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RESEARCH ARTICLE

GGE biplot analysis for identification of ideal cultivars and testing locations of pearl millet (*Pennisetum glaucum* L.R. Br.) for peninsular India

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Abstract

Pearl millet is a climate resilient crop grown by resource poor farmers. Identification of the ideal genotypes for broad and specific adaptation and ideal locations for testing in peninsular India (classified as B-zone) will address the needs of farmers and researchers working in this region. In the present study, performance of eight hybrids and four varieties over seven locations across three rainy seasons (2017-2019) was investigated using GGE biplot analysis. Location attributed higher proportion (59.3–89.9%) of the variation for eight traits, while genotype and genotype×environment interaction accounted for 57 to 65% of total variability for grain and dry fodder yields. The hybrids 86M86, KSB and NBH5061 are identified as ideal genotypes for cultivation across B-zone. Majority of the testing locations were highly correlated with Vijayapura, which is most discriminative and representative location. 'Which-won where' study partitioned the testing locations into two mega-environments: first with four locations with 86M01 as winning genotype and second encompassed three locations with KSB as the winning genotype. The Vijayapura, Ananthapuram and Dhule locations were identified for initial testing of genotypes. Hybrid advantage over varieties for grain and fodder yields was clearly observed from the study.

Keywords: GGE biplot, mega-environment, multi-environment data, pearl millet, stability

Introduction

Pearl millet (*Pennisetum glaucum* L. R. Br.) is cultivated on about 30 million ha in more than 30 countries across five continents viz., Asia, Africa, North America, South America and Australia. The majority of crop area is in Asia (>10 million ha) and Africa (about 18 million ha) though grown non-traditionally in several countries such as Brazil, USA, Canada and Mexico (Yadav and Rai 2013). India has the largest area under pearl millet in the world (6.93 m ha) and it is fourth most widely cultivated cereal crop after rice, wheat and maize in the sub-continent (Satyavathi 2020). In India, the cultivated area under pearl millet is divided into three zones – A_1 zone of northwestern India receiving <400 mm of annual rainfall, and A zone of northern and central India with sandy loam soils receiving >400 mm of annual rainfall and B zone of peninsular India with heavy soils receiving >400 mm of annual rainfall (Rai et al. 2015). Zone B occupies an area of 1.14 m ha and comprises of the states of Maharashtra, Andhra

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Pradesh, Telangana, Karnataka, Tamil Nadu and Odisha. Most of pearl millet is grown in rainy (*kharif*) season (June/July–September/October) in this zone. Both open-pollinated varieties and commercial hybrids are available as cultivar options in pearl millet due to the existence of protogyny enabled highly cross-pollinated nature and exploitation of cytoplasmic-nuclear male sterility system. The best hybrids had 30% yield advantage over best OPVs in pearl millet (Rai et al. 2015), though OPVs have their advantage of broad adaptation, greater resilience to existing and emerging pests and diseases and less input cost to the farmer.

Research on Pearl millet improvement in India is carried through the All India Coordinated Research Project on Pearl Millet (AICRP-PM) administered by Indian Council of Agricultural Research (ICAR) through a network of 13 AICRP-PM centers. The experimental hybrids developed by public and private sectors are evaluated in initial trial followed by two advanced trials. Those genotypes with consistent yield advantage over a period of three years and other desirable traits are released for cultivation in specific zones where they are consistent or on all-India level. Through ICAR-AICRP-PM, a total of 175 hybrids and 62 varieties were identified and released for cultivation in different agro-ecological zones of the country (Satyavathi 2020). Among them, few have gained popularity and are widely cultivated in respective zones. As numerous cultivars are released in pearl millet, there is a need for evaluating the performance of popularly cultivated hybrids and varieties which provides information on most suitable cultivars as well as diversity of testing locations.

Multi-environment trial (MET) data is often less utilized. Mostly genotype main effects are considered for genotype evaluation, whereas genotype environment interactions (GEI) are ignored as noise or confounding factor. GEI in MET causes changes in relative ranking of genotypes which complicates their evaluation. In MET, understanding the performance of genotypes along with stability over diverse environments is an important aspect of identifying high yielding varieties (Scapim et al. 2000). For studying GEI, various statistical techniques such as variation co-efficient, linear regression, analysis of variance (ANOVA), additive main effects, multiplicative interaction (AMMI) or genotype plus GEI (GGE) biplot analysis are available (Pan-pan et al. 2016). Among them, AMMI and GGE biplot are frequently used for MET data analysis. In AMMI analysis, GEI is taken into account while genotype effects are ignored. The GGE Biplot analysis proposed by Yan et al. (2000) considers both genotype main effects and GEI effects for the analysis. Therefore, GGE biplot model is considered as efficient method for identifying best genotypes and test environments. GGE biplot has been used for MET data in rice (Dwivedi et al. 2020), durum wheat (Heidari et al. 2016), sorghum (Rakshit et al. 2012), baby corn (Choudhary et al. 2019) among cereals and groundnut (Ajay 1et al. 2021), pigeonpea (Kumar et al. 2021) and urdbean (Kumar et al. 2020) among pulses.

Table 1. A list of released hybrids and varieties used in the study

Cultivar	Year of release	Developing Organization
Hybrids		
86M01	2015	Pioneer Overseas Corp.
86M64	2011	Pioneer Overseas Corp.
86M86	2012	Pioneer Overseas Corp.
GHB558	2003	ICAR-AICRP-PM, JAU, Jamnagar
KSB (Kaveri Super Boss)	2012	Kaveri Seed Co. Ltd.
NBH5061	2014	Nuziveedu Seeds Pvt. Ltd.
NBH5767	2015	Nuziveedu Seeds Pvt. Ltd.
Pratap	2012	Nuziveedu Seeds Pvt. Ltd.
Varieties		
Dhanshakthi	2014	ICRISAT, Patancheru
ICMV155	1991	ICRISAT, Patancheru
ICMV221	1993	ICRISAT, Patancheru
PC612	2011	ICAR-IARI, New Delhi

In the current study, eight hybrids and four varieties that were released for commercial cultivation after testing and popularly grown were assessed across the years and locations in a released hybrids and varieties trial (RHVT) to understand GEI pattern across pearl millet growing regions of South India/Peninsular India/B-zone, to identify highly stable and adaptable pearl millet cultivars, and to determine ideal test locations.

Materials and methods

Genetic material, test locations and experiment

This study deployed Released Hybrid and Varietal Trial (RHVT) data sets of AICRIP-PM for the years 2017, 2018 and 2019 (hereafter referred to as Y1, Y2 and Y3). Eight hybrids and four varieties that were released from 1991 to 2015 and popular with farmers in B-zone were used for the current study. The information pertaining to hybrids and varieties used in the study are presented in Table 1. The multi-location testing was done at seven locations in five states. The states of Maharashtra and Karnataka were represented with two locations while the states of Andhra Pradesh, Telangana and Tamil Nadu were represented with one location each. Detailed features of these test locations and dates of sowing are given in Table 2. Fig. 1 presents further information on the locations and their geographic distribution. The crops were sown with onset of monsoon in each of these locations. In each location, the experiment was conducted in a randomized complete block design with three replications. The plot size of each genotype varied from 12 to 14.4 m^2 across years and locations. Plot yield data were converted to tons per hectare using the plot size as factor.

Table 2. Test locations used in the study

Location	Soil	pH	Date of sowing			Latitude	Longitude	Altitude
			2017	2018	2019			
Aurangabad	Medium Black	7.5	5-Jul	7-Jul	2-Jul	19°86′ N	75°30′ E	568 m
Dhule	Medium Black	8.6	5-Jul	25-Jun	7-Jul	21°08′ N	74°01′ E	210 m
Ananthapuram	Red Sandy Loam	6.5	31-Jul	15-Aug	19-Aug	14°68′ N	77°60′ E	335 m
Palem	Sandy Loam	7.9	8-Jul	17-Jul	27-Jun	16°35′ N	78°10′ E	642 m
Vijayapura	Shallow Black	8.7	10-Jul	17-Jul	21-Jul	16°50′ N	75°43′ E	594 m
Malnoor	Medium Black	8.2	1-Aug	4-Aug	19-Jul	17°03′ N	76°15′ E	460 m
Coimbatore	Clay Loam	7.8	30-Jun	29-Jun	2-Jul	11°02′ N	76°96′ E	427 m

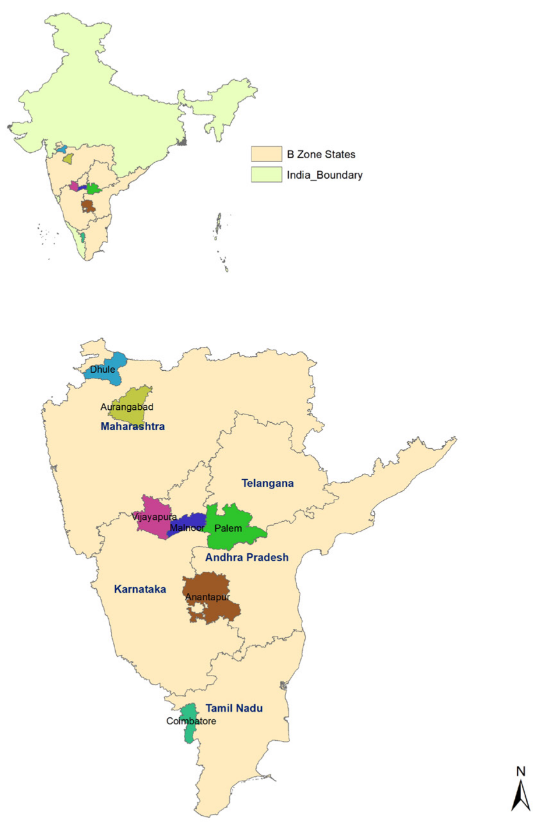

Fig. 1. Geographical locations of the testing environments

Trait measurements and statistical analysis

Data were recorded for eight yield related traits that included flowering time (DF), plant height (PHT), number of productive tillers (NPT), panicle length (PL), panicle diameter (PD), grain yield (GY), dry fodder yield (DFY) and 1000-grain weight (1000 GWT) following standard methodology (Reddy et al. 2021).

The data for eight traits were subjected to combined analysis of variance to investigate the genotypes (G), environments (E) and Genotype × Environment interaction (GEI) effects using Genstat 12th edition. In the combined ANOVA, genotypes were considered as fixed effects, while environments and replications were considered as random effects. As the GEI was significant, GGE biplot method (Yan et al. 2000) was employed to analyze of GE interaction and to assess stability of GY and DFY data and the pattern of response of hybrids tested in seven locations. For the GGE Biplot to be generated, the mean matrix must be environment-centered and then decomposed into principal components by Singular value decomposition (SVD); the first two PCs are then used to generate the graphics (Yan and Tinker 2006). The genotype-centered and the environment-centered singular value partitioning (SVP) are used for the evaluation of genotypes and environments respectively and the symmetric scaling is preferred for study of which-won-where pattern. GGE biplot analysis was used to generate graphs for: (i) the mean performance and stability analysis, (ii) the which-won-where pattern, (iii) relationship among test locations, (iv) ranking discrimination and representativeness of test locations and (v) ranking of genotypes relative to ideal environment. The GGE Biplot analyses was performed using the package GGplot2 of R studio (a simplifed version 4.0.0 of R statistical software) developed by the R Core Team (R Development Core Team 2019).

For the eight individual trials, the Pearson's correlation coefficients were calculated using MS Excel. The repeatability of a variety trial is the proportion of the variation among line means that is due to the variation in genotype effects. This statistic, also denoted as broad-sense heritability (H) is the ratio of genetic variance to the total of genetic variance and environmental variance, was calculated for the target traits. The broad-sense heritability was calculated as: $h^2 = \sigma^2_g / (\sigma^2_g + \sigma^2_{ge} / n + \sigma^2_e / nr)$, where σ^2_g is the genotypic variance, σ^2_{ge} is the interaction variance of genotype with environment, σ^2_e was the error variance, n was the number of environments, and r was the number of replicates. The estimates of $\sigma^2 g$, σ^2_{ge}, σ^2_e were obtained from an analysis of variance with environment considered as a random effect as mentioned by Xie et al. (2020).

Results and discussion

Pearl millet is grown in marginal soils with limited resources. Under the AICRP on pearl millet, over a period of time, several cultivars are released for three specific zones or for all-over India cultivation. Among them, evaluation of the best released and popular cultivars in MET will generate valuable information on very high yielding and highly stable cultivars for broad and specific adaptations and comparison between the hybrids and OPVs. The B-zone consisting of peninsular India has highly variable agro-ecological conditions. The seven multi-location testing sites in B-zone handled by AICRP on pearl millet represent diverse pearl millet production ecosystems of peninsular India. GGE biplot has been effectively used to analyze MET data in several crops to interpret complex GEI (Yan and Tinker 2006). We have studied the GEI among 12 pearl millet cultivars (8 hybrids and 4 varieties) across 7 locations over 3 years using GGE biplot analysis.

Analysis of variance

ANOVA was performed for data across locations in individual years and combined ANOVA pooled over years. Significant variation among the genotypes (G) was observed for all the traits in all the years and combined over years except number of productive tillers in Y1 as indicated by the ANOVA (Table 3). The ANOVA also shows that the environment as well as GE (Genotype × Environment) interaction were

Table 3. ANOVA, proportion of variation (G+E+GE) explained by genotype (G), environment (E) and GE interaction (GEI) and heritability (broad sense) for various traits

Trait/Year/ Source	Year	G		E		GE		$h^2_{(bs)}$
		MSS	Proportion (%)	MSS	Proportion (%)	MSS	Proportion (%)	
Grain yield (t/ha)	Y1	8.8**	33	17.0**	64	0.77**	3	0.91
	Y2	5.2**	18	22.8**	80	0.6**	2	0.88
	Y3	3.7**	19	15.0**	77	0.8**	4	0.79
	Across	16.2**	54	12.7**	43	1.0**	3	0.94
Dry fodder yield (t/ha)	Y1	24.5**	17	120.3**	81	3.0**	2	0.88
	Y2	11.5**	11	95.2**	88	2.0**	2	0.82
	Y3	17.0**	42	20.9**	51	2.8**	7	0.84
	Across	44.8**	60	26.7**	36	3.4	5	0.92
Days to 50% flowering	Y1	217.7**	31	466.0**	67	14.2**	2	0.93
	Y2	242.9**	54	196.2**	44	10.4**	2	0.96
	Y3	134.1**	32	274.5**	65	14.0**	3	0.90
	Across	518.8**	44	645.4**	55	19.9**	2	0.96
Plant height (cm)	Y1	4888.1**	25	13952.3**	72	503.8**	3	0.90
	Y2	2929.2**	9	29992.1**	90	470.0**	1	0.84
	Y3	3034.3**	12	20935.2**	85	576.8**	2	0.81
	Across	9610.8**	16	51591**	83	687.0**	1	0.93
Number of productive tillers	Y1	0.3	7	3.1**	83	0.37*	10	0.47
	Y2	0.7**	4	16.0**	94	0.27*	2	0.62
	Y3	0.6**	5	10.8**	92	0.35*	3	0.42
	Across	1.0**	5	17.7**	92	0.49	3	0.53
Panicle length (cm)	Y1	100.5**	48	98.3**	47	9.0**	4	0.91
	Y2	51.9**	33	96.0**	62	7.7**	5	0.85
	Y3	56.6**	46	61.7**	50	6.0**	5	0.89
	Across	201.6**	53	169.7**	44	11.3**	3	0.94
Panicle width (cm)	Y1	1.1**	3	32.9**	97	0.12**	0	0.89
	Y2	1.0**	41	1.4**	56	0.08*	3	0.92
	Y3	1.4**	20	5.4**	79	0.01**	1	0.93
	Across	3.3**	14	20.1**	86	0.1	0	0.97
1000 grain weight (g)	Y1	12.3**	38	17.5**	54	2.5**	8	0.80
	Y2	19.1**	13	123.9**	85	3.0**	2	0.84
	Y3	21.0**	11	171.8**	86	6.1**	3	0.71
	Across	54.5**	63	17.6**	20	14.1**	16	0.74

significant for all the traits in individual years and across years except for GE effects for DFY, NPT and PD in the pooled data across years. The relative magnitude of G, E and GE showed that the environment is the most important source of variation in individual years for all the traits. However, in the combined data over years, variance due to genotype was higher for GY, DFY, PL and 1000 GWT narrowly followed by variance due to environment with environment or location contributed 20–92% of the variation in the data, while contribution of genotype was from 5 to 63% for eight traits. Environment explained most of the variation in PHT (83%), PD (86%) and NPT (92%) (Table 3). Gauch and Zobel (1997) reported that normally in MET data, environment accounts for about 80% of the total variation. High environmental variation has been reported in several crops such as pearl millet with 73.9% (Reddy et al. 2021), baby corn with 87% (Choudhary et al. 2019), in proso millet up to 85% (Pan-pan et al. 2016), 56.8% in pigeonpea (Kumar et al. 2021) and upto 70% in durum wheat (Heidari et al. 2016). However, Oyekunle et al. (2017) reported a moderate (47.3%) variation being explained by environment in maize MET data and Tena et al. (2019) reported 48.8% in sugarcane MET data. The variance due to GE was very less (0 to 16%) though significant for all the traits across all the years and in combined analysis. The repeatability of the trial, determined by broad-sense heritability was high for all the traits except for NPT, for which it was moderate (Table 3). The cultivars involved in the study are known for their yield and stability being released for wider cultivation and this explains the lower GE interaction compared to variation due to G. Though low, the significant GE interaction contributes for differential performance of cultivars across locations. The GGE biplot analysis can be used to explain complex GEI, if the first two PCs explain more than 60% of the (G and GE) variability in the data, and the combined (G and GE) effect account for more than 10% of the total variability (Rakshit et al. 2012). In our study, the first two PCs explained 93.0% variation for grain yield and 85.1% for fodder yield. In addition, Table 3 indicates that G and GL together accounted for 57 and 65% of total variability for grain and fodder yields respectively. Thus, graphical representation of biplots can be used for visualizing stable and ideal genotypes and ideal environments.

Mean performance and stability of genotypes

Mean values of the hybrids and varieties for all the traits combined across locations and years and the performance of traits across locations combined over genotypes and years is presented in Table 4. Over years and locations,

Table 4. Trait means of pearl millet varieties and hybrids over years and locations

Location/genotype	GY	DFY	DF	PHT	NPT	PL	PD	1000 Gwt
Hybrids								
86M01	3.49	6.33	49	177	2.6	25.5	3.3	11.9
86M64	3.10	5.08	50	174	2.6	25.0	3.5	11.7
86M86	3.35	5.96	51	180	2.6	24.0	3.4	11.1
GHB558	2.33	4.39	45	149	3.0	21.3	3.2	11.9
Kaveri Super Boss	3.24	6.87	53	191	2.7	26.3	3.3	10.8
NBH5061	3.23	6.16	52	184	2.6	25.7	3.5	11.7
NBH5767	2.66	5.22	47	167	2.6	22.8	3.1	10.6
Pratap	2.83	5.02	48	157	2.6	22.3	3.3	12.1
Varieties								
Dhanshakthi	2.20	4.54	44	169	2.7	22.3	3.1	12.6
ICMV155	2.16	4.61	48	174	2.7	25.2	2.8	9.8
ICMV221	2.16	4.26	44	168	2.5	22.1	3.1	11.7
PC612	2.39	5.25	48	190	2.7	26.1	2.8	9.6
Locations								
Aurangabad	3.25	4.69	52	173	2.2	23.3	3.0	12.0
Dhule	2.98	5.52	51	219	2.2	25.9	3.3	11.1
Ananthapuram	2.76	4.91	45	170	2.6	25.8	4.0	11.0
Palem	2.24	4.84	48	164	3.1	22.8	2.8	11.1
Vijayapura	2.63	5.65	47	149	2.8	23.4	3.0	11.0
Malnoor	2.48	6.03	50	165	2.6	23.8	3.3	11.1
Coimbatore	2.99	5.51	46	175	3.2	23.5	2.9	11.8
Grand mean	2.76	5.31	48.4	173	2.7	24.1	3.2	11.3

86M01 among the hybrids and PC612 among varieties had high grain yield with a yield advantage of 1.1 t/ha in favor of the hybrid. On an average across years and locations, test hybrids had a grain yield advantage of 0.80 t/ha and dry fodder yield advantage of 0.96 t/ha over varieties. The performance of genotypes for other traits is given in Table 4. The grain yield is highly correlated with greater dry fodder yield, late flowering and more panicle diameter. The dry fodder yield was highly correlated with greater plant height and panicle length that contributed to biomass apart from grain yield (Fig. 2).

Performance and stability of genotypes can be evaluated by AEC (average environment coordination) and visualized graphically through GGE biplot (Yan 2002). For this, environment centered (centering = 2) genotype-metric (SVP = 1) biplots without scaling (scaling=0) for grain yield and fodder yield, the economically important traits are presented in Fig 3a-b, respectively. The first two PCs explained 93.0% variation for grain yield and 85.1% for fodder yield. AEC abscissa passes through the biplot origin and acts as a marker for average environment and points towards higher mean values. The perpendicular lines to the AEC passing through the biplot origin are referred to as AEC ordinate. These ordinates are depicted as dotted lines in Fig. 3a–b. The greater the absolute length of the projection of a cultivar, the less stable it is. Furthermore, the average yield of genotypes is approximated by the projections of their markers to the AEC abscissa. Accordingly, 86M01 was the best performing genotype in terms of grain yield followed by 86M86 while ICMV 221 and ICMV 155 were the poor yielders. However, 86M01 was least stable for grain yield with higher projection from the AEC abscissa. The hybrid 86M64 was highly stable with moderate grain yield and the hybrids 86M86, KSB and NBH 5061 were comparatively good yielders with moderate stability. The varieties ICMV 155 and Dhanshakthi had high stability though poor yielders as compared to hybrids (Fig. 3a). For dry fodder yield, KSB followed by 86M01 and NBH 5061 had highest yields but low stability. The hybrid 86M86 had good fodder yield with moderate stability while the hybrid NBH 5767 was highly stable. Compared to the hybrids, the varieties had low fodder yield (Fig. 3b).

A genotype with high yield and stable across environments is considered as ideal one for recommendation. For deriving ideal genotypes, the quality of the data over years is found to be quite reliable due to moderate to high broad-sense heritability (53–96%) over years (Table 3). It is a known fact that the OPVs in pearl millet would have more stable yields, more widely adapted than hybrids and less vulnerable to pests and diseases (Charyulu 2014). The genotypes such as KSB, NBH 5061 and ICMV 155 were stable for grain yield and showed poor stability for fodder yield. The genotypes NBH 5767, GHB 558 were highly stable for fodder yield and unstable for grain yield across locations. A genotype need not be stable for all traits as different traits are governed by a different set of genes. Apart from this, the genes for individual traits interact differently with the environment. The cumulative expression of different

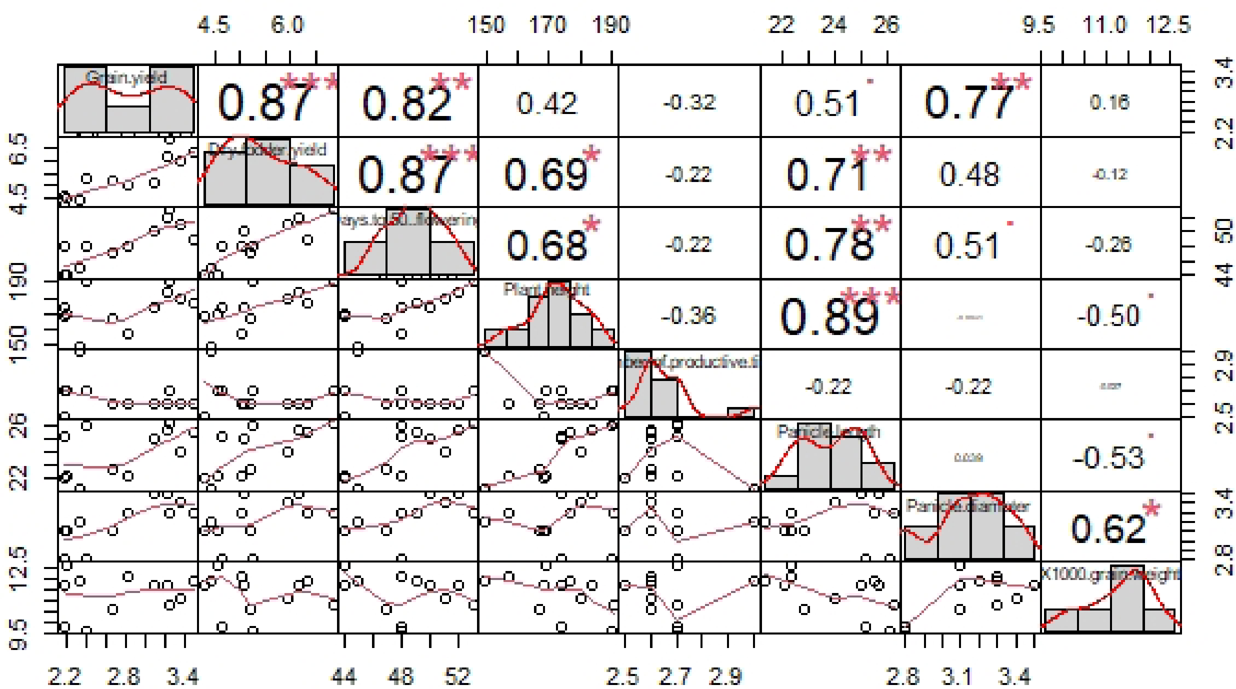

Fig. 2. Correlation among grain yield and traits recorded on 12 genotypes over seven locations and three years

set of genes due to G and GE, the genotypes vary for yield and stability for grain yield (Fig. 3a), fodder yield (Fig. 3b). Similar observations were reported by Rakshit et al. (2012) in sorghum and Reddy et al. (2021) in pearl millet. As grain yield is the more preferred trait by farmers in B-zone, the hybrids 86M86, KSB and NBH 5061 are identified as the ideal genotypes to be recommended to the farmers in this zone.

Relationship among environments

The relationships among the test environments were studied by environment centered (centering = 2), environment metric (SPV = 2) and without scaling (scaling = 0). Combined analysis of variance for three years for grain yield (Fig. 4a) and fodder yield (Fig. 4b) showed that the majority of the angles between their vectors are acute. Acute vector angles are indicative of closer relationship among the environments (Yan and Tinker 2006). Thus, majority of the locations were highly correlated with an exception between Aurangabad and Ananthapuram for grain yield and between Malnoor and Palem for fodder yield which has right angle between them showing no-relationship. Distance between two environments measures their ability in discriminating the genotypes. Thus, seven locations could be divided into three groups for grain yield; one with Aurangabad, Palem and Dhule, second with Vijayapura, Malnoor, Coimbatore and third with Ananthapuram. For fodder yield, three groups were formed with Malnoor, Dhule and Ananthapuram in one group, Vijayapura, Coimbatore and Aurangabad in

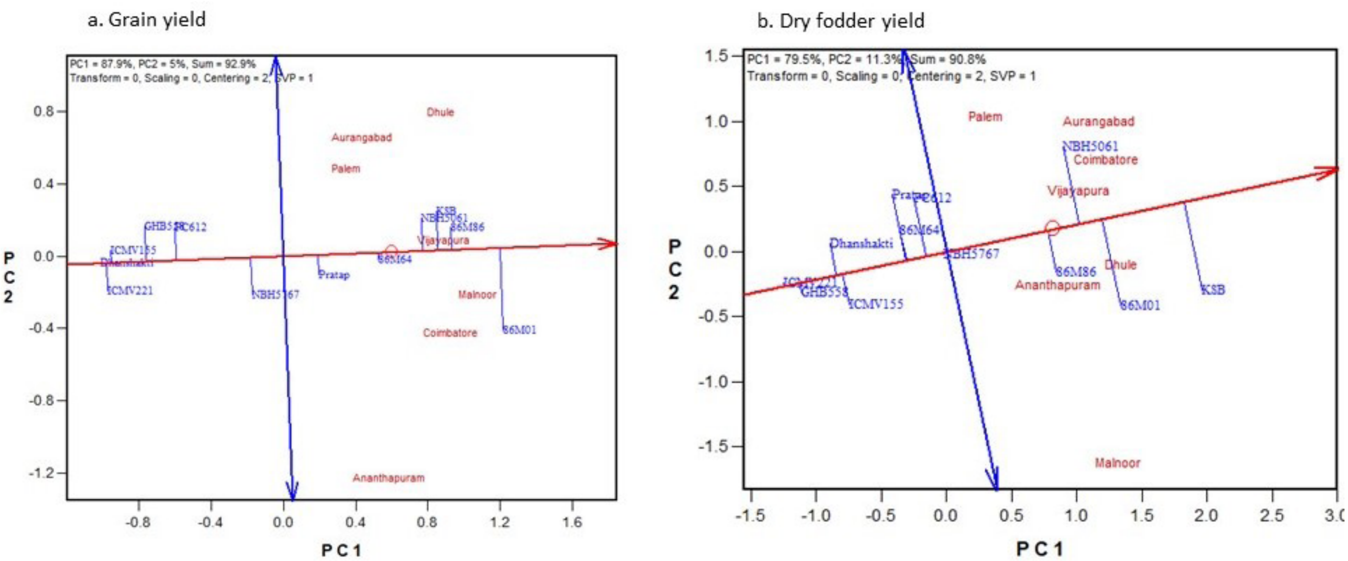

Fig. 3. GGE biplot showing "mean vs. stability" of 12 pearl millet cultivars across seven locations pooled over three years for, a) Grain yield and, b) Dry fodder yield

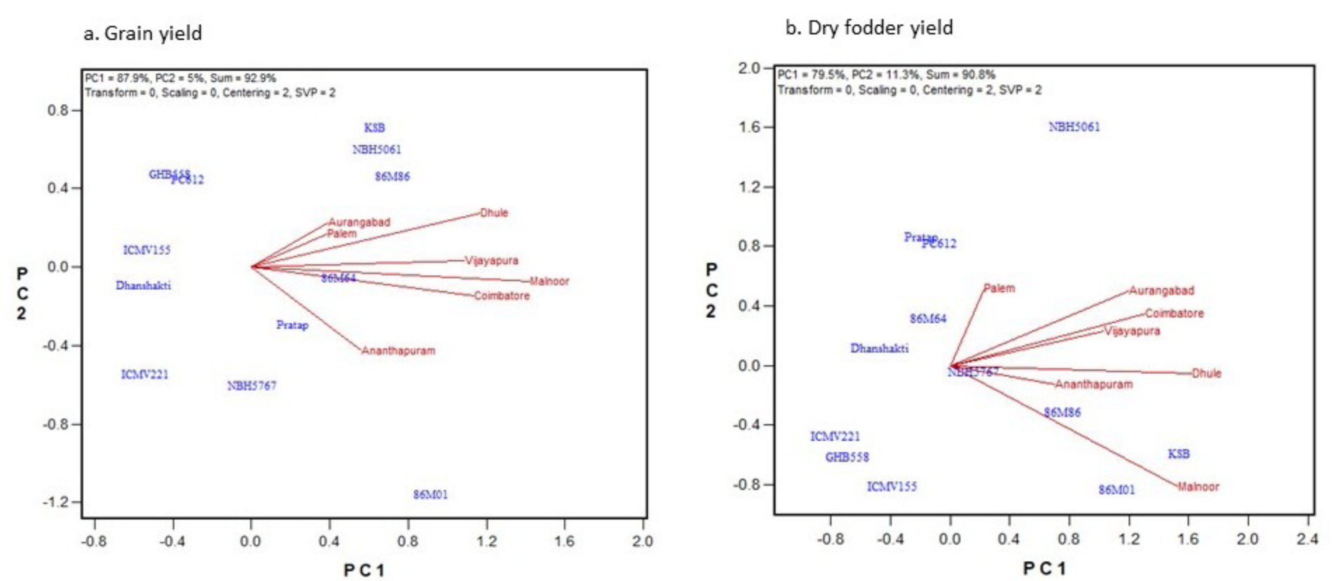

Fig. 4. GGE biplot showing "relationship among environments" of 12 pearl millet cultivars across seven locations pooled over three years for, a) Grain yield and, b) Dry fodder yield

second group and Palem in third group. When both grain and fodder yields are observed, Vijayapura and Coimbatore were placed in one group while the other location groupings did not match for these two traits.

The "ideal" test environment discriminates the genotypes as well as represents all other environments under study thereby it should be able to predict best genotype for the peninsular India. In the Fig. 5, the 'average environment' is represented by a small circle on the AEA. The longer environmental vectors are, the environment is more differentiating for the trait among the genotypes. Environments with smaller angles with the AEA are most representative of the average test environments. From the biplot, the locations, Dhule, Vijayapura, Malnoor, Coimbatore and Ananthapuram with more vector lengths are more discriminating. The, near average locations, like Vijayapura and Malnoor are more representative and are suitable for selecting more adapted genotypes. On the other hand, Dhule and Ananthapuram with being discriminating and non-representative are useful for selecting specifically adapted genotypes. Cultivar choices and breeding schemes are framed for such generally adapted and specific environments identified from this graphical representation. Similar views are put forth by Rakshit et al. (2012) in sorghum and Reddy et al. (2021) in pearl millet. Narrow angles between the test environments indicate that same information could be obtained from these environments. Thus, for initial testing, similar environments may be removed in future multi-location testing of pearl millet cultivars. This also ensures to optimally allocate the scarce resources while formulating MLTs. Absence of wide obtuse angles between environment vectors (Fig. 5), indicates there were no negative correlations among the test environments suggesting the absence of strong crossover GEI across locations for grain and fodder yields as suggested by Yan and Tinker (2006). This indicated that the cultivars performing better in one environment would also be performing in the same direction in another environment which means that ranking of genotype does not change from location to location. Though the MET data is expected to consist of both crossover and non-crossover types of GEI (Rao et al. 2011), current data did not show crossover type of interaction. This again can be explained by the cultivars with high stability involved in the study. Being more discriminative and representative among all the testing locations, Vijayapura is the ideal environment. At this ideal testing environment of Vijayapura also, the hybrids KSB, NBH 5061 and 86M86 had high grain yield (Fig. 6). Ananthapuram was identified as ideal location for exclusively testing OPVs across India in earlier study (Reddy et al. 2021) while Mandor was identified as the ideal testing location in arid zone/A1 zone in pearl millet (Mamta and Hooda 2020)

Which won where and mega environment identification

Mixture of crossover and non-crossover types of GEI in MET data is of very common occurrence that can be graphically visualized in GGE biplot (Rao et al. 2011). 'Which-won-where graph is constructed by joining the farthest genotypes in a polygon. From the origin of the biplot, perpendicular lines referred to as equity lines are drawn to the sides of the polygon separating the polygon into several sectors. Genotype at the vertex is the best performing genotype in the environment falling in that sector (Yan and Tinker 2006). Which-won-where biplots for GY and FY are presented in the Fig. 7a, b. The biplots indicated existence of mega-environments. For grain yield, the heptagon has seven genotypes, KSB, 86M86, 86M01, ICMV221, Dhanshakthi, ICMV155 and GHB558, at its vertices. The equity lines divided the biplot into seven sectors of which two retained

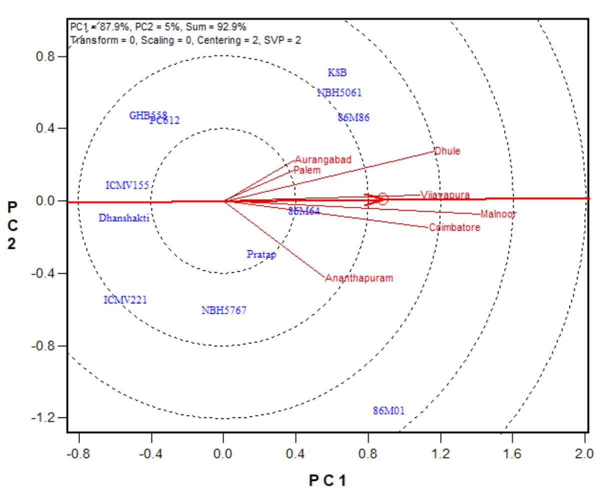

Fig. 5. Ranking of environments for grain yield based on discriminating ability and representativeness

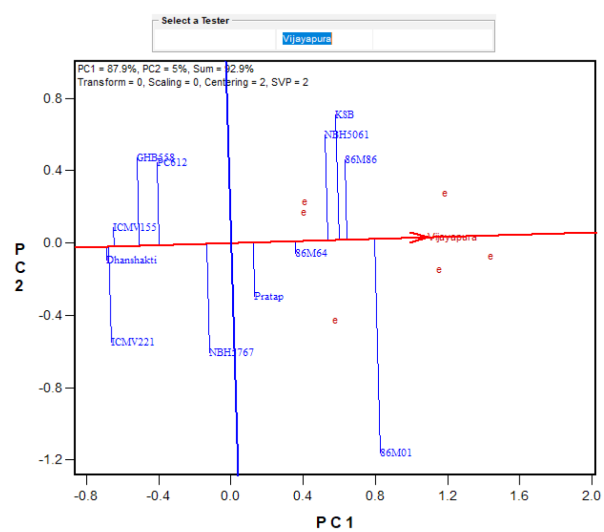

Fig. 6. Ranking of genotypes based on their performance for grain yield in near ideal location, Vijayapura

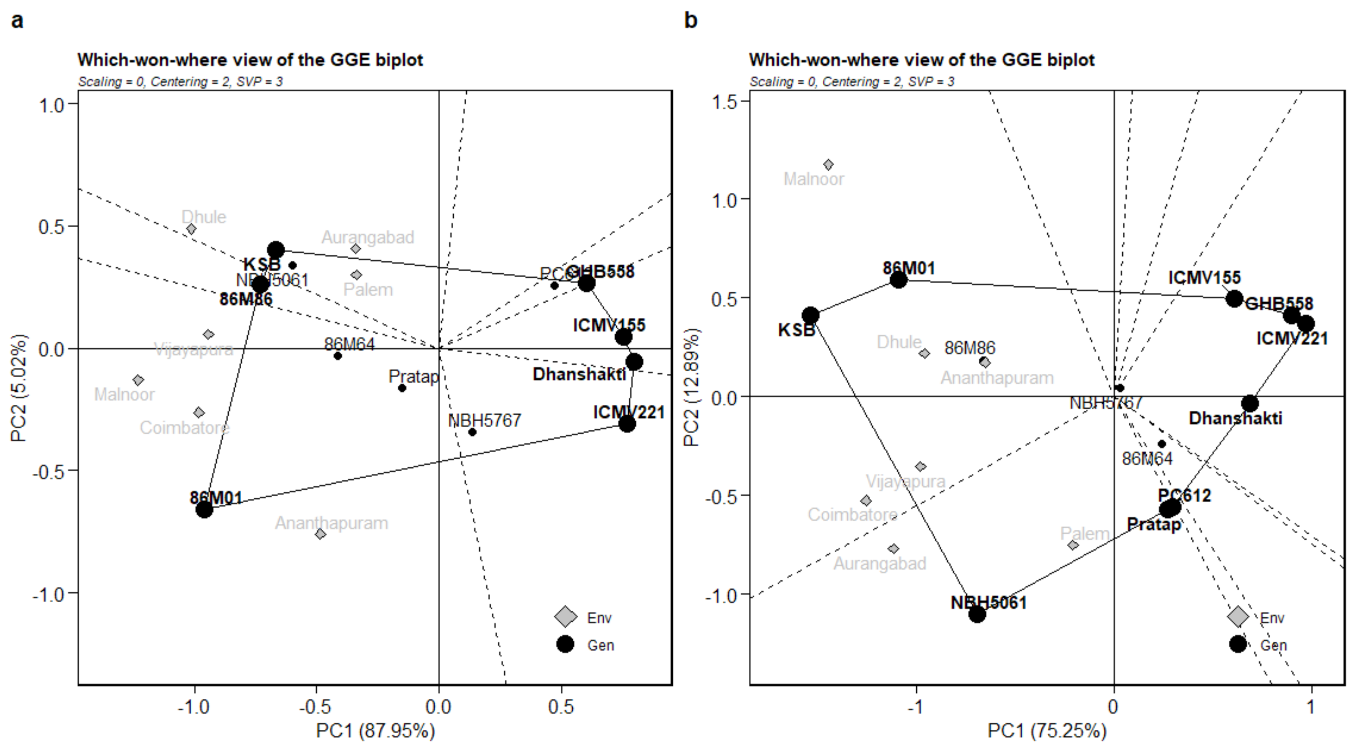

Fig. 7. Which-won-where analysis of the genotypes for, a) Grain yield and, b) Fodder yield

all seven locations. The testing locations partitioned into two mega environments (ME), ME1 with the locations Vijayapura, Malnoor, Coimbatore and Ananthapuram with 86M01 as the winning genotype. The ME2 consisted of the locations Palem, Aurangabad and Dhule with KSB as the winning genotype (Fig. 7a). The correlation among locations existed in terms of geographical location. The locations towards south of peninsular India in the states of Karnataka, Tamilnadu and Andhra Pradesh grouped into ME1 while the states towards north of peninsular India in the states of Maharashtra and Telangana grouped into ME2.

As locations from each ME are deemed to give similar results, one or two locations can be selected from each ME for initial testing. From ME1, Vijayapura and Ananthapuram can be selected as they have wider relation among themselves (Fig. 4a) and Dhule can be selected from ME2, as it has closer relationship with Palem and Aurangabad but is more discriminative (Fig. 4a and Fig. 5) for initial testing of cultivars and planning of breeding activities. However, this mega-environment pattern needs to be verified through multi-year and -environment trials (Rakshit et al. 2012) as proposed in wheat (Yan et al. 2000). Hybrid advantage for grain and fodder yields can be clearly observed from the study. Hence, more efforts can be targeted for hybrid development. As the advantage of OPVs in resource constrained and environment challenged areas cannot be ignored, testing locations specifically for OPVs need to be identified and tested separately. For fodder yield, eight genotypes were placed at the vertices of the octagon and the biplot was divided into nine sectors. Two sectors had all the seven locations. Palem and Aurangabad were placed in ME1 with NBH5061 as winning genotype while the other five locations were placed in ME2 with KSB and 86M01 as winning genotypes (Fig. 7b).

Authors' contribution

Conceptualization of research (CTS, VK); Designing of experiments (CTS); Contribution of experimental materials (CTS,VK); Execution of field/lab experiments and data collection (HTP, RN, HHB, KI, AMT, KS, and BKA); Analysis of data and interpretation (PSR); Preparation of manuscript (PSR).

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