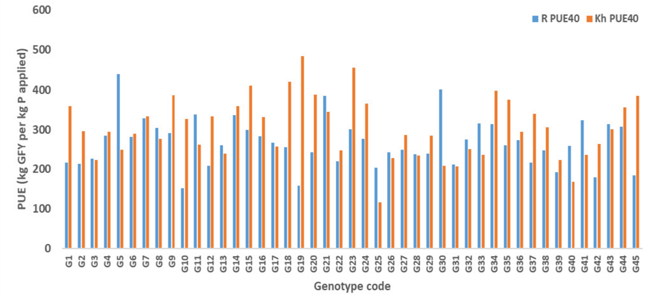

Fig 1b. PUE of fodder cowpea genotypes in phosphorus optimum condition (P40)

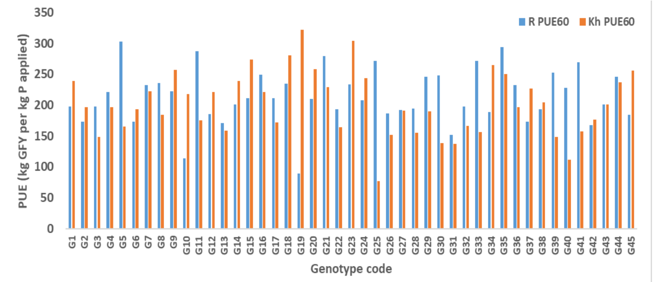

Fig 1c. PUE of fodder cowpea genotypes in phosphorus sufficient condition (P_{60})

Based on the AMMI analysis of variance conducted for phosphorus use efficiency (Table 3) in fodder cowpea genotypes, it was observed that there was highly significant variation (p <0.01) recorded among the genotypes and the environments. The genotype by environment interactions explained the highest portion of the total variation (57.35%), followed by the genotypes with 25.11% and environment with 17.52% contribution towards variation. PC 1 contributed 57.1% and PC 2 accounted for 23.9% of the total G×E interaction. Mekonnen *et al.* (2022) in their study on grain yield

Table 2. ANOVA for phosphorus use efficiency of cowpea genotypes in individual test environments

Environment	Mean sum of squares	
	Replication (DF:2)	Genotype (DF:44)
RP20 (E1)	3317.47	29127.85**
RP40 (E2)	6435.92	11202.50**
RP60 (E3)	1302.00	5881.94**
KhP20 (E4)	1072.04	51051.12**
KhP40 (E5)	1417.82	1758.88**
KhP60 (E6)	1630.11	7781.51**

** (P<0.01)

observed 63.98, 2.66 and 16.30% contribution towards variation by genotype, environment and the interaction in cowpea across five environments. In their study on grain yield in cowpea, Kindie *et al.* (2021) observed that genotype by environment interaction explained the most variation.

In the AMMI-1 biplot for phosphorus use efficiency, we found that the 45 genotypes were sufficiently diverse in their adaptation towards different environmental conditions, with each quadrant having a set of genotypes (Fig 2). The genotype by environment interaction accounted for a major portion of variation, while the main effects (G and E) recorded 42.63% of total variation. The environment vectors were adequately scattered across four quadrants, indicating differences in their effect. E1 (RP20) and E2 (RP40) were similar in their effect due to their close proximity and presence in the same quadrant. E4 is supposed to have a high interaction effect. All the genotypes closer to origin had stable responses to different environments viz., G4 (MFC-18-8), G6 (MFC-20-3), G11 (NBC-43), G13 (UPC-5287), G24 (CO-(FC)-8), G29 (UPC 625), G32 (MFC-18-4), G33 (MFC-20-7). The mean performance of these genotypes was found to be above average. As per the representation on the biplot G18 (UPC-805), G19 (UPC-2001), G21 (N-311) and G34 (EC-402154) are the most unstable genotypes in terms of their phosphorus use efficiency.

Both PC1 (57.1%) and PC2 (23.9%) of the interaction component were used to construct an AMMI-2 biplot (Fig 3). All the environment vectors as well as the genotypes fall in four different quadrants, inferring that there is sufficient variation for the testing environment as well as among the genotypes. Mohammadi and Amri (2009) in their study of GEI in wheat found that genotypes located farther from the centre of the biplot exhibited higher G × E interaction, while those positioned closer to or near the origin. From the graph (Fig 3), it was realised that G1 (MFC-08-14), G11 (NBC-43), G23 (FD-1161), G24 (CO-(FC)-8), G27 (F-6R-211-184-2), G29 (UPC 625), G32 (MFC-18-4) and G44 (C0-9) are closer to the origin which means they are the highly stable genotypes across the environment. E1 and E4 possess the longest vectors, indicating that they are the most challenging environments. As far the individual environment was concerned, G8 (MFC-09-1), G13 (UPC-5287), G17 (UPC-804), G28 (Sweta), G43 (FD-1259) are adapted to E1 while G15 (UPC-801), G18 (UPC-805), G20 (UPC-2002), G23 (FD-1161), G32 (MFC-18-4) and G37 (UPC-618) are specifically adapted to E4. Genotypes G3 (MFC-18-2), G25 (Vijayar), G30 (TNFC 926), G35(IC-402096), G39 (UPC-5286), and G40 (UPC-803) were in a closer proximity to E2 and E3 and were adapted to both environments. Similarly, G10(IC-219489), G14 (UPC-9202), G38 (UPC-628), G44 (C0-9) and G45 (IFC-24094) are adapted to both E5 & E6.

To comprehend how genotypes respond to different environments, the effects of the environment, genotype, and their interaction (GEI) on the trait expression are generally examined. In the present investigation, it was seen that the interaction component contributed most to

Table 3. AMMI ANOVA of cowpea genotypes for PUE (kg GFY per kg P applied)

Source	Df	Mean sum of squares	% of G-E sum of squares	F-calculated	% Contribution of G×E interaction SS
Replications in environment	12	669.99	0.12	0.45	-
Genotype	44	37200.11**	25.11	25.10	-
Environment	5	228376.36**	17.52	340.87	-
Genotype x Environment	220	16989.42**	57.35	11.47	-
IPCA1	48	44450.02**	32.74	30	57.1
IPCA2	46	19431.22**	13.71	13.11	23.9
IPCA3	44	12689.22**	8.57	8.56	14.9
IPCA4	42	3382.04**	2.17	2.28	3.8
IPCA5	40	246.59**	0.15	0.17	0.3
Residuals	528	1481.79	-	-	-

**(P<0.01)

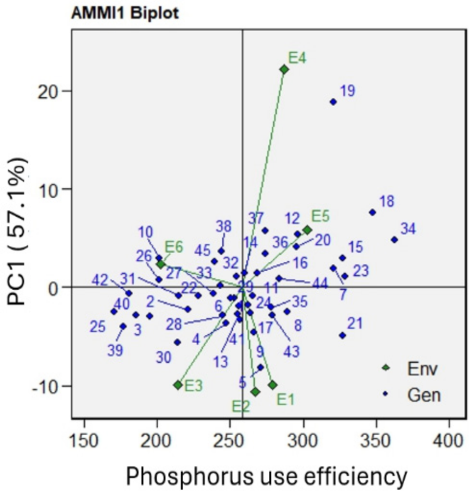

Fig 2. AMMI-1 biplot depicting main effects and G × E interaction of 45 fodder cowpea genotypes

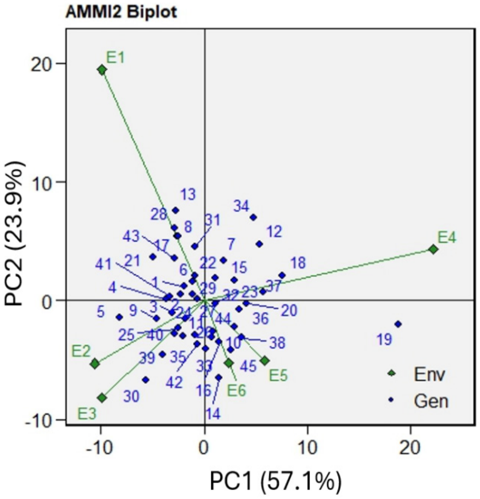

Fig 3. AMMI-2 biplot of G × E interaction of 45 fodder cowpea genotypes

the variation. Hence, deployment of the AMMI model to study different environments and the genotypes performing best across the environment will be considered most suitable for varying phosphorus levels. Significant GEI was observed in cowpea by Sansa *et al*. (2025) for drought tolerance and yield stability; Sharma *et al*. (2024) and Aleme *et al*. (2024) reported significant GEI for the seed yield trait in cowpea. Ajayi *et al*. (2022) in their study on grain yield in cowpea found the highest contribution of significant variation by GEI, followed by genotype and environment. In their investigation on groundnut genotypes, Esan *et al*. (2023) found that PC 1 and PC 2 together contributed 90% of the GEI.

***AMMI stability measures*:** AMMI model can provide an insight into an overall picture of what the stable genotypes but to score the stability among genotypes, it is essential to have some estimates to compare and conclude. Here, we took 12 different stability parameters that are derived from the AMMI model-based stability measures and drew inferences. Here, the lowest stability score was ranked highest and increased values were ranked lowest (Table 4).

The AMMI-based stability parameter (ASTAB) predicted that G20, G34, G15, G42 and G22 were the most stable in decreasing order, while G11 was found to be the most unstable genotype. AMMI stability index (ASI) considers the first two principal components that have revealed genotype G20, followed by G16, G22, G15 and G42 were the most stable genotypes. Through the AMMI stability value (ASV), which is derived from the IPCA1 and IPCA2 scores of the AMMI model for each genotype, it was found that the genotypes G20, G16, G22, G15 and G42 were the most stable genotypes in decreasing order, while G25 was the least stable genotype. The sum across environments of the absolute value of genotype by environment interaction (AVAMGE) value was found to be lowest for G20, followed by G39, G15, G22 and G42, while G11 accounted for the highest score for the stability parameter. The Annicchiarico's D parameter (DA), which is a distance-based parameter of the PC point in space from the origin for all the significant PCs, revealed that G20, G22, G15, G42 and G39 were stable in succession. Zhang's D parameter (DZ) that takes into consideration the distance of IPC points from the origin for the significant principal components predicted that G20, G39, G23, G15 and G34 were the most stable genotypes in decreasing order, while G45 accounted for the lowest rank. Through the EV that is derived from the averages of the squared eigen vector values, for the jth cultivar in the significant PCs, it was found that G20, G39, G23, G15 and G34 were the most stable genotypes while G11 was identified as the most unstable genotype. Stability measure based on fitted AMMI model (FA) considers all the significant PCs into account and through this measure, it was observed that G20, G22, G15, G42 and G39 were the most stable genotypes. Through the modified AMMI stability index (MASI) that considers all the significant principal components, it was found that G20, G22, G15, G42 and G39 were the most stable with G45 being the most unstable genotype. Through the modified AMMI stability value (MASV) that takes all the significant PCs into consideration, contrary to the ASV, it was observed that G20 was the most stable genotype, followed by G22, G15, G39 and G42, while G45 remained the most unstable genotype. As per the SIPC (the sum of the absolute values of the IPC scores for the ith genotype, based on the number of significantly contributing principal components), it was observed that G20, G39, G22, G15 and G23 were the most stable genotypes in decreasing fashion, while G11 is the

Table 4. Mean phosphorus use efficiency (kg GFY per kg P applied) and estimates of AMMI based stability parameter of 45 fodder cowpea genotypes

Genotype Code	Mean PUE	ASTAB	ASI	ASV	AVAMGE	DA	DZ	EV	FA	MASI	MASV	SIPC	Za
MFC-08-14 (G1)	256.29	44.82	1.16	4.84	318.62	143.42	0.32	0.03	20568.92	1.47	24.52	10.81	0.10
MFC-09-3 (G2)	221.12	37.35	1.76	7.37	315.88	142.25	0.27	0.02	20234.88	1.91	20.65	10.33	0.12
MFC -18-2 (G3)	195.14	33.22	0.87	3.63	282.71	125.04	0.27	0.02	15634.57	1.13	19.91	8.81	0.08
MFC-18-8 (G4)	247.52	57.26	3.30	13.79	379.23	196.22	0.31	0.02	38501.71	3.30	15.60	13.19	0.17
MFC-18-10 (G5)	271.02	64.61	2.39	10.01	345.14	193.49	0.34	0.03	37439.42	2.39	13.77	11.04	0.13
MFC-20-3 (G6)	250.18	70.06	1.77	7.41	320.97	175.03	0.44	0.05	30635.27	1.78	12.21	13.40	0.11
EC-107120 (G7)	320.93	17.64	1.70	7.13	214.60	103.72	0.19	0.01	10757.16	1.73	10.38	8.17	0.09
MFC-09-1 (G8)	289.05	15.51	1.19	4.98	170.72	94.79	0.17	0.01	8984.31	1.20	7.57	6.22	0.07
NBC-40 (G9)	265.81	36.59	1.98	8.27	260.42	147.70	0.25	0.02	21815.71	1.98	10.81	9.21	0.11
IC-219489 (G10)	201.75	64.50	4.35	18.16	414.14	226.64	0.30	0.02	51363.61	4.35	18.76	12.04	0.18
NBC-43 (G11)	265.72	361.61	10.77	45.03	1170.73	549.76	0.66	0.11	302231.97	10.77	45.13	22.54	0.40
UPC-4200 (G12)	296.22	22.45	1.30	5.45	210.71	108.36	0.22	0.01	11740.99	1.44	16.92	7.54	0.08
UPC-5287 (G13)	255.34	20.05	2.37	9.91	289.33	125.09	0.17	0.01	15646.54	2.38	11.56	6.61	0.10
UPC-9202 (G14)	259.57	41.89	2.93	12.24	337.82	169.15	0.27	0.02	28611.84	2.93	13.41	11.14	0.14
UPC-801 (G15)	326.70	8.14	0.69	2.88	120.48	60.36	0.15	0.01	3643.65	0.69	4.43	4.97	0.04
UPC-802 (G16)	268.63	27.55	0.62	2.59	233.36	109.79	0.26	0.02	12053.57	0.97	19.80	7.52	0.06
UPC-804 (G17)	263.99	27.86	1.11	4.65	205.53	115.52	0.25	0.02	13344.84	1.30	18.53	9.18	0.09
UPC-805 (G18)	347.63	89.75	1.51	6.33	340.85	184.54	0.53	0.07	34053.43	1.81	27.02	17.31	0.13
UPC-2001 (G19)	321.02	16.86	0.86	3.61	180.41	92.80	0.18	0.01	8612.73	0.94	11.30	6.67	0.07
UPC-2002 (G20)	295.61	1.18	0.37	1.55	45.85	26.11	0.05	0.00	681.93	0.39	3.72	1.70	0.02
N-311 (G21)	326.72	48.36	2.21	9.25	298.40	167.66	0.30	0.02	28110.78	2.21	12.11	10.70	0.12
IFC-9304 (G22)	228.67	10.60	0.64	2.68	122.30	56.20	0.21	0.01	3158.96	0.65	4.09	4.66	0.03
FD-1161 (G23)	328.66	11.92	1.75	7.30	170.87	93.23	0.14	0.01	8690.94	1.75	7.63	5.65	0.08
CO-(FC)-8 (G24)	262.44	117.22	3.61	15.10	514.86	250.59	0.53	0.07	62794.73	3.65	22.27	21.07	0.22
Vijayar (G25)	170.44	22.94	1.20	5.01	210.42	111.77	0.21	0.01	12493.10	1.21	8.76	7.15	0.07
TSFC-20-06 (G26)	201.51	17.41	0.76	3.19	188.16	91.17	0.20	0.01	8312.11	0.92	14.25	7.15	0.07
F-6R-211-184-2 (G27)	238.85	51.65	0.96	4.04	356.77	155.34	0.33	0.03	24131.30	1.31	24.26	10.33	0.09
Sweta (G28)	245.07	82.88	3.22	13.46	455.94	220.89	0.41	0.04	48794.43	3.22	16.80	15.93	0.18
UPC 625 (G29)	252.93	37.36	1.38	5.79	282.85	128.28	0.32	0.03	16456.46	1.49	15.86	12.01	0.11
TNFC 926 (G30)	213.82	27.02	1.98	8.28	222.93	128.72	0.22	0.01	16568.82	2.06	17.01	8.53	0.10
KBC-2 (G31)	215.02	33.67	3.27	13.67	329.75	167.32	0.20	0.01	27997.38	3.27	13.81	7.38	0.12

most unstable genotype. Za is the absolute value of the relative contribution of IPCs towards the interaction and through this measure, it was found that G20, followed by G22, G15, G39 and G42 were the stable genotypes. A similar method of stability analysis was employed by Anuradha *et al.* (2022) in finger millet and Ajay *et al.* (2020) in peanut genotypes under phosphorus stress. Based on the aforementioned stability parameters, the genotypes i.e., G15 (UPC-801), G16 (UPC-802), G20 (UPC-2002), G22 (IFC-9304), G23 (FD-1161), G34 (EC-402154), G39 (UPC-5286) and G42 (FD-1052) were found to be the most stable genotypes whereas G11 (NBC-43) remained to be the most unstable genotype through all these methods. Of these, G15, G20 and G34 were the ones having high phosphorus use efficiencies, whereas G11 and G16 were genotypes with above-average phosphorus use efficiency and the rest had below-average performance.

From this result, it was evident that stability in PUE alone cannot be a criterion to select a genotype for adaptation to multiple environments and the breeder should consider the performance of individual genotypes with respect to PUE. The stable genotypes having high phosphorus use efficiency are more desirable than stable genotypes having low PUE. To identify stable genotypes with high phosphorus use efficient genotypes we consider the top 15 genotypes and their stability in performance was evaluated based on stability index (SI). To estimate SI, the stability parameters were ranked first and the genotypes possessing any rank from 1 to 15 were considered as stable. If a genotype is found to be stable in 6 out of 12 parameters taken for the study, then the stability index would be 6/12, i.e., 0.50 and genotypes having an SI value more than 0.50 were considered as stable (Table 5). Seven out of 15 top rankers (G7, G8, G15, G19, G20, G23 and G37) were found to be stable and high-phosphorus-use efficient genotypes.

Genotype selection index (GSI) of Farshadfar (2008) and simultaneous selection index (SSI) of Rao and Prabhakaran (2005) were also worked out, taking the mean phosphorus use efficiency into consideration and compared with our result.

***Association among the stability parameters*:** Ranks of the twelve stability parameters were subjected to Spearman's correlation (Fig 4). All the parameters were found to be significantly positively correlated (P>0.05). ASTAB was found to show a high positive correlation with AVAMGE, DA, DZ, EV, FA, and SIPC. ASI and ASV; DA and FA; DZ and EV showed complete correlation (r= 1.00) while ASI & ASV showed high positive correlation with MASI. ASTAB and Za were found to be highly associated with other stability parameters, followed by SIPC and MASI. MASV was found to be least associated with other stability parameters.

To decipher the relationship among these parameters, the rank correlation matrix was subjected to principal

MFC-18-4 (G32)	254.69	24.74	2.18	9.13	225.30	130.70	0.20	0.01	17082.50	2.19	11.31	8.48	0.11
MFC-20-7 (G33)	243.50	62.26	2.53	10.59	314.59	174.93	0.41	0.04	30598.88	2.54	13.51	14.45	0.14
EC-402154 (G34)	362.85	17.80	2.12	8.88	201.34	115.41	0.16	0.01	13319.99	2.14	11.66	6.28	0.09
IC-402096 (G35)	278.09	33.53	1.76	7.35	305.94	135.73	0.26	0.02	18422.56	1.86	17.96	10.79	0.12
EC-458418 (G36)	274.23	24.29	1.90	7.94	288.52	122.56	0.21	0.01	15022.13	1.97	16.29	7.52	0.10
UPC-618 (G37)	273.75	23.41	0.95	3.96	243.54	106.36	0.23	0.01	11312.37	1.03	12.47	8.53	0.07
UPC-628 (G38)	244.18	29.44	1.86	7.78	265.71	126.35	0.26	0.02	15965.10	1.87	9.80	9.97	0.11
UPC-5286 (G39)	176.70	8.04	0.81	3.38	119.57	67.30	0.12	0.00	4529.63	0.81	4.85	4.30	0.05
UPC-803 (G40)	185.79	55.05	1.79	7.50	348.38	167.30	0.34	0.03	27989.38	1.96	22.79	13.72	0.14
FD-739 (G41)	256.40	94.36	4.68	19.58	549.17	255.42	0.42	0.04	65240.36	4.71	23.60	16.72	0.21
FD-1052 (G42)	181.09	10.23	0.75	3.13	130.25	63.04	0.19	0.01	3973.84	0.76	5.33	5.89	0.05
FD-1259 (G43)	278.99	24.37	1.35	5.65	238.56	113.06	0.23	0.01	12781.85	1.41	12.66	9.47	0.09
C0-9 (G44)	283.46	37.18	1.95	8.13	267.66	148.47	0.25	0.02	22042.96	1.95	11.69	9.32	0.11
IFC-24094 (G45)	238.97	73.52	2.64	11.05	351.26	200.64	0.39	0.04	40255.10	2.84	29.54	14.45	0.16
Mean	258.58	45.29	2.03	8.48	292.46	146.40	0.27	0.02	27613.39	2.10	15.25	9.97	0.11

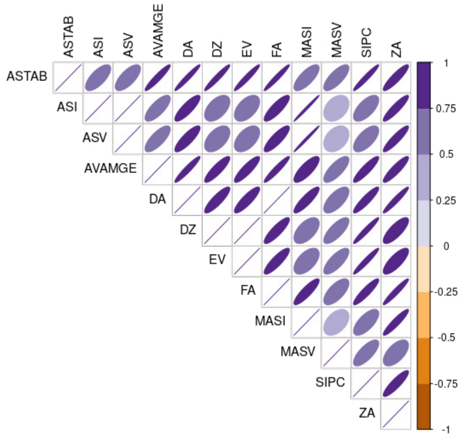

Fig 4. Spearman's rank correlation among estimates of different stability parameters

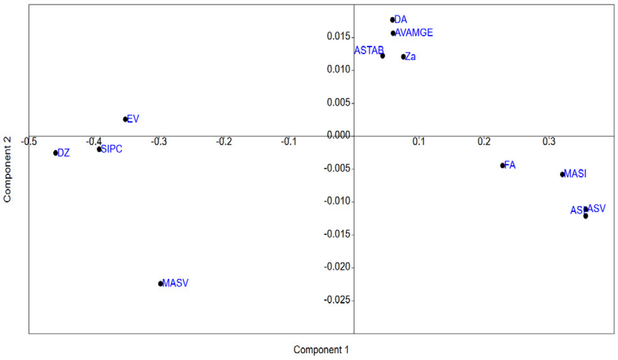

Fig 5. Biplot using PCA coordinates (PC1 v/s PC2) to depict relationship among the twelve stability parameters

component analysis (PCA) as per Sabaghnia *et al.* (2013), where the first two principal components were used to draw a biplot (Fig 5). The PC1 contributed to 87.73 % of the total variation, while PC2 explained 8.17% of the variation among the ranks of the stability parameter. Twelve stability parameters were distributed in four different quadrants.

Here, it was found that stability parameters grouped together were closely associated; hence, based on the observation ASTAB, Za, AVAMGE and DA; FA, MASI, ASV and ASI; DZ, SIPC and MASV; EV formed separate clusters. Za, ASTAB, and AVAMGE were found closer to the origin in comparison to others, indicating that they may be more reliable parameters. Thus, Za, ASTAB, AVAMGE could be useful in selecting stable genotypes with high phosphorus use efficiencies (Ajay *et al.*, 2020).

***Comparison of different methods*:** Comparison of different methods (SI, GSI & SSI) for selecting stable and high P-use efficient genotypes (Table 6) indicated that seven out of 15 top-ranked genotypes, namely G23, G15, G19, G7, G20, G8 & G37 were found to be stable and high

Table 5. Identification of stable and high phosphorus use efficient genotypes based on stability index (SI) parameter

Genotype code	PUE rank	ASTAB rank	ASI rank	ASV rank	AVAMGE rank	DA rank	DZ rank	EV rank	FA rank	MASI rank	MASV rank	SIPC rank	ZA rank	Stability index (SI)
G34	1	11	31	31	10	16	5	5	16	31	15	8	17	0.50 (6/12)
G18	2	42	19	19	35	37	44	44	37	22	43	43	35	0.00 (0/12)
G23	3	6	21	21	7	8	3	3	8	20	7	5	12	0.75 (9/12)
G21	4	32	33	33	27	33	31	31	33	33	17	29	33	0.00 (0/12)
G15	5	3	4	4	3	3	4	4	3	3	3	4	3	1.00 (12/12)
G19	6	8	8	8	8	7	8	8	7	7	12	10	7	1.00 (12/12)
G7	7	10	20	20	14	10	10	10	10	19	10	17	18	0.58 (7/12)
G12	8	13	16	16	13	12	17	17	12	16	30	16	13	0.42 (5/12)
G20	9	1	1	1	1	1	1	1	1	1	1	1	1	1.00 (12/12)
G8	10	7	14	14	6	9	6	6	9	11	6	7	9	1.00 (12/12)
G44	11	27	28	28	22	29	23	23	29	26	16	24	29	0.00 (0/12)
G43	12	17	17	17	18	15	19	19	15	15	20	25	19	0.25 (3/12)
G35	13	24	22	22	28	25	25	25	25	23	32	30	30	0.00 (0/12)
G36	14	16	27	27	25	18	16	16	18	28	28	14	20	0.08 (1/12)
G37	15	15	10	10	19	11	20	20	11	9	19	20	11	0.58 (7/12)

Table 6. Comparison among SI, GSI and SSI methods

List of top 15 genotypes	Stability index	GSI based ranking			SSI based ranking		
		ASTAB	AVAMGE	Za	ASTAB	AVAMGE	Za
G34	0.50	4	4	5	25	17	26
G18	0.00	20	15	14	29	31	25
G23	0.75	2	3	4	42	36	45
G21	0.00	12	11	15	35	5	28
G15	1.00	1	1	1	44	38	43
G19	1.00	5	5	3	15	30	14
G7	0.58	6	7	9	41	10	41
G12	0.42	8	8	7	22	39	16
G20	1.00	3	2	2	43	41	39
G8	1.00	7	6	6	32	23	29
G44	0.00	16	12	17	45	12	44
G43	0.25	9	9	11	36	22	34
G35	0.00	15	19	18	26	34	32
G36	0.08	10	18	12	27	4	33
G37	0.58	11	14	10	27	4	22
Frequency	7/15	13/15	13/15	13/15	1/15	5/15	1/15

P-use efficient genotypes based on the stability index parameter. The GSI method of ranking was used for ASTAB, AVAMGE & Za parameters and 13 genotypes were selected in case of each parameter. GSI-based ASTAB parameters selected all the genotypes except G18 and G44; GSI-based AVAMGE and Za parameters selected the top 12 and 10 genotypes in a sequence, along with other genotypes. SSI method of ranking was also used for ASTAB, AVAMGE & Za parameters, but the frequency of desirable genotype (1/15, 5/15, 1/15) selected by this approach was much less compared to the GSI approach. This result suggested that the GSI approach was the best, followed by the SI approach and the SSI method was not rewarding for the selection of stable and high P-use efficient genotypes. A similar approach to stability ranking has been used by Mahmodi *et al*. (2011) and Farshadfar *et al.* (2011) as the yield stability index (YSI) in bread wheat. Anuradha *et al*. (2022) also reported the same finding while working in finger millet. The fodder cowpea genotypes FD-1161, UPC-801, UPC-2001, EC-107120, UPC-2002, MFC-09-1 and UPC-618 were identified as stable and high P-use efficient genotypes based on SI and GSI approaches.

Conclusion

From the AMMI model it was concluded that MFC-09-1, UPC-5287, UPC-804, Sweta, FD-1259 were specifically adapted to E1 (RP20) while UPC-801, UPC-805, UPC-2002, FD-1161, MFC-18-4 and UPC-618 were specifically adapted to E4 (KhP20) both the environment being phosphorus deficient. MFC-08-14, NBC-43, FD-1161, CO-(FC)-8, F-6R-211-184-2, UPC 625, MFC-18-4 and C0-9 were found to be highly stable genotypes across the environment. As per the AMMI-based stability parameter, EC-402154, N-311 and EC-107120 were highly stable genotypes with high phosphorus use efficiency, while UPC-802, UPC-804, EC-458418, FD-1259, and C0-9 were stable genotypes with moderate phosphorus use efficiencies. All the stability measures were found to be positively correlated with each other, while Za, ASTAB and AVAMGE could be used to identify genotypes with high phosphorus use efficiency in fodder cowpea. Phosphorus-efficient varieties are less impacted by changes in phosphorus availability, allowing them to maintain effective phosphorus uptake and utilization regardless of whether the soil is phosphorus-rich or deficient. This trait makes them highly adaptable to varying soil conditions and more sustainable for long-term agricultural productivity.

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