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Research Article

Insights into yield stability: A comparative analysis of regression, AMMI indices and Biplot Methods in pearl millet

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Abstract
Pearl millet is a vital crop in India cultivated across diverse agro-ecological zones. One of the primary challenges in millet farming is the absence of superior genotypes well-suited to local conditions. Hence, there is a need to develop pearl millet genotypes that exhibit high yield and stability to enhance production. With this regard, the study aimed to identify genotypes with high and stable yields across diverse seasons. Twenty-three genotypes were evaluated in four seasons in a randomized block design. Statistical analysis, including the Eberhart and Russell model, AMMI, and GGE biplot, were employed to assess genotype-environment interactions. The genotype ICMB 07999 was observed to have be stable with consistent mean yield, while PT 6679 , PT 7058 and PT 7054 were observed to have above-average stability. These findings were supported by AMMI biplots and various stability indices. GGE biplots revealed two mega-environments, from which *Kharif* seasons (mega environment 2) provided more informative assessments of genotype stability compared to *summer* seasons. Across all models and various parameters analysed, PT 6679 and PT 7058 emerged as stable inbreds with high mean seed yield. These inbreds could be tested further in larger environments for potential use in breeding program.

Key words : Pearl millet, grain yield, stability analysis, AMMI Model

INTRODUCTION

Pearl millet (*Pennisetum glaucum* (L.) R. Br.) holds significant importance as a staple food crop in arid and semi-arid regions worldwide. It has wide genetic diversity and adaptability, most predominantly cultivated under rainfed conditions (Kalagare *et al.,* 2022). In India, the area, production and productivity of pearl millet during 2021-22 was it 6.84 million ha, 9.78 million tones and 1430 kg ha^{-1} respectively (Indiastat, 2023). It is the sixth most important cereal globally after wheat, rice, maize, barley, and sorghum and fourth important staple food in India after rice, wheat and Maize. Most of the cultivated pearl millet varieties are considerably low yielders. The insufficient production of pearl millet in India underscores the need for the development of stable, high-yielding varieties and hybrids with enhanced adaptability (Narasimhulu *et al.,* 2023). In initial period of pearl millet breeding, the adoption of the male-sterility systems has proven significant role in boosting pearl millet yields through commercial hybrid seed production (Kelley *et al.,* 1996). Conversely, a few varieties are widely cultivated due to their resilience in marginal and harsh conditions, coupled with good grain quality and reasonable yields. The quality and weight of the seed are affected by rate and duration of seed filling (Yang and Zhang, 2006). Hence the selection of genotypes capable of buffering crop production against multiple stresses associated with climate change is crucial. This selection aims to ensure sustainable yields and maximize profitability in the face of evolving environmental challenges (Patil *et al.,* 2020).

The stability analysis proposed by Eberhart and Russell (1966) relies solely on an additive model. This model could ascertain through statistical tests whether genotypes, environments, and genotype x environment interactions had a significant impact, but it does not reveal which specific genotypes, environments, or genotype x environment combinations were responsible (Sharma *et al.,* 1998). As a result, the ANOVA model was integrated with the PCA model to conduct a more in-depth analysis of the residuals within the ANOVA model, which inherently encompasses the genotype-environment (G x E) interaction (Zobel *et al.,* 1988). AMMI (Gauch, 1988) and GGE biplots (Yan *et al.,* 2000; Yan and Kang, 2002) provides a visual depiction of the interaction between genotypes and environments and to visualize how different genotypes respond to varying environmental conditions, offering insights into the adaptability and stability of genotypes over different locations. Also numerous selection indices have been formulated to choose a genotype that combines stability and high yields effectively. It includes Kang's Yield Stability Index (Kang, 1993), the Simultaneous Selection Index (Rao and Prabhakaran, 2005), and the Non-parametric Genotype Selection Index (Farshadfar, 2008). These indicators offer direction for concurrently choosing genotypes that exhibit both stability and a high yield, incorporating insights from stability parameters and grain yield data. The goal of this study was to identify pearl millet genotypes that could consistently exhibit high performance across multiple crop seasons, utilizing various stability indices.

MATERIALS AND METHODS

The experiment was conducted with 23 pearl millet genotypes and 3 checks namely Dhanasakthi, COH10 and 86M38. All the materials were collected from Department of Millets, Tamil Nadu Agricultural University, Coimbatore. The genetic materials were evaluated over two years for four seasons *viz* Summer'22, *Kharif'*22, Summer'23 and *Kharif'23* which were represented as E_1, E_2, E_3 and E_4 respectively. Randomized Block Design with two replications were adopted in each environment. All the recommended management practices were followed in all the four seasons. The statistical analysis was carried out for seed yield per plant. Bartlett test for homogeneity of error variances (Bartlett, 1937), and Genotype x Environment interactions were studied as per Eberhart and Russell (1966) model and analysed in OPSTAT online analysis. AMMI model (Zobel *et al.,* 1988 and Gauch, 1992) and GGE biplot (Yan, 1999 and Yan, 2001) analysis were carried out using PB tools software developed by IRRI, Philipines.

AMMI stability indices for each genotype was calculated by assessing the proportional contributions of the principal component axis scores (IPCA1 and IPCA2) and its interaction sum of squares by following various methods such as averages of squared eigen vector values (EV) (Zobel, 1994), Zhang's D parameter, Annicchiarico's D parameter (Annicchiarico, 1997), ASV (Purchase, 1997), AMMI distance (DZ) (Zhang *et al.,* 1998), ASTAB (Rao and Prabhakaran, 2005), stability measure based on the fitted AMMI model (FA) (Zali *et al.,* 2012), sum across environments of the absolute value of genotype-environment interaction modeled by AMMI (AVAMGE) (Zali *et al.,* 2012), ASI (Jambhulkar *et al.,* 2014), MASI (Ajay *et al.,* 2018b), MASV (Ajay *et al.,* 2019), YSI (Kang, 1993) and SSI (Rao and Prabhakaran, 2005). All the indicess were computed by using "agricolae" package (De Mendiburu, 2015) and the "ammistability" package (Ajay *et al.,* 2018a) in the R programme (R package, 2018).

RESULTS AND DISCUSSION

The observation on grain yield per plant was analysed individually for each environment. The results suggested the significance to the genotypes for all the four environments studied. This indicates the presence of considerable variation for the trait. Bartlett's test was performed to test the homogeneity of error variances which indicted the presence of homogeneity of the trait studied across environments. Pooled analysis of variance was done for the data collected from four environments (**Table 1**).

Assessing the stability through regression approach: Eberhart and Russell (1966) proposed the consideration of both linear (bi) and non-linear (S^2di) components of Genotype-Environment (G x E) interaction to determine the phenotypic stability of a specific genotype. The pooled analysis of variance revealed the significance of both genotypes and environment when tested with pooled error and pooled deviation, suggesting the existence of variation in the genotypes and environments considered in the study (Solomon and Yohans, 2021; Gajera *et al.,* 2022; Narasimhulu *et al.,* 2023). Additionally, the variance attributed to Genotype x Environment was found to be significant when tested with pooled error, indicating that the genotypes exhibited different responses in diverse environments (Asungre *et al.,* 2021; Gajera *et al.,* 2022; Reddy *et al.,* 2021; Sodhaparmar *et al.,* 2023). E + G x E variance was also found to be significant which indicated that the diverse nature of environments and G x E interaction in the phenotypic expression of inbreds. The variance due to environment (linear) was significant which indicating response of genotypes to environments was linear and differed significantly for the trait studied. Dhuppe *et al.* (2017) reported that these variations might be variations in soil and weather factors in diverse environments. Among the total variations studied (**Table 1**), the variance due to G x E was less but significant for the trait across the environments. The ANOVA model reported only 85.93 % of trial variance, focusing solely on genotype and environment effects (Sharma *et al.,* 1998; Reddy *et al.,* 2022). Hence, to study the impact of Genotype-Environment Interaction (G x E), the data was subjected to various stability analysis.

A stable genotype is characterized with the higher mean and a minimal deviation from regression value S^2di. Among the genotypes ICMB 07999 (G4) had average stability across environments with moderate yield and non significant deviation with regression coefficient value near to 0. The inbred PT 6679 (G13) showed higher mean than grand mean with non significant deviation with b value greater than one which indicated that below average stability in favourable conditions while the inbreds PT 7058 (G16) and PT 7061 (G17) observed with higher mean value with non significant deviation with b value less than one. This indicated that these genotypes could perform better even under unfavourable environment conditions. Likewise Patel *et al*. (2019) and Sodhaparmar *et al.*(2023) reported stable genotypes in bajra by following this criteria (**Table 4, Fig. 1**). The significant deviation from the regression (S^2di) was observed in nine genotypes and hence these inbreds are considered as unstable (Patel *et al*., 2019).

Additive main effects and multiplicative interaction approach: AMMI model incorporates both additive and multiplicative components, making it a potent approach for analyzing the impact of Genotype-Environment (G x E) interaction (Zobel *et al.,* 1988). Through the biplot and genotypic stability statistics, it facilitates the clustering of genotypes with similar performances across various environments.

The AMMI analysis of variance revealed the significance for genotypes, environments, and G x E interaction components, which suggested the presence of considerable variation among environments and genotypes. Among them genotypes accounted for a substantial portion of the overall variation (57.62 %), whereas environment and genotype-environment interaction (GEI) contributed approximately 28.31 % and 14.07 % respectively. Notably, the analysis demonstrated that the first three principal components (PCs) significantly explained GEI. Specifically, the first PC contributed 55.0% to the total GEI, whereas second and third PCs contributed 25.8% and 19.2% respectively which infers that these components together provide a complete explanation for the G x E interaction influencing seed yield (**Table 2**).

The AMMI biplots illustrates the association between test genotypes and experimental environments over various seasons and it was depicted as the "grain yield vs. PC1 scores" (**Fig. 2**). A stable genotype was characterized by consistent performance, unaffected by variations in the environment along with high average yield. Among the checks, COH10 (G22) had higher mean yield (114 g). Among the genotypes, PT 7058 (G16) followed by PT 6679 (G13) and PT 7064 (G19) were observed with high average yields of 102 g, 101 g and 93 g, respectively, while PT 7091 (G8), PTB 7082 (G6) and PTB 7083 (7) recorded low mean yields of 63 g, 64 g and 66 g, respectively. The greater IPCA1 score indicated that interaction of genotypes with environment would be high and it was observed for Dhanasakthi followed by 86M38 (G23) and COH10 (G22) (Checks). The IPCA values of the inbreds PT 7091(G8) and PT 7064 (G19) were placed near to 0 and indicated that these genotype were stable (**Fig.2**). However, the genotypes PT 7064 (G19) had higher mean and it exhibited stable performance over environments.

In AMMI biplot 2 (**Fig. 3**), the environment with the longer spoke and acute angle with average environment axis is considered as more interactive and most discriminative. (Pan- pan *et al*., 2016; Kiruba *et al*., 2023; Narasimhulu *et al.,* 2023). Specifically, both E2 and E4, representing *Kharif* seasons, exhibited the longest spokes from which E2 forms smallest angle with optimal environment axis indicating that *Kharif* seasons are more interactive and

Table 1. Pooled analysis of variance for pearl millet genotypes (Eberhart and Russell, 1966)

Source of Variation	df	Sum of Squares	Mean Squares	% of SS
Total	91	27388.65	3360.32	100
Genotype	22	15781.53	717.342**++	57.62
Environment	3	7753.78	2584.59**++	28.31
Genotype x Envionment	66	3853.34	58.384**	14.07
Environment + Variety x Environment	69	11607.12	168.219**++	
Environment (Linear)	1	7753.78	7753.78**++	
Environment x Genotype (Linear)	22	1327.73	60.351**	
Pooled Deviation	46	2525.62	54.905	
Pooled Error	88	1209.21	13.741	

**, ++ represents significance at 1% level with pooler error and pooled deviation respectively

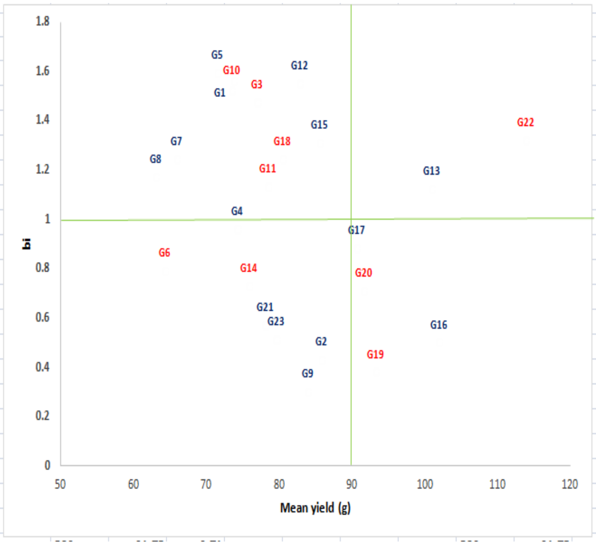

Fig 1. Regression based model for identifying genotypes with high mean yield

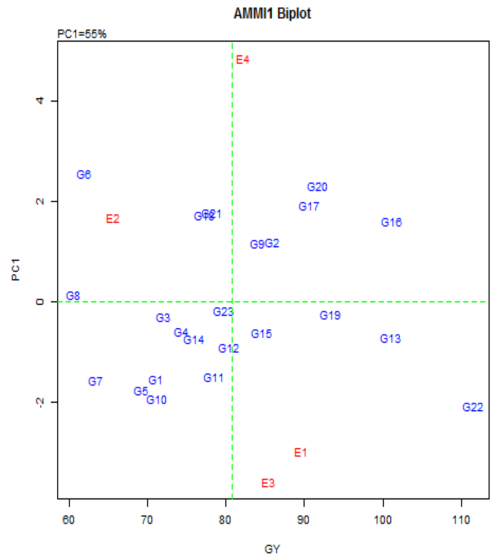

Fig. 2. AMMI Biplot 1 for grain yield per plant

Table 2. AMMI analysis of variance with interaction PCA and their cumulative percentage

Source of Variation	Df	Sum of Squares	Mean Squares	% SS (Cumulative %)
Genotype (G)	22	31563.06	1434.68**	57.62 (57.62*)
Environment (E)	3	15507.57	5169.19**	28.31(85.93*)
Genotype x Envionment (G x E)	66	7706.67	116.77**	14.07 (100*)
PC1	24	4585.86	191.08**	55.00 (55.00*)
PC2	22	215.19	97.96**	25.80 (80.98*)
PC3	20	1597.93	79.89**	19.2 (100*)
Residuals	92	1239.49	13.47	0

*,** represents significance at 5% and 1% probability level;
* values in parenthesis represents cumulative percentage of sum of squares

most discriminating environments compared to summer seasons. In terms of genotypes, those positioned closer to the origin are perceived as less interactive with environments. Applying this criterion, genotypes PTB 7091 (G8) and PT 6679 (G13) were identified as less interactive with environments. The AMMI biplot analysis (**Fig. 2 and 3**), identified genotype PTB 7091 (G8) as stable one with consistent seed yield.

Prediction of stable genotypes through AMMI stability indices: Visualizing of AMMI biplots poses challenges when studying of more genotypes, many of which overlapped, causing a somewhat indistinct figure. Hence various stability parameters associated with AMMI analysis, including ASI, ASV, AVAMGE, ASTAB, DA,DZ, FA, EV, MASI and MASV were calculated and are presented in **Table 3**. Also the ranking of the genotypes for these parameters are depicted in heatmap (**Fig. 4**). From the parameters, EV exhibited notably low scores with minimal variation among different genotypes. This suggests that these parameters may not be significantly involved in subsequent calculations of SSI (Anuradha *et al.,* 2022). A genotype will be considered more stable when any given stability parameter is having a lower score, and conversely, higher scores indicate less stability (Mamta and Hooda, 2020; Asungre *et al.,* 2021). According to ASI and ASV, the genotypes PTB 7091 (G8) followed by ICMB 07999 (G4) were most stable whereas ICMB 07999 (G4) followed by PT 6679 (G13) were shown low scores for all the other parameters. Based on SIPC, genotypes PT 6679 (G13) followed by PT 7054 (G15) were highly stable whereas Za showed that genotypes PT 6679 (G13) followed by ICMB 07999 (G4) had more stability (**Table 3**). The variations observed in

Table 3. Estimation of stability parameters by different approaches of stability models

G. no	Genotype	Mean Yield (g)	Regression parameters		AMMI stability indices															
			b_i	S^2_{di}	IPCA1	IPCA2	ASI	ASV	AVAMGE	ASTAB	DA	EV	DZ	FA	MASI	MASV	SSI	YSI
G1	ICMB 93222	73.59 (19)	1.52	19.18	-1.53	1.02	0.86 (16)	3 .00 (16)	23.33 (15)	3.76 (10)	12.26 (12)	0.03 (10)	0.31 (10)	150.33 (12)	0.87 (16)	3.25 (13)	32 (18)	35 (18)
G2	ICMB 98222	85.89 (7)	0.43	1.23	1.2	-1.2	0.76 (12)	2.64 (12)	20.68 (11)	3.27 (8)	11.27 (9)	0.03 (7)	0.29 (7)	127.01 (9)	0.76 (12)	3.04 (11)	18 (7)	19 (8)
G3	ICMB 06111	77.09 (17)	1.47	85.84**	-0.28	1.96	0.45 (5)	1.55 (5)	30.76 (23)	9.14 (22)	16.14 (20)	0.11 (22)	0.57 (22)	260.51 (20)	0.66 (10)	3.50 (15)	32 (19)	22 (10)
G4	ICMB 07999	74.31 (16)	0.96	6.64	-0.57	-0.42	0.34 (2)	1.18 (2)	8.8 (1)	0.73 (1)	5.24 (1)	0.01 (1)	0.14 (1)	27.44 (1)	0.34(1)	1.37 (1)	17 (5)	18 (7)
G5	PTB 7080	71.63 (20)	1.59	20.58	-1.75	0.92	1 (18)	3.49 (18)	26.61 (18)	4.78 (14)	13.97 (16)	0.04 (13)	0.35 (13)	195.1 (16)	1.01 (18)	3.74 (17)	37 (21)	38 (22)
G6	PTB 7082	64.42 (22)	0.79	160.31**	2.57	0.93	1.42 (23)	4.95 (23)	30 (22)	8.04 (21)	18.68 (22)	0.06 (19)	0.43 (19)	348.87 (22)	1.42 (23)	5.09 (22)	44 (23)	45 (23)
G7	PTB 7083	65.93 (21)	1.24	19.91	-1.54	-0.02	0.83 (15)	2.90 (15)	19.58 (10)	2.90 (6)	11.09 (7)	0.02 (4)	0.27 (4)	123.09 (7)	0.84 (15)	2.97 (9)	30 (17)	36 (20)
G8	PTB 7091	63.06 (23)	1.17	17.58	0.15	0.43	0.24 (1)	0.82 (1)	19.28 (9)	5.04 (16)	11.8 (10)	0.06 (18)	0.43 (18)	139.34 (10)	0.46 (4)	2.43 4)	27 (14)	24 (13)
G9	PTB 7095	84.05 (9)	0.30*	19.18	1.17	-1.69	0.82 (14)	2.85 (14)	22.05 (12)	4.58 (13)	13.04 (15)	0.04 (14)	0.36 (14)	170.06 (15)	0.82 (13)	3.51 (16)	25 (12)	23 (12)
G10	PTB 7102	73.76 (18)	1.56	46.11**	-1.92	0.67	1.07 (19)	3.73 (19)	27.84 (20)	5.1 (17)	14.58 (18)	0.04 (15)	0.36 (15)	212.56 (18)	1.08 (19)	3.91 (19)	37 (22)	37 (21)
G11	PT 6067	78.5 (12)	1.13	64.02**	-1.47	-0.29	0.8 (13)	2.79 (13)	18.65 (8)	3.91 (12)	12.14 (11)	0.04 (11)	0.33 (11)	147.27 (11)	0.83 (14)	3.09 (12)	24 (10)	25 (14)
G12	PT 6129	82.9 (10)	1.55*	-4.67	-0.89	1.38	0.63 (10)	2.20 (10)	16.87 (5)	2.89 (5)	10.28 (6)	0.03 (5)	0.28 (5)	105.68 (6)	0.63 (8)	2.76 (7)	17 (6)	20 (9)
G13	PT 6679	101.01 (3)	1.12	5.91	-0.71	-0.08	0.39 (3)	1.35 (3)	9.06 (2)	0.77 (2)	5.53 (2)	0.01 (2)	0.14 (2)	30.53 (2)	0.40 (3)	1.43 (2)	5 (1)	6 (1)
G14	PT 6708	75.87 (15)	0.73	21.38*	-0.74	-1.19	0.57 (8)	2.00 (8)	24.31 (16)	4.81 (15)	12.37 (13)	0.05 (17)	0.39 (17)	152.97 (13)	0.63 (7)	3.02 (10)	25 (11)	23 (11)
G15	PT 7054	85.58 (8)	1.31*	-5.29	-0.61	0.72	0.39 (4)	1.36 (4)	10.6 (3)	0.92 (3)	5.93 (3)	0.01 (3)	0.16 (3)	35.18 (3)	0.39 (2)	1.60 (3)	11 (4)	12 (4)
G16	PT 7058	102.05 (2)	0.5	2.17	1.61	-1.35	0.49 (6)	1.72 (6)	16.88 (6)	3.09 (7)	10.06 (5)	0.03 (9)	0.31 (9)	101.13 (5)	0.52 (5)	2.57 (6)	8 (3)	8 (2)
G17	PT 7061	90.68 (6)	0.88	14.75	1.94	0.72	1.07 (20)	3.74 (20)	22.21 (13)	5.65 (18)	15.11(19)	0.05 (16)	0.38 (16)	228.16 (19)	1.09 (20)	4.00 (20)	26 (13)	26 (15)
G18	PT 7062	80.53 (14)	1.24	125.07**	1.72	1.98	1.1 (18)	3.83 (21)	27.62 (19)	7.45 (20)	16.84 (21)	0.07 (21)	0.45 (21)	283.64 (2)	1.1 (21)	4.53 (21)	35 (20)	35 (19)
G19	PT 7064	93.31 (4)	0.38	30**	-0.23	-2.46	0.7 (11)	2.45 (11)	22.91 (14)	6.22 (19)	14.32 (17)	0.06 (20)	0.43 (20)	205.19 (17)	0.71 (11)	3.78 (18)	22 (9)	15 (5)
G20	PT 7075	91.75 (5)	0.71	189.53**	2.33	0.88	1.29 (22)	4.49 (22)	29.65 (21)	11.66 (23)	20.55 (23)	0.11 (23)	0.59 (23)	422.1 (23)	1.36 (22)	5.10 (23)	28 (16)	27 (16)
G21	Dhanasakthi	78.17 (13)	0.57	18.43	1.77	-0.43	0.97 (21)	3.37 (17)	24.72 (17)	3.82 (11)	12.82 (14)	0.03 (8)	0.3 (8)	164.26 (14)	0.97 (17)	3.45 (14)	27 (15)	30 (17)
G22	COH10	114.02 (1)	1.32	25.53*	-2.06	-0.58	0.59 (9)	2.07 (9)	16.49 (4)	2.82 (4)	9.96 (4)	0.03 (6)	0.29 (6)	99.11 (4)	0.63 (9)	2.45 (5)	6 (2)	10 (3)
G23	86M38	79.68 (11)	0.51	14.66	-0.16	-1.9	0.54 (23)	1.90 (7)	17.89 (7)	3.76 (9)	11.13 (8)	0.04 (12)	0.34 (12)	123.81 (8)	0.55 (6)	2.93 (8)	19 (8)	18 (6)

*,** represents significance at 5% and 1% level ; IPCA1, IPCA2 and IPCA3 were interaction principal components; ASI – AMMI Stability Index; ASV – AMMI Stability Value; AVAMGE - sum across environments of GEI modeled by AMMI; ASTAB - AMMI-based stability parameter; DA - Annicchiarico's D parameter; EV, averages of the squared eigenvector values; DZ, Zhang's D parameter; FA - stability measure based on fitted AMMI model; MASI - Modified AMMI Stability Index; MASV- Modified AMMI stability value;; SSI - Simultaneous Selection Index; YSI - Yield Stability Index; Numbers included in (..) indicated ranking of the genotypes

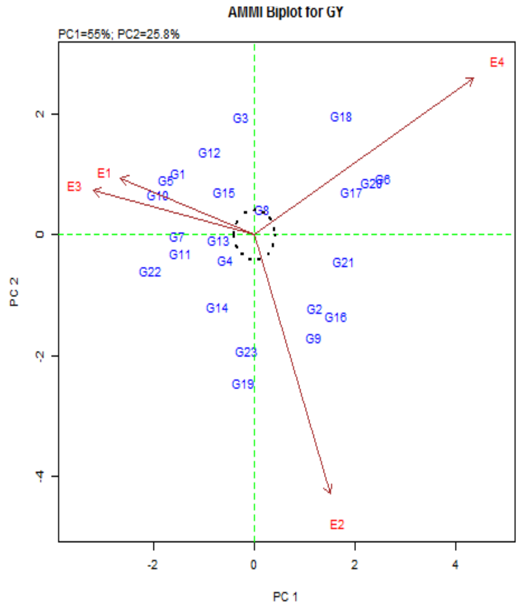

Fig. 3. AMMI Biplot 2 for first two IPCA scores

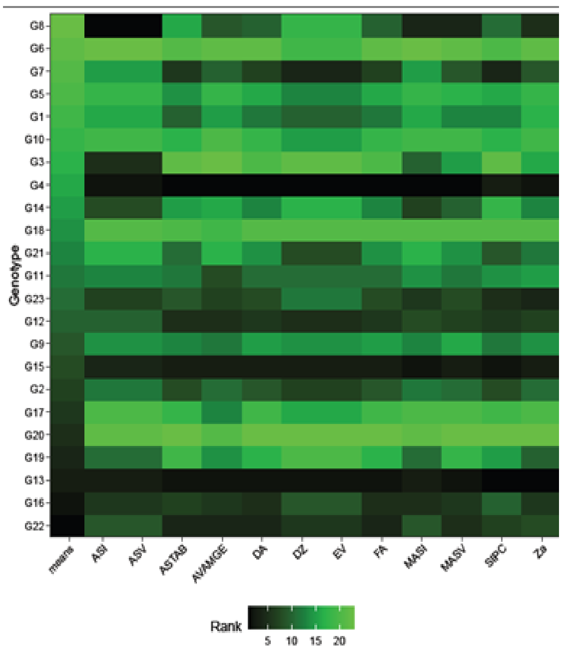

Fig. 4. Response of the genotypes for different AMMI stability parameters

the parameters suggested the differences in estimation methods, specifically whether they take into account only the first two or all significant principal components (PCs). Nevertheless, when considered collectively, probably all stability parameters exhibited a consistent pattern in identifying reliable genotypes (Cheloei *et al.,* 2020).

Association between stability parameters: To elucidate the correlation between AMMI stability parameters, Spearman's rank correlations was performed and it demonstrated the robust association among the calculated AMMI-based indices (**Fig. 5**). The positive and significant correlation was reported among all the stability parameters inferred that the genotypes that are highly stable remain consistent across different indices calculated, suggesting subtle variations in the calculation process. Notably, among the significant correlations, ASI and ASV were calculated based on first two principal components (PCs), exhibited a strong correlation, inferring a similar pattern in assessing genotypes stability. Although MASI is based on all three significant PCs, it displayed an extremely high correlation (r = 0.98) with ASI and ASV and also displayed strong correlation (r=0.93) with MASV, suggesting a comparable ranking pattern of genotypes. This could be attributed to exhibiting a substantial portion of G x E interaction by the first two PCs. Similar studies on association between stability indices were reported in finger millet (Anuradha *et al.,* 2022) and peanuts (Ajay *et al.*, 2020).

Identification of stable high yielding genotypes : Genotypes with stability scores below the mean were categorized as "stable genotypes". Among those qualified genotypes, the one with the highest yield was considered as the most advantageous. For this, two indices namely SSI and YSI were estimated from genotypes mean rank and its corresponding MASV and ASV rankings. From the Simultaneous Selection Index (SSI) and Yield Stability Index (YSI) rankings, the hybrid COH10 registered high average yield with stable performance. Among the test entries PT 6679 (G13) followed by the genotypes PT 7058 (G16) and PT 7054 (G15) recorded low scores and could be identified as stable genotypes with high seed yields.

Discrimination of genotypes based on GGE Biplot: The GGE biplot aids in recognizing patterns of GxE interaction in the data, offering a clear understanding of which genotype performs well in specific environments. This facilitates the discrimination of mega-environments more effectively than AMMI. Both GGE and AMMI models are considered equivalent in terms of accuracy (Gurmu *et al.,* 2012).

Relationship among tested environments: The association among the studied environments were determined by vector angle between the environments (Reddy *et al.,* 2021). In **Fig. 6**, the environmental vectors E1, E2, E3 and E4 exhibited a positive correlation among them, as evidenced by the acute angle between them. It implied that genotypes performs well in one tested environment may perform better in other environments. Greater the angle (obtuse angle) between environmental vectors, the more dissimilar they are in their ability to differentiate genotypes (Narasimhulu *et al.,* 2023). The longest

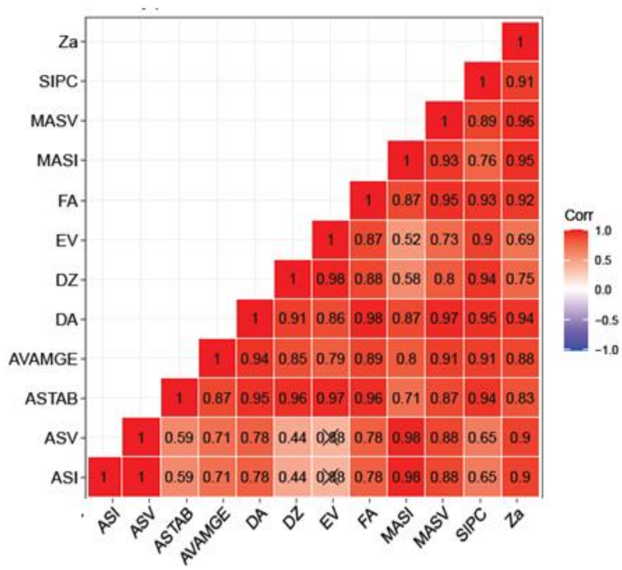

Fig. 5. Correlation between different AMMI stability parameters

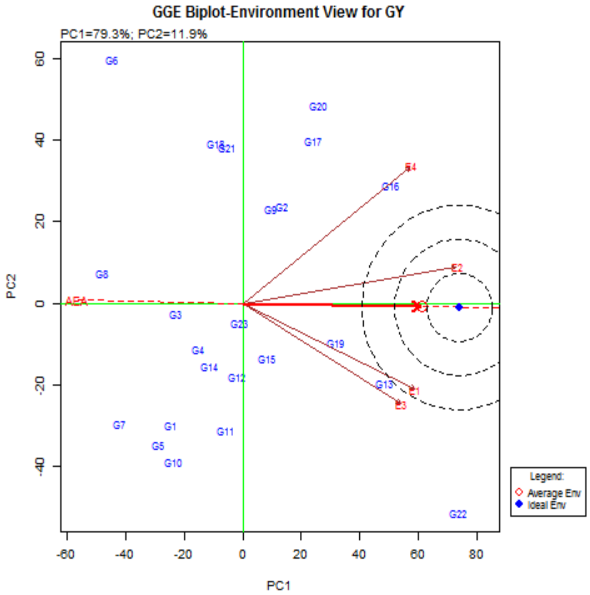

Fig. 6. Ranking the environments based on representativeness and their discriminating ability

environmental vector is associated with E2, indicating its superior discriminating ability, followed by E4, and E1. This suggests that the *kharif* seasons serves as more discriminating environment when compared to the summer seasons.

The Average Environmental Axis (AEA) represents the average coordinates of all test environments and extends from the origin to the average environment point (Yan, 2001). As shown in **Fig. 6**, environment E2 forms an acute angle with the AEA, suggesting that E2 is the most representative across all test environments, while E4 is the least representative. Consequently, E4 is also discriminating but less representative environment hence it is valuable for selecting specifically adapted genotypes and eliminating unstable ones (Narasimhulu *et al.,* 2023). These findings indicate that *kharif* seasons provide more informative assessments of genotype stability compared to summer seasons.

The central position (Focal Point) within the concentric circles corresponds to a position on the Average Environmental Axis (AEA), positioned at a distance equivalent to the longest environmental vector from the origin in the positive direction. E2 is in close proximity to this point, making it the optimal test environment for the selection of genotypes well-adapted to diverse environments.

An examination of both genotype and environmental vectors (**Fig. 7**) provides insights into the distinct interaction between genotype and environment. The performance of genotypes PT 6679 (G13), PT 7054 (G15) and PT 7064 (G19) and the check COH10 (G22) demonstrates superiority compared to the average (as indicated by acute angles) in E1 and E3 while remaining genotypes exhibit performance below the average in E1 and E3. Within E2 and E4, genotypes ICMB 98222 (G2), PTB 7095 (G9), PT 7058 (G16), PT 7061 (G17) and PT 7075 (G20) and the check COH10 (G22) surpass the average while other genotypes perform below the average in E2 and E4.

Mean and stability performance of the genotypes: The single-arrowed line, denoted as the Average Environment Coordination Abscissa (AEC) in **Fig. 8**, indicates the direction of higher average yield per plant across environments (Yan, 2001). On the other hand, the double-arrowed line represents the AEC coordinate, illustrating the highest variation in either direction. Consequently, genotypes PT 7064 (G19), PT 7054 (G15) and PT 6679 (G13), PT 7075 (G20), PT 7058 (G16), ICMB 93222 (G1) and the checks COH10 (G22) and 86M38 (G23) were identified as stable, while the remaining genotypes display high interaction with the environment. An ideal genotype is characterized by both high mean and stability across various environments (Sharma *et al.,* 1998). In this context, genotypes G13 (PT 6679), G19 (PT 7064) and G15 (PT 7054) are ideal due to their high mean and stability. Additionally, genotype PT 7058 is recognized for its high average yield with a moderate level of interaction with the environment. It inferred that a genotype demonstrating stability across various environments doesn’t necessarily imply superior performance, and *vice versa* (Solomon and Yohans, 2021). Hence, the genotype selection and breeding strategies are designed based on the graphical

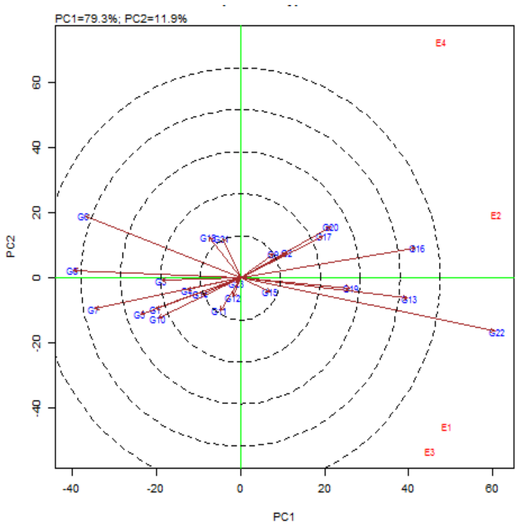

Fig. 7. GGE Biplot- Genotype view representing relationship of genotypes with test environments for grain yield per plant

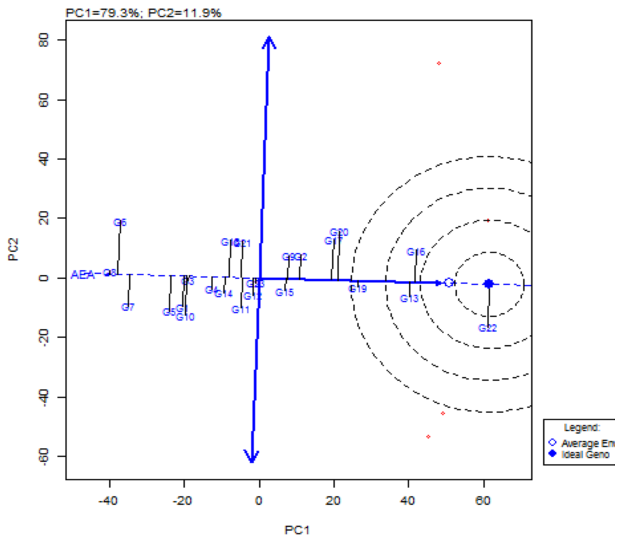

Fig 8. Ranking the test genotypes based on mean performance for seed yield per plant

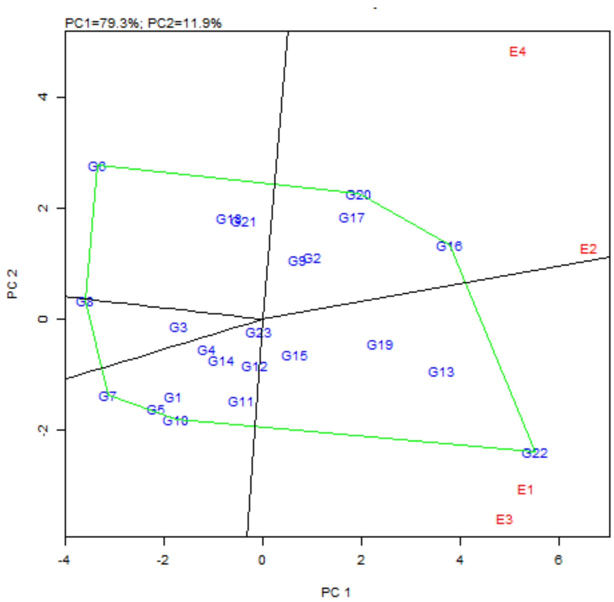

Fig. 9. Which won where biplot of 23 pearl millet genotypes for seed yield per plant

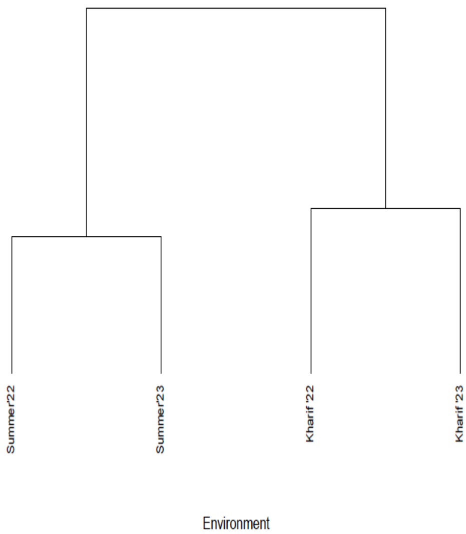

Fig 10. Dendrogram for seed yield per plant among environments (Ward method)

representation to target trait for both broadly adapted and specific environments (Reddy *et al.,* 2021).

Which won where biplot for seed yield: The graphical representation of the GGE biplot's "which-won where feature" deals visually with crossover genotype-environment interaction, differentiation of mega-environments, specific adaptation of genotypes, and so forth (Rao *et al.,* 2011). The genotypes positioned at the vertices of the polygon inferred that superior or poorly performing genotypes in one or more environments. The equality line serves to divide the biplot into distinct sectors, with winning genotypes situated at the vertices of each sector. The equality lines partitioned the biplot into five sections (**Fig. 9**) and the studied environments partitioned into two mega environments, ME1 and ME2. Grouping environments also supported with dendrogram (**Fig. 10**) which was drawn from the genotype performance over the tested environments. ME1 included with E1 (*Summer'22*) and E3 (*Summer'23*). Specifically, G22 (COH10) emerges as the top performer in E1 and E3, while G16 (PT 7058) and G20 (PT 7075) lead in E2 and E3 respectively. However, these genotypes exhibited poor performance in other environments. Hence, different genotypes need to be selected and deployed for each mega-environment.

The growth of crops is significantly influenced by genetic (G), environmental (E), and their interaction (G×E). The interaction between genetics and environment (G×E) is a widespread phenomenon in the biological realm and forms the basis for influencing the stability of cultivars. Stability tends to decrease as the G×E interaction effect becomes more pronounced. The combined analysis of variance showed significant genotype-environment interaction (GEI), indicating considerable variation comes from environment. From the regression model (Eberhart and Russel, 1966) the genotype ICMB 07999 is identified as average stable performer while PT 6679 identified as below average stability under favourable conditions. In contrast, the inbreds PT 7058 and ICMB 98222 exhibited better performance under low environmental conditions. The AMMI and GGE biplots visually represent the relationship between evaluated genotypes and test environments across various seasons. Among the genotypes, PT 7064 observed with both high mean grain yield and stable performance followed by the genotypes PT 6679 and PT 7058. Also different stability parameters, including ASV, ASI, AVMGE, ASTB, DA, EV, DZ, FA, MASV, MASI, YSI and SSI were assessed in this investigation and demonstrated their equal effectiveness in identifying stable genotypes. Considering various parameters, it can be concluded that the genotypes PT 6679 followed by PT 7058 and PT 7054 and along with check COH10 had low SI scores and among B lines ICMB 07999 followed by ICMB 98222 were identified as stable genotypes with high seed yield. Based on Average Environment Coordinate - GGE biplots, *Kharif* seasons were represented as representative and discriminative than summer based on their interaction with genotypes and discriminating ability. Therefore, distinct genotypes should be chosen for each environment. In this context, the genotypes PT 7058 and PT 7075 performed well in *Kharif* seasons while the hybrid COH10 shown yield superiority in summer seasons.

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