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RESEARCH ARTICLE

# Identification of stable cultivars of pearl millet (*Pennisetum glaucum* (L.) R. Br.) based on GGE Biplot and MTSI index

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## Abstract

The present study was conducted to evaluate a total of 20 hybrids and five open-pollinated (OPVs) released varieties for their adaptability and stability and to identify traits that contributed towards yield increase under diverse ecological conditions. Variation due to location was predominantly greater, emphasizing the importance of specific adaptation. Thus, two mega environments (ME) were identified, ME1 bearing arid locations, Bikaner, Mandor and Jaipur with MPMH 17 as winning hybrid and ME2 with semi-arid locations, Gwalior, Hisar and Jamnagar with KSB and MP 7792 as winning hybrids. Hybrids with good tillering are suited for arid situations, while hybrids with higher grain and fodder yields, greater plant height, greater panicle length and late flowering are suitable for semi-arid situations. Pearson's correlation indicated a positive and significant correlation among grain yield, dry fodder yield, panicle diameter and days to 50% flowering. The hybrids GHB 905, 86M01, HHB 197 and GHB 558 were selected through MTSI as superior hybrids for stability and performance for most of the agronomical traits across all evaluated locations. This selection index also supported 86M01 as a stable and high-mean-performing hybrid that was also widely adapted based on GGE Biplot.

**Keywords:** Pearl millet, GGE, Productive tillers, Mega environment, Adaptability.

## Introduction

Given the increase in global climatic temperatures by 5°C above pre-industrial level by 2100 (Tollefson 2020), crops like pearl millet (*Pennisetum glaucum* (L.) R. Br.) with efficient photosynthetic system (C4) and tolerant to abiotic stresses (heat and salinity) are termed as climate-smart as they meet the food and fodder requirements even under harsh environmental conditions. India is the largest producer of this crop, both in terms of area (6.93 m ha) and production (8.61 mt) (Sanjana Reddy et al. 2021). The northwestern India receiving < 400 mm of annual rainfall and with sandy soils constitutes A1 or the arid zone. Some areas of western India receive as low as 150 mm of rainfall. The A1 zone holds about 25% of the total pearl millet area of the country. Both hybrids and open-pollinated varieties (OPVs) with early maturity and high tillering are grown along with locally adapted landraces. In semi-arid regions such as northern and central India, receiving more than 400 mm of annual rainfall and with sandy loam soils, the crop is grown for food and feed, has high productivity and is designated as A-zone. More than 90% of the area is covered with hybrids with medium to late maturity. As the private sector targeted more favorable areas, a much wider choice of cultivars is available as compared to the stress-prone arid regions. More than 80% of the area under pearl millet is grown in the two zones – A1

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and A in India (Yadav and Rai 2013). Through ICAR- All India Coordinated Research Project on Pearl millet (AICRP-PM), a total of 207 hybrids (public 116 and private sectors 91) and 66OPVs were identified and released for cultivation in different agro-ecological zones of the country. Among them 39 cultivars are released for A1 zone. There is a need to assess the performance of the released cultivars across locations to study the GE and stability of these cultivars in the current climatic conditions. Identifying the ideal location for initial testing and later on testing in MET (multi-environment trials) using the data from released cultivars will be more reliable towards resource use efficiency and improving the precision of research trials. The cultivars released for arid and semi-arid regions can be compared for their adaptation traits that contributed towards an increase in grain yield. Thus, the current study with proven cultivars is taken up to study GE patterns, identify ideal testing locations and ideal cultivars as well as estimate traits that need to be focused in the breeding programs. Among several methods available to study the patterns of G×E interaction, genotype main effect plus genotype × environment interaction (GGE) biplot methodology (Yan et al. 2000) as used in several crops, is used in the current study.

In order to choose stable and high-yielding genotypes for multiple characteristics based on multi-environment trait data, Olivoto et al. (2020) established the theoretical basis of MTSI, taking into account fixed-effect and random models. Factor analysis is used to compute it based on the desired genotype–ideotype distance. Stable genotypes with a positive selection differential for traits meant to be promoted and a negative selection differential for traits meant to be lowered can be selected based on this selection index. This helps breeders select for yield and stability at the same time by combining the average performance and stability of the traits. Based on this background, the current study proposes to identify suitable and stable hybrids of pearl millet using GGE Biplot and to identify ideal and high-yielding ideotypes combining several traits based on multi-factorial multi-trait stability analysis using the MTSI index.

## Materials and methods

### *Plant material*

The experimental material consisted of 20 hybrids released from 2003 to 2016 and five OPVs released from 1993 to 2016. These cultivars are under cultivation and present in the seed chain. Of the 20 hybrids, four hybrids are released exclusively for an arid zone, while 16 hybrids are released for semi-arid zone. Among the OPVs, two varieties (ICMV 221, ICTP 8203 Fe) are widely adaptable and suitable for both zones, while three varieties are suitable for a semi-arid zone (Table 1).

### *Test locations and experiment*

The material was evaluated simultaneously at six locations spread across arid (Mandor, Bikaner) and semi-arid (Gwalior, Hisar, Jaipur, Jamnagar) regions of the north and northwestern India during rainy seasons of three consecutive years of 2017, 2018 and 2019 (Table 2) as a part of AICRP on Pearl Millet trials. The Mandor and Bikaner are identified as the representative locations of MEs in an exclusive study of an arid zone (Mamata and Hooda 2020), while the Jaipur location falls in between arid and semi-arid types of climate. The individual trial was evaluated in a randomized block design with three replications. The plot size varied from 12 to 14.4 $m^2$ across locations and years, which was extrapolated to one hectare.

### *Trait measurements*

Nine yield-related traits were measured in each of the trials. The flowering time (DF) was measured as the number of days taken for 50% of plants to show full stigma emergence from the date of sowing. The days to maturity (DM) was measured as the time taken from the date of sowing to attain physiological maturity indicated by the appearance of a black spot at the hilum. The length of a fully matured plant from the base of the plant to the top of the ear head in centimeters is recorded as plant height (PHT). The number of productive tillers (NPT) is counted as the total number of tillers bearing earheads with grains. The panicle length (PL) was measured from the base of the panicle to its tip and recorded in centimeters. The panicle diameter (PD) was measured at the maximum thickness of the panicle in centimeters. Grain yield (GY) was estimated by weighing the grains obtained after drying and threshing of panicles at 12% moisture content and expressed in grams. Then, the weight per plot is extrapolated into t/ha. For measuring dry fodder yield (DFY), harvested plants are allowed for sun drying for 7 to 10 days. The weight recorded per plot is extrapolated to t/ha. For measuring 1000-grain weight (GWT), a sample of 1000 grains was counted randomly from the threshed seed and the weight is recorded in grams.

### *Analysis of variance*

Data were subjected to combined analysis of variance to investigate the genotypes (G), environments (Locations, Years) and Genotype × Environment interaction (GEI) effects. In the combined ANOVA, genotypes were considered as fixed effects, while environments and replications were considered as random effects. As the GEI was significant, the GGE biplot method (Yan et al. 2000) was employed to analyze of GE interaction and to assess the stability of GY and the pattern of response of hybrids and OPVs tested in 6 locations and three years. The repeatability of a variety trial is the proportion of the variation among line means that is due to the variation in genotype effects. Variance components and heritability across locations were estimated. The broad-sense heritability was calculated as: $h^2 = \sigma^2_g / (\sigma^2_g + \sigma^2_{gl} / l + \sigma^2_{gy} / y + \sigma^2_{gyl} / yl + \sigma^2_e / lyr)$, where $\sigma^2_g$ is the genotypic variance, $\sigma^2_{gl}$ is the interaction variance of genotype with

**Table 1.** A list of cultivars used in the study

| Cultivar | Breeding organization | Adaptation region | Year of release |
|---|---|---|---|
| **Hybrids** | | | |
| GHB538 | AICPMIP, Jamnagar | Arid | 2005 |
| HHB67 Imp | AICPMIP, CCSHAU, Hisar | Arid | 2005 |
| RHB177 | AICPMIP, SKRAU, Bikaner | Arid | 2011 |
| MPMH21 | AICPMIP, Jodhpur | Arid | 2016 |
| HHB272 | AICPMIP, CCSHAU, Hisar | Arid | 2016 |
| GHB558 | AICPMIP, Jamnagar | Arid and Semi-Arid | 2003 |
| Proagro9444 | ProAgro | Semi-Arid | 2004 |
| GHB732 | AICPMIP, Jamnagar | Semi-Arid | 2008 |
| GHB744 | AICPMIP, Jamnagar | Semi-Arid | 2008 |
| HHB197 | AICPMIP, CCSHAU, Hisar | Semi-Arid | 2008 |
| HHB223 | AICPMIP, CCSHAU, Hisar | Semi-Arid | 2010 |
| RHB173 | AICPMIP, SKRAU, Bikaner | Semi-Arid | 2011 |
| 86M86 | Pioneer Overseas Corp. | Semi-Arid | 2012 |
| KSB | Kaveri Seeds Co. Ltd. | Semi-Arid | 2012 |
| MP7792 | Metahelix Life Science Ltd. | Semi-Arid | 2012 |
| GHB905 | AICPMIP, Jamnagar | Semi-Arid | 2013 |
| MPMH17 | AICPMIP, Jodhpur | Semi-Arid | 2013 |
| KBH108 | Krishna Seeds (P) Ltd. | Semi-Arid | 2014 |
| 86M01 | Pioneer Overseas Corp. | Semi-Arid | 2015 |
| XMT1497 | Bayer BioScience | Semi-Arid | 2016 |
| **Varieties** | | | |
| ICMV221 | ICRISAT | Arid and Semi-Arid | 1993 |
| JBV2 | AICPMIP Gwalior and ICRISAT | Semi-Arid | 1999 |
| PC383 | IARI, New Delhi | Semi-Arid | 2001 |
| Dhanshakti (ICTP 8203 Fe) | ICRISAT | Arid and Semi-Arid | 2014 |
| PC701 | IARI, New Delhi | Semi-Arid | 2016 |

location, $\sigma^2_{gy}$ is the interaction variance of genotype with year, $\sigma^2_{gyl}$ is the interaction variance of genotype with year and location, $\sigma^2_e$ was the error variance, l was the number of locations, y was the number of years, and r was the number of replicates. The estimates of variances were obtained from an analysis of variance with the environment considered as a random effect, as mentioned by Xie et al. (2020).

### *GEI analysis-GGE Biplots*

The grain yield stability and suitability of test environments is tested using GGE Biplot based on the model proposed by Yan et al. (2000). The genotype-centered and the environment-centered singular value partitioning (SVP) are used for the evaluation of genotypes and environments, respectively but the symmetric scaling is preferred for the study of which-won-where pattern. Genotype-by-trait biplot (GT biplot) is generated from combined data using the 'Genotype-by-trait biplots Scaling = 1 option' of GGE biplot software by combining data from all environments. Here, traits were considered as 'tester'.

### *Multi-Trait Stability Index (MTSI)*

A linear mixed model (LMM) was used to create a Singular Value Decomposition (SVD) of the matrix of Basic Linear Unbiased Predictions (BLUPs) for the GEI impacts and by calculating the Weighted Average of Absolute Scores (WAAS) using a linear mixed effect model, the stability of each of the hybrid is determined. The hybrid with the lowest MTSI score is closer to the ideotype and exhibits better mean performance and stability in a range of environments.

Euclidean distance between the scores of accessions and the ideal accessions was computed as the MTSI index using the following equation:

$$MTSI_i = \sum_{j=1}^{f} \left[ (F_{ij} - F_j)^2 \right]^{0.5}$$

Where, $MTSI_i$ is the multi-trait stability index for the $i^{th}$ genotype, $F_{ij}$ is the $j^{th}$ score of the

$i^{th}$ genotype, and $F_j$ is the $j^{th}$ score of the ideotype. The selection differential for all traits was performed considering a selection intensity of approximately 15%.

### *Statistical packages*

The pooled analysis of variance was conducted using Genstat 12 edn. The GGE Biplot analyses were performed using GGE biplot ver. 8.2 (Yan 2001). MTSI computations were performed in the R software using the 'metan' package (Olivoto et al. 2020) using RStudio, specifically with R version 4.3.2 (R Studio 2024).

## Results and discussion

Pearl millet is a highly climate-resilient crop grown in arid as well as semi-arid regions during the rainy season, with adaptable cultivars developed for both situations. Replacement of old hybrids with new ones is essential to harness genetic gains continuously. Owing to the availability of the CMS system and the active role of the private sector, several hybrids and OPVs are released by public and private sector organizations. The seed production chain, managed by different agencies, has directly influenced the popularization of cultivars in farmer's fields. With the cumulative effort, several cultivars have been grown by farmers over the years. The residual variability in this cross-pollinated crop can also influence the performance of a genotype over a period of time. Hence, a need was felt to assess the released cultivars for their suitability within/across zones. It is a known fact that the potential performance of genotypes under marginal conditions is considerably affected by GEI (Lubadde et al. 2017). Studying the GEI complexity will help to identify highly adaptable and stable cultivars for defined mega environments.

Analysis of variance (ANOVA) was performed for data collected on 20 hybrids and five varieties across six locations in two zones for three years and combined ANOVA pooled over locations. The combined analysis of variance across environments evidenced highly significant differences among genotypes for all the recorded traits. The first-order interaction of genotype with location, genotype with year and location with year were significant for all the traits. The second-order interaction of genotype with location and year was also significant for all the traits. The variance due to location had the largest influence among all variances for all traits except PHT, for which Location ×Year interaction was the largest, followed by variance due to location. The importance of environment in genotype performance has been reported earlier in pearl millet (Gupta et al. 2013; Ezeaku et al. 2014; Lubadde et al. 2017; Malathi et al. 2024). The dominant variance due to location indicates the need for defining mega-environments and developing cultivars suitable for specific MEs. Similar views on the unsuitability of a single cultivar across all environments have been expressed earlier by many workers (Yadav et al. 2021; Sanjana Reddy et al. 2021, 2022; Narasimhulu et al. 2023), thereby recommending breeding for MEs in pearl millet. The broad-sense heritability ranged from 0.79 to 0.97, indicating higher precision/repeatability of the trial across locations and years (Table 3). The ANOVA adequately identified GEI as a significant source of variation, but it is not able to explore the nature that may mask true genotype performance; hence, GGE biplot was adopted for the economically important trait, grain yield.

### *Mean performance and stability*

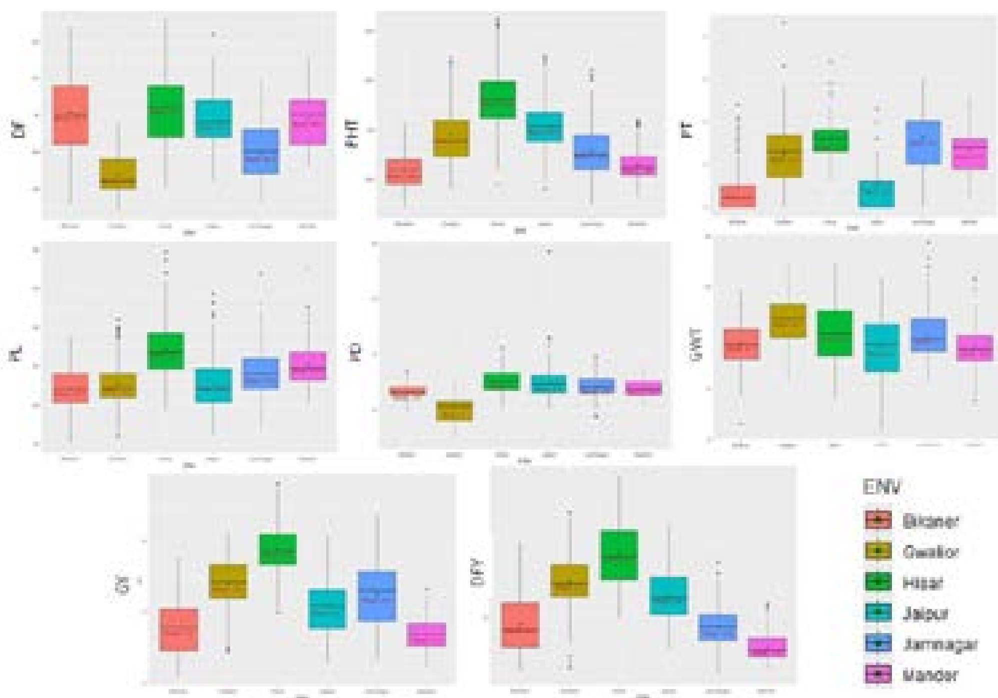
The arid zone adapted hybrids were five days early in flowering, shorter in height, had more productive tillers, lesser grain yield, lesser fodder yield, shorter panicle length, lesser panicle width and smaller grain size than semi-arid zone adapted hybrids. Among the arid zone released hybrids, RHB 177 and MPMH 21 had higher grain yield (2.34 to 2.4 t/ha), while MP 7792, MPMH 17 and XMT 1497 had higher grain yield (2.7 to 2.76 t/ha) among semi-arid zone released hybrids. Widely adapted OPVs showed a similar trend as arid zone hybrids, except that they had few productive tillers, more panicle width and greater grain size than the OPVs released for semi-arid regions. As expected, the performance of the cultivars was poor in arid locations compared to semi-arid locations. The comparative advantage of hybrids or OPVs has been often debated in the past. Hybrid advantage has been proved in earlier studies (Yadav et al. 2021) similar to that derived from the current study. Among the arid-zone locations, Bikaner was more productive for GY (1.56 t $ha^{-1}$) and FY (4.53 t $ha^{-1}$), while Hisar was more productive in semi-arid zone locations (GY: 3.77 t $ha^{-1}$, FY: 9.10 t $ha^{-1}$) (Table 4). Likewise, the boxplot (Fig. 1) depicts the mean of the characters of individuals for each environment.

The "mean *vs*. stability" view of the biplot representing differential responses of cultivars to diverse environments due to cross-over interactions is presented in Fig. 2. The complex GEI for GY is simplified in different PCs and graphically presented in the GGE Biplot. In the present study, the first two PCs explained 74.6% variation for GY, indicating that the variability for GY is adequately represented. AEC abscissa passes through the biplot origin points towards higher mean values, while the length of perpendicular lines to the AEC abscissa is inversely related to stability (Yan 2001). Thus, the cultivars XMT 1497 followed by 86M01 had

**Table 3.** Combined analysis of variance and broad sense heritability for yield and related traits in 25 cultivars across 18 environments

| Source of variation | df | Mean squares | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | GY | DFY | DF | PHT | NPT | PL | PD | GWT |
| Genotype variance | 24 | 4.83** | 27.33** | 589.99** | 13631.76** | 3.12** | 240.20** | 2.88** | 29.21** |
| Location variance | 5 | 174.65** | 1094.48** | 3004.41** | 170097.79** | 65.08** | 804.10** | 31.74** | 92.38** |
| Year variance | 2 | 16.96** | 63.08** | 15.50** | 8758.83** | 3.94** | 34.34** | 0.31** | 14.56** |
| Genotype × Location variance | 120 | 0.65** | 3.57** | 13.14** | 892.33** | 0.57** | 10.93** | 0.19** | 4.60** |
| Genotype × Year variance | 48 | 0.49** | 2.69** | 11.04** | 353.33** | 0.48** | 6.31** | 0.12** | 2.05** |
| Location × year variance | 10 | 24.42** | 153.25** | 221.62** | 18539.33** | 8.37** | 114.48** | 4.58** | 70.31** |
| Genotype × Location × Year variance | 240 | 0.44** | 2.16** | 8.51** | 406.59** | 0.39** | 8.40** | 0.13** | 3.09** |
| Residual variance | 898 | 0.08725 | 0.3877 | 1.58 | 77.64 | 0.0993 | 2.543 | 0.05428 | 0.3944 |
| $h^2bs$ | | 0.86 | 0.85 | 0.97 | 0.94 | 0.79 | 0.96 | 0.94 | 0.88 |
| CV (%) | | 12.6 | 10.7 | 2.6 | 4.7 | 15 | 6.7 | 8.6 | 7 |

GY = Grain yield (t/ha), DFY = Dry fodder yield (t/ha), DF = Days to 50% flowering, PHT = Plant height (cm), NPT = Number of productive tillers, PL = Panicle length (cm), PD = Panicle width (cm), and GWT = 1000 grain weight (g)




*kharif* 2017-2019. The dashed line shows the overall mean. DF = days to 50% flowering, PHT = Plant height, PT = Number of productive tillers per plant, PL = Panicle length, PD = Panicle diameter, GWT = 1000 seed weight, GY = Grain yield, DFY =: Dry fodder yield, ENV = Environments

**Fig. 1.** Box plots showing mean performances of the studied traits across all environments during

higher yields (2.67–2.70 t $ha^{-1}$) and were stable across 18 environments. The OPVs recorded poorer yields, the lowest in the widely adapted OPVs, ICMV 221 and ICTP 8203.

### *Correlations among traits over environments*

Pearson's correlation was performed, and a network plot of correlation was developed as per Singamsetti et al. (2023)

among all traits using mean over environment data (Fig. 3). Positive and significant correlation was observed between GY and DFY, PD, DF and non-significant with other traits. Panicle diameter was found to contribute towards higher grain yields in several studies. Late flowering cultivars are assumed to accumulate more photosynthates, contributing towards higher grain and biomass yields (Sanjana Reddy et al. 2021). The network plot did not indicate any distinct clustering pattern and distance between traits. The traits PL, DF, DFY, and PHT were at one end with a positive significant association among them, while GWT, PD, and NPT were at another end associated with each other.

### *Relationship among environments*

The relationship among the test environments for grain yield is evaluated by correlation value measured by the cosine of the angle between them as depicted in Fig. 4. Combined analysis of variance (Fig. 4) showed that the majority of the angles between their vectors are acute. Acute vector angles are indicative of a closer relationship among the environments (Yan and Tinker 2006). Distance between two environments measures their ability to discriminate the genotypes. Bikaner and Mandor were highly correlated and correlated with the semi-arid location of Jaipur. Jaipur has been reported to fall in between arid and semi-arid types. Based on earlier studies involving nine arid zone locations with varying levels of aridity, Bikaner, Mandor and Jaipur were found to fall in three separate MEs with aridity increasing in the order Bikaner>Mandor>Jaipur. Similarly, semi-arid locations, Jamnagar and Gwalior, were highly correlated and correlated with Hisar and grouped apart from arid groups. Thus, six locations could be divided into two groups for grain yield which correlates well with the general observance over the years, one group representing arid locations and another group representing semi-arid

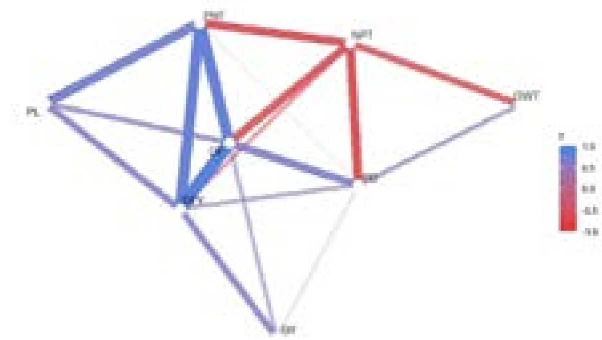



**Fig. 3.** Pearson's correlation network plot considering different

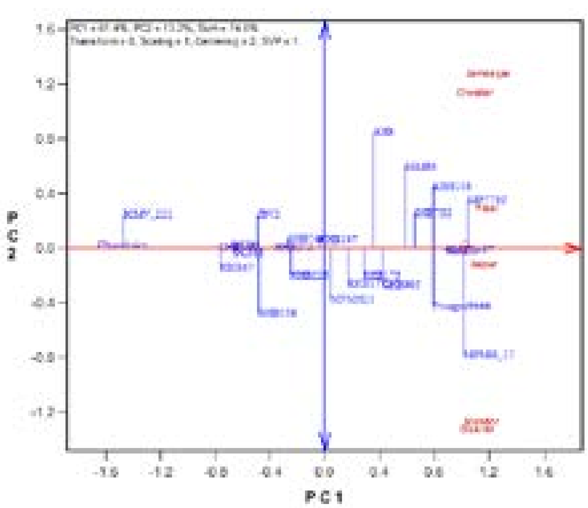



**Fig. 2.** GGE biplot showing "mean vs. stability" of 25 pearl millet cultivars across 6 locations pooled over three years for grain yield

locations. This again stresses developing cultivars specific to individual locations rather than broad adaptation. Similar studies were reported earlier in pearl millet (Sanjana Reddy et al. 2022).

In Fig. 4, the 'average environment' is represented by a small circle on the AEA. The length of environmental vectors is proportional to the standard deviation of the genotypes in the environments. The longer environmental vectors indicate that 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. A suitable environment should be both distinctive and a target environment. Thus, the Hisar location was closest to the average environment and thus is the most representative as well as discriminating environment when genotypes are tested across multiple sites in north and northwestern India and the objective is to look for broad adaptation.

### *Which won where and mega environment identification*

Which-won-where biplot for GY over pooled environments is presented in Fig. 5. The biplot indicated the existence of cross-over GEI and the existence of mega-environments (ME). For grain yield over pooled locations, the hexagon has six genotypes, MPMH 17, MP 7792, KSB, ICMV 221, Dhanshakthi, and GHB 538 at its vertices. The equity lines divided the biplot into six sectors, of which three retained six locations. The testing locations were partitioned into three ME, ME1, with the locations Bikaner, Mandor, and Jaipur, with MPMH 17 and GHB 538 as the winning genotypes. Though MPMH 17 has been released for a semi-arid zone, it is highly popular with the farmers in the arid zone. This supports the current study of evaluating released cultivars across zones for the identification of best-suited cultivars for recommendation to farmers. The ME2 consisted of the Hisar location, with no cultivar performing better at this location. However, XMT 1497 and 86M01 can be recommended for this ME from the biplot. The ME3 consisted of Gwalior and

**Table 4.** Performance of pearl millet cultivars for grain yield and related traits pooled across locations and years

| Cultivar/Location | GY | DFY | DF | PHT | NPT | PL | PD | GWT |
|---|---|---|---|---|---|---|---|---|
| GHB538 | 2.14 | 4.75 | 45.5 | 175 | 2.1 | 22.0 | 2.5 | 9.0 |
| HHB67 Imp | 2.04 | 4.92 | 41.8 | 168 | 2.4 | 21.2 | 2.2 | 9.0 |
| RHB177 | 2.40 | 4.96 | 43.1 | 174 | 2.3 | 23.0 | 2.6 | 9.2 |
| MPMH21 | 2.34 | 5.37 | 45.4 | 172 | 2.3 | 21.1 | 2.6 | 7.6 |
| HHB272 | 2.20 | 5.24 | 43.4 | 164 | 2.2 | 20.7 | 2.6 | 8.6 |
| **Mean of arid region adapted hybrids** | 2.22 | 5.05 | 43.8 | 171 | 2.3 | 21.6 | 2.5 | 8.7 |
| GHB558 | 2.05 | 5.46 | 48.0 | 178 | 2.0 | 23.2 | 2.9 | 9.1 |
| Proagro9444 | 2.64 | 6.53 | 49.5 | 193 | 2.1 | 23.0 | 2.8 | 9.0 |
| GHB732 | 2.63 | 5.78 | 49.5 | 187 | 2.3 | 23.0 | 2.6 | 8.9 |
| GHB744 | 2.25 | 5.13 | 49.6 | 185 | 2.1 | 23.3 | 2.7 | 9.1 |
| HHB197 | 2.32 | 5.28 | 44.9 | 174 | 2.3 | 22.9 | 2.6 | 9.3 |
| HHB223 | 2.25 | 5.33 | 44.4 | 184 | 2.3 | 22.4 | 2.5 | 8.2 |
| RHB173 | 2.44 | 5.97 | 47.7 | 184 | 2.4 | 27.6 | 2.5 | 8.6 |
| 86M86 | 2.62 | 6.67 | 52.9 | 196 | 1.8 | 24.1 | 3.1 | 9.6 |
| KSB | 2.53 | 7.07 | 54.4 | 219 | 1.7 | 27.1 | 2.9 | 9.4 |
| MP7792 | 2.76 | 6.19 | 49.0 | 196 | 1.8 | 23.6 | 3.0 | 9.5 |
| GHB905 | 2.49 | 5.59 | 47.1 | 176 | 2.6 | 25.5 | 2.6 | 7.8 |
| MPMH17 | 2.71 | 5.79 | 46.0 | 177 | 2.4 | 24.4 | 2.7 | 8.6 |
| KBH108 | 2.67 | 6.99 | 54.3 | 216 | 1.7 | 24.4 | 3.2 | 9.8 |
| 86M01 | 2.67 | 6.56 | 50.7 | 196 | 1.9 | 27.1 | 2.8 | 10.7 |
| XMT1497 | 2.70 | 6.49 | 50.0 | 187 | 2.0 | 23.0 | 2.9 | 8.5 |
| **Mean of semi-arid region adapted hybrids** | 2.52 | 6.05 | 49.2 | 190 | 2.1 | 24.3 | 2.8 | 9.1 |
| **Mean of hybrids** | 2.44 | 5.80 | 47.9 | 185 | 2.1 | 23.6 | 2.7 | 9.0 |
| ICMV221 | 1.79 | 5.19 | 45.1 | 186 | 1.9 | 22.1 | 2.9 | 9.7 |
| Dhanshakti (ICTP 8203 Fe) | 1.68 | 4.71 | 46.2 | 186 | 1.8 | 23.4 | 2.8 | 10.4 |
| Mean of widely adapted OPVs | 1.73 | 4.95 | 45.6 | 186 | 1.9 | 22.8 | 2.9 | 10.1 |
| JBV2 | 2.16 | 6.38 | 49.6 | 214 | 1.9 | 27.3 | 2.5 | 8.3 |
| PC383 | 2.08 | 6.46 | 49.3 | 217 | 2.1 | 27.2 | 2.5 | 8.3 |
| PC701 | 2.09 | 6.04 | 47.7 | 207 | 2.0 | 26.6 | 2.5 | 8.5 |
| **Mean of semi-arid region adapted OPVs** | 2.11 | 6.29 | 48.8 | 213 | 2.0 | 27.0 | 2.5 | 8.4 |
| **Mean of varieties** | 1.96 | 5.75 | 47.6 | 202 | 1.9 | 25.3 | 2.6 | 9.0 |

*Contd ....*

*Contd ....*

| Location | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Bikaner | 1.56 | 4.53 | 50.3 | 158 | 1.4 | 22.1 | 2.6 | 8.7 |
| Mandor | 1.36 | 3.11 | 49.5 | 164 | 2.3 | 25.2 | 2.8 | 8.4 |
| Gwalior | 2.78 | 7.27 | 41.9 | 194 | 2.3 | 22.7 | 2.0 | 10.1 |
| Hisar | 3.77 | 9.10 | 51.3 | 232 | 2.5 | 27.1 | 3.0 | 9.2 |
| Jaipur | 2.12 | 6.40 | 49.1 | 203 | 1.5 | 22.8 | 2.9 | 8.5 |
| Jamnagar | 2.48 | 4.35 | 44.8 | 178 | 2.6 | 23.9 | 2.8 | 9.1 |
| **Mean of arid locations** | 1.46 | 3.82 | 49.9 | 161 | 1.85 | 23.7 | 2.7 | 8.6 |
| **Mean of semi-arid locations** | 2.79 | 6.78 | 46.8 | 202 | 2.23 | 24.1 | 2.7 | 9.2 |
| lsd (p<0.05, cultivar) | 0.11 | 0.24 | 0.5 | 3 | 0.1 | 0.6 | 0.1 | 0.2 |
| lsd (p<0.05, location) | 0.05 | 0.12 | 0.2 | 2 | 0.1 | 0.3 | 0.0 | 0.1 |

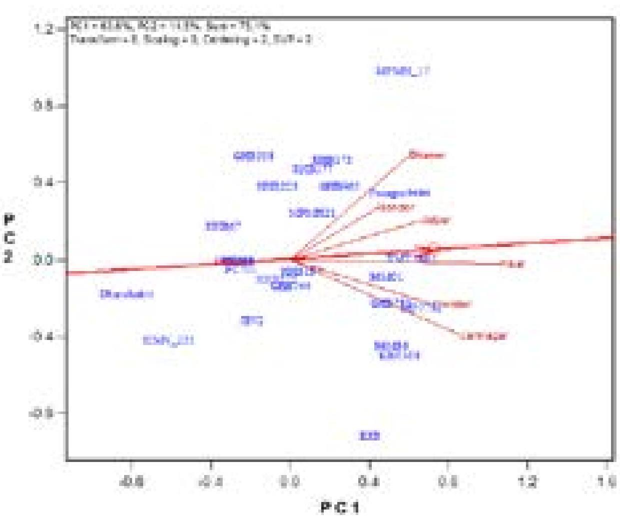



**Fig. 4.** Relationship among environments, their representativeness and discriminating ability

Jamnagar, with MP 7792 and KSB as the winning genotypes. The OPVs, as well as a few cultivars released in the early years, such as HHB 67, GHB 558, HHB 272, GHB 744, and HHB 197, had lower yields and did not perform well in any particular location. Thus, from the biplot, an indication of genetic gain that has happened over the years for yield and stability is clearly seed. However, in the arid zone, there has been very limited adoption of new cultivars as compared to the semi-arid zone due to their inadequate adaptation to the marginal environmental conditions. Though XMT 1497 and 86M01 had been shown to be high yielding, stable across environments and performed well in an ideal location of Hisar, it is preferable to recommend ME-specific cultivars. This is due to the wide variation in the climatic conditions in the respective zones. As seen from the biplot, across three years of study, the hybrids outperformed OPVs in both zones. The wide gap between the grain yields of hybrids and OPVs is thought to be due to the rapid development and dissemination of hybrids due to the active role of the private sector, which has pushed OPVs to marginal areas. As compared to the released OPVs used in the current study, the potential of genetic improvement through OPVs has been demonstrated (Sanjana Reddy et al. 2021). Hence, a conclusion against OPVs should not be made from the current study and the development of OPVs using recombinant breeding approaches should be planned in the interest of the arid zone farming community.

'Which is best for what' analysis of the Genotype × Trait biplot helped to compare genotypes on the basis of multiple traits and to identify genotypes superior for particular trait as well as traits that made the genotype ideal (Fig. 6). The biplot indicates that KSB was the best for GY, DFY, PHT, PL and late flowering, KBH 108 for PD, GHB 905 for PT and Dhanshakthi for GWT. The hybrid MPMH 17 that, was found to be the winning genotype for the arid zone was found to be good for productive tillers. Under arid conditions with restricted assimilate supply, high-tillering, small-panicled landraces are better able to produce a reproductive sink than are large-panicled ones (van Oosterom et al. 2006). The high-yielding and highly stable hybrid XMT 1497, as well as the winning hybrid for semi-arid zone KSB, were best performing for the traits GY, DFY, PHT, PL, and late flowering.

### *Multi-Trait Stability Index (MTSI)*

Eberheart and Russell's model (Eherhart and Russell 1966) is widely used for the selection of stable genotypes based on mean, regression, and departure from regression parameters, which may not provide a clear explanation of mean performance and trait stability. This restriction has

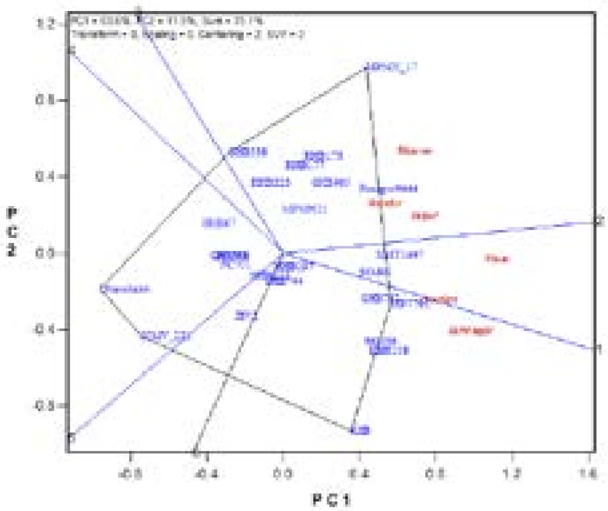


**Fig. 5:** Which-won-where analysis for grain yield

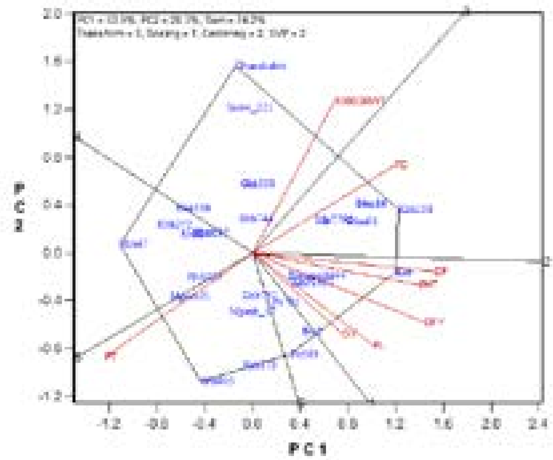


Fig. 6: Polygon view of GT biplot indicating which is the best genotype for the target traits

**Table 5.** Eigenvalues, explained variance, factorial loadings after varimax rotation, communalities, and uniqueness obtained in the factor analysis of the GEI significant variables studied in 25 pearl millet hybrids across six locations during 2017 to 2019 *kharif* seasons

| Traits | FA1 | FA2 | FA3 | FA4 | Communality | Uniqueness |
|---|---|---|---|---|---|---|
| GY | 0.313 | -0.703 | 0.169 | 0.471 | 0.843 | 0.157 |
| DFY | 0.319 | -0.828 | -0.237 | 0.0369 | 0.845 | 0.155 |
| DF | -0.302 | -0.057 | 0.889 | -0.107 | 0.896 | 0.104 |
| PHT | 0.87 | -0.162 | -0.208 | -0.087 | 0.834 | 0.166 |
| PT | 0.0956 | 0.0698 | 0.909 | 0.0446 | 0.843 | 0.157 |
| PL | 0.81 | -0.182 | 0.0655 | 0.104 | 0.705 | 0.295 |
| PD | -0.016 | -0.081 | -0.065 | 0.971 | 0.953 | 0.047 |
| GWT | 0.607 | 0.662 | -0.19 | 0.0947 | 0.852 | 0.148 |
| Eigen value | 2.59 | 1.84 | 1.34 | 1 | 0.846[a] | |
| Variance (%) | 32.4 | 23 | 16.7 | 12.5 | | |
| Accumulated (%) | 32.4 | 55.4 | 72.1 | 84.6 | | |

aAverage of the commonality. FA: factor Analysis, GY: grain yield, DFY: dry fodder yield, DF: days to 50% flowering, PHT: plant height, PT: productive tillers per plant, PL: panicle length, PD, panicle diameter, GWT: 1000 seed weight

led to the development of the multi-trait stability index approach into a sophisticated quantitative genetics tool that can be used to identify desired ideotypes using multiple traits (Olivoto et al. 2019).

In this study, all traits included in the MTSI calculation were highly significant for GEI in the joint ANOVA. Data from eight characters were used to perform exploratory factor analysis. This analysis generated four PCs with 84.6% cumulative variance (Table 5). Communality reflected shared variance among traits ranging from 0.705 (PL) to 0.953 (PD), with a mean value of 0.846 after varimax rotation. Specific variance relates to the part of the variability not shared with other variables due to a unique factor that was found to be higher for PL and lower for PD (Table 5). Selection criteria for mean performance was set as the nature of traits like DF was negatively selected and the rest of the characters were selected in a positive direction. Similarly, the WAASBY value was extracted by giving equal weight to the mean and stability. The traits included in the analysis were categorized into four factors by extracting the WAASBY value from each corresponding character (Table 6). PHT and PL clustered in FA1; GY, DFY and GWT were in FA2; DF and PT were in FA3; and PD was in FA4 (Table 6). Similarly, the WAASBY value was extracted by giving equal weight to the mean and stability. The MTSI index provided the desired selection differential for 7 out of 8 traits. The DF had a positive selection differential, which is undesirable. The selection of stable hybrids with higher mean performance for multiple variables is the most important part of stability analysis (Yue et al. 2021). MTSI aids in the selection of genotypes by identifying those

**Table 6.** Selection differential for a mean of the traits and WAASBY index for 8 traits of 25 pearl millet hybrids across six locations during 2017 to 2019 *kharif* seasons

| Traits | Factor | Mean performance | | | WAASBY | | |
|---|---|---|---|---|---|---|---|
| | | Overall (Xo) | Selected genotypes (Xs) | SD (%) | Overall (Xo) | Selected genotypes (Xs) | SD (%) |
| GY | FA2 | 2.34 | 2.38 | 1.64 | 57.2 | 71.2 | 24.6 |
| DFY | FA2 | 5.79 | 5.72 | -1.24 | 56.7 | 60 | 5.88 |
| DF | FA3 | 47.8 | 47.7 | 0.961 | 59.8 | 68.8 | 15 |
| PHT | FA1 | 188 | 181 | -3.89 | 56.3 | 59.5 | 5.72 |
| PT | FA3 | 2.1 | 2.21 | 5.21 | 45.6 | 55 | 20.6 |
| PL | FA1 | 24 | 24.7 | 2.98 | 59.2 | 75.4 | 27.3 |
| PD | FA4 | 2.7 | 2.72 | 1.03 | 49.1 | 59.7 | 21.5 |
| GWT | FA2 | 8.97 | 9.19 | 2.37 | 51.7 | 60.2 | 16.5 |

FA: Factor Analysis, GY: grain yield, DFY: dry fodder yield, DF: days to 50% flowering, PHT: plant height, PT: productive tillers per plant, PL: panicle length, PD, panicle diameter, GWT: 1000 seed weight, SD: Selection differential and WAASBY: Weighted average of absolute scores of stability with yield. Xo: mean of all hybrids, Xs: mean of selected hybrids.

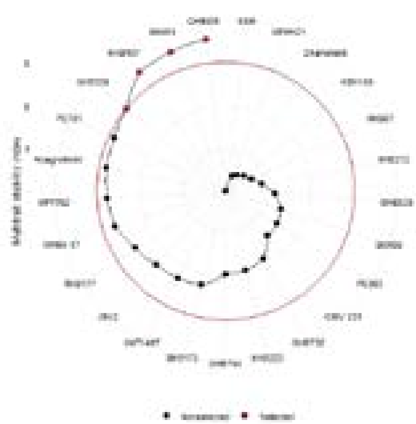


**Fig. 7.** Hybrid ranking and selected hybrids among 25 pearl millet hybrids for multi-trait stability index (MTSI) view

with both higher stability and superior mean performance across all significant interacting variables. Hybrids with lower MTSI values are chosen in the selection process, with a selection intensity of 15%. In the current investigation, GHB 905 with an MTSI of 4.45, 86M01 with an MTSI of 4., HHB 197 with an MTSI of 4.59 and GHB 558 with an MTSI of 4.99 were chosen due to their maximum stability and high mean performance across the analyzed traits (Fig. 7). The hybrid 86M01 was identified as a winning hybrid in studies conducted in peninsular India (Sanjana Reddy et al. 2022). In Fig. 7, the red circle signifies the cutoff point with an MTSI value of 4.99, while KSB exhibited a higher MTSI value of 7.95, followed by MPMH 21 (MTSI = 7.58), Dhanshakti (MTSI = 7.50), and KBH 108 (MTSI = 7.4). These hybrids were identified as unstable, demonstrating poor performance for the traits under current investigation. These findings corroborate previous findings reported in different crops (Benakanahalli et al. 2021; Soni et al. 2024; Kumar et al. 2024).

## Authors' contribution

Conceptualization of research (CTS); Designing of the experiments (VK); Execution of field/lab experiments and data collection (PCS, LDS, KDM, MKT, DY); Analysis of data and interpretation (RKS, PP, PSR); Preparation of the manuscript (PSR).

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