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RESEARCH ARTICLE

Stability of maize hybrids under drought, rainfed and optimum field conditions revealed through GGE analysis

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Abstract

Identification of high-yielding and stable cultivars across different environments through multi-location trials are very important in maize breeding. A study was conducted to evaluate 30 maize hybrids in three diverse environments, viz., drought, rainfed and optimal conditions during the years, 2016 and 2017. Environments, genotypes and Genotype × Environment interactions (G × E) were found to be highly significant in both the years. The biplot explained 69.49% of total variation which was partitioned into 53.61 and 15.88% relative to genotype and genotype by environment interaction. Genotype, ZH15449 performed considerably well in 2016 under optimum (113.41 q/ha) and drought (54.19 q/ha) while in 2017, under optimum (82.28 q/ha) and rainfed (65.37 q/ha) conditions. ZH 161285 gave considerable grain yield at all three ecologies (108.70, 74.29, 60.60 q/ha) in year 2016, whereas genotype, ZH 161330 performed well under rainfed (67.76 q/ha) and drought (52.87q/ha) conditions in year 2017.

Keywords: Maize, genotype and environment interaction, additive main effects and multiplicative interaction, GGE biplot, principal component analysis

Introduction

Maize is an important crop that adapts easily to a wide range of climatic conditions (Yasin et al. 2022). In India, maize is grown on a wide range of environments, extending from extreme sub-arid to sub-humid and humid regions; from sea level to >4000 m above sea level, under irrigated to semi-arid conditions. Maize in India constitutes 9% of the total volume of cereals produced and is the third most important food grain after rice (42%) and wheat (38%) (Murdia et al. 2016). During the last three decades, maize production in India has markedly increased. Maize is one of the major predominantly grown crops. It has been used for diverse purposes such as grain, oil, forage, starch and ethanol products. It is also used in different industries such as food, pharmaceutical and many more. The crop thrives well in tropical, subtropical, and temperate climates due to tremendous genetic variability (India Maize Summit 2014).

Grain yield is affected at a wide scale by adverse conditions such as drought. Drought is identified as the major constraint in alleviating maize production as in the dry season; maize suffers from severe water scarcity. The grain yield loss in maize varies from 30 to 90%, which generally depends upon the intensity and duration of drought stress and crop stage. The flowering and grain-filling stages are affected severely from water scarcity. Drought stress has a comprehensive and wide impact on plant organization, which often results in complex and spontaneous physiological and cellular responses. The vegetative, silking (flowering) and ear stages (grain filling) of maize are the most susceptible to drought stress with yield losses of up to 25.50 and 21%, respectively (Sah et al. 2020).

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In present times, the agriculture sector is facing the biggest challenge of climatic change with recurrent drought spells. Furthermore, drought being a complex trait, hampers the speed development of drought-tolerant maize cultivars. Also, to assess the G × E interactions, which is an important step in drought tolerance maize breeding, multi-location testing of the germplasm is required (Sheoran et al. 2022).

Identification of high-yielding and stable genotypes across wide range of environments has been a constant challenge to plant breeders. The characterization of stable genotypes is often made difficult by the prevalence of genotype-environment interactions (GEI). Thus, to address the GEI, there is need to evaluate genotypes in multi-environment under both favorable as well as unfavorable conditions. Trials conducted under drought, rainfed and optimum conditions pave a way for the identification of genotypes suited for these climates. Also, drought seems to be one of the key abiotic stresses for maize production which results in severe yield losses. Under rainfed conditions, there is non-uniform rain distribution that causes prolonged dry periods, so selection for drought can eventually become the selection for rainfed as the drought-tolerant varieties can perform well under rainfed conditions.

A significant GEI often results in changes in the performance of genotypes from one environment to another and hinders breeding progress during the selection and advancement of genotypes (Pham and Kang 1988). A genotype is considered to be stable if its performance is relatively similar and less affected across different environments. According to Becker and Leon's (1988) concept of biological or static stability, a stable genotype is one with minimal variance for yield across different environments. However, breeders and agronomists prefer genotypes with high mean yields and the potential to respond to good agronomic inputs and favorable environmental conditions (Becker 1981). High-yielding and stable cultivar usually refers to the ability of a genotype to perform uniformly across a wide range of environments and also record higher yield. The GEI results in inconsistent performances between the genotypes across environments. Thus, the measures of GEI are very important for setting up the breeding objectives, identifying the ideal test conditions and making recommendations for an adapted cultivar. Various statistical methods (parametric and non-parametric) have been proposed to study GEI. Finlay and Wilkinson (1963) and Eberhart and Russel (1966) stability methods have largely been used to estimate G×E interaction which are based on simple and multiple regressions. However, the main problem associated with stability statistics is that they do not provide an accurate measure of the complete response pattern (Hohls 1995), because the response of a genotype to varying environments is better in multivariate (Lin et al. 1986) analysis, whereas the stability indices are usually univariate (Gauch 1988; Crossa 1990).

The additive main effects and multiplicative interaction (AMMI) model is a well-liked variant of ANOVA for examining GE interaction (Gauch 1992). The AMMI model is a hybrid analysis that takes into account the two-way data structure's additive and multiplicative elements. Yan et al. (2000) proposed a modification of the conventional AMMI analysis called GGE (genotype and genotype-environment interaction) that has been used for GEI analysis. The GGE analysis pools genotype effect (G) with GE (multiplicative effect) and submits these effects to principal component analysis. According to Yan et al. (2000), this biplot is identified as a GGE biplot. The GGE biplot has been recognized as an innovative methodology in biplot graphic analysis to be applied in plant breeding (Yadawad et al. 2023; Kottawa-Arachchi et al. 2022; Lal et al. 2021; Das et al. 2021). Best-performing genotypes can be identified and ranked by assessment of genotype-environment interactions and yield stability analysis. The objectives of the present study were, therefore, to identify the genotypes that have both high adaptability and stability across environments and to study the relationships among genotypes and environments.

Materials and methods

Plant materials and field trials

A total of 30 maize genotypes consisting of a set of experimental hybrids were provided by CIMMYT in the Climate Resilient Maize for Asia (CRMA) project (Table 1) and were planted in three environmental conditions, *viz*., optimum, rainfed and drought during 2016 and 2017. Rainfed trials were conducted during the rainy season at Ludhiana and Godhra, whereas the drought trials were conducted during the winter season at Godhra and Varanasi. The trials for optimum conditions were conducted at Delhi and Ludhiana. The trials were conducted in a randomized block design (RBD) in two replications. The inter-row spacing was 70 cm with an intra-row spacing of 25 cm in a row length of 3.0 meters. All necessary agronomic and cultural practices were timely followed to ensure a good plant stand. The trials were conducted under normal irrigated, rainfed and drought conditions during the years 2016 and 2017, and all locations were considered as different environments.

Controlled irrigation for creating drought

Under optimum conditions, six irrigations were provided *i.e.* after sowing, two-leaf stages, four-leaf stages, before onset of flowering, after flowering stage and at grain filling stage. Whereas, irrigation was withheld about two weeks before anthesis under drought conditions, for creating managed drought stress. Irrigation was resumed about two weeks after the end of male flowering. Data was collected on days to 50% anthesis and silking, anthesis-silking interval (ASI). After harvesting, data was collected for grain yield. Grain yield (q/ha, at 15% moisture) was used for further analysis. For all locations, data was subjected to a combined analysis of variance. GGE biplot models were used to analyze G × E interaction and yield stability of hybrids.

Statistical analysis

The variation due to genotypes and G × E for grain yield was examined using the GGE biplot based on the principal component analysis (PCA) of environment-centered data (Yan et al. 2000). The GGE biplot was created by using GEA-R software. The association of G × E was represented by which-won-where pattern (Gauch and Zobel 1997; Yan 2002), relationships among test environments (Cooper et al. 1997) and genotypes (Yan 2001) were visualized using their respective GGE biplots. An average environment coordinate (AEC) was drawn on the genotype-focused biplot to visualize the mean and stability of the hybrids (Yan and Kang 2003). The ideal environments and hybrids were identified using the AEC.

Results and discussion

Yield variation among the genotypes on individual locations

Mean grain yield for all the locations has been presented in Table 1. In the year 2016, a wide range in the mean grain yield was observed among the performance of genotypes. It varied from 43.1to 113.43 q/ha, 33.35 to 83.04 q/ha and 6.54 to 60.60 q/ha under optimum, rainfed and drought conditions, respectively. The comparative performance in terms of grain yield was observed to be lower as it ranged from 43.50 to 87.81 q/ha (optimum), 47.15 to 70.12 q/ha (rainfed) and 14.56 to 61.05 q/ha (drought). Considering the mean grain yield across locations and years, genotype ZH 161285 recorded more than mean grain yield under optimum (108.70 q/ha), rainfed (70.29 q/ha) and drought (60.60 q/ha) conditions in rainy and winter 2016, respectively. While, genotype ZH 161330 had a grain yield of 67.80, 67.76 and 52.87 q/ha under optimum, rainfed and drought conditions in 2017, respectively. Lower yields under drought conditions could be ascribed to a reduction in photosynthesis at flowering, an increase in ASI and kernel and ear abortion. An estimated 15 to 20% of maize grain yield is lost each year due to drought and there is a possibility that these losses may further increase as a result of more severe and frequent drought occurrences in future (Chávez-Arias et al. 2021).

The trials conducted during 2016 indicated that the genotypes ZH15449, ZH161285, ZH161418, ZH161271 performed well under optimum condition, whereas ZH161047, ZH161039, ZH161285, ZH161120 were good performers under rainfed condition. ZH161285, ZH161102, ZH15449, ZH161330 performed well under drought condition. Similarly, during 2017, under optimum conditions the good-performing genotypes were ZH161100, ZH161078, ZH161079, ZH15449, whereas under rainfed conditions the genotypes, viz., ZH161289, ZH161330, ZH15449, ZH161078 performed better. Under drought conditions the genotypes, viz., ZH161051, ZH161330), ZH161039 and ZH161102 were better performers. The response of maize hybrids to the tested environment is the variable indicated by the GEIs. The GEI effect also has implications in the plant selection process. The emergence of GEIs can make the selection process difficult and inefficient (Ruswandi et al. 2022).

Combined analysis of variance

The results on the combined analysis of variance of grain yield are presented in Table 2, which shows highly significant differences for environments, genotypes as well as for Genotype × Environment interactions (G×E) for both the years. Sum of squares due to G × E interactions was high, may be due to the large differences in environmental mean for yield. ANOVA revealed that most of the variation was explained by genotype × environment interactions (39.79%) followed by environments (20.03%) and genotypes (14.17%). In a study conducted by Shiri (2013), seven maize hybrids were tested under different drought stress regimes, and it was found that G x E interaction accounted for 9.24% of the total variation for grain yield, while genotypes contributed for only 2.37%. Even, the G × E interaction sum of squares was almost 3.9 times larger than that for genotypes which suggested the significant differences in hybrid responses across the different environments. Another study was conducted to identify maize hybrids under rainfed conditions, and it was observed that maximum variation was explained by differences in environmental conditions (55.92%) and least by genotypes (9.81%).

Per cent reduction in grain yield

The grain yield under rainfed and drought conditions was compared with the optimum conditions and percent reduction in grain yield was calculated (Table 1). In 2016, the maximum reduction under rainfed (47.21%) and drought (86.29%) conditions was in ZH 161418 and ZH 161095), respectively. The lowest reduction in yield was noticed in genotype ZH161418 and ZH161095, respectively under both environments (rainfed, drought); (0.00%, 3.18%), respectively. In 2017, the maximum reduction in grain yield was computed for ZH 161064 (50.57%) and lowest in ZH 161330 (0.06%) in rainfed condition. Under drought conditions, the maximum reduction was recorded for genotype ZH 161078 (80.04%) and lowest for ZH 161051 (10.82%) genotype. In a study carried out by Bruce et al. (2001), an evaluation trial for maize hybrids was planted in Weslaco, Texas, in 2000, which recorded mean grain yields of 5.1 and 3.0 t/ha, under optimum and water deficit conditions respectively, which resulted in approximately 40% yield losses. Liu et al. (2017) reported the estimation of maize yield potential and yield gap under irrigated as well

Table 1. Mean grain yield (q/ha) and percent reduction in rainfed and drought environments as contrary to optimum conditions across the years

S. No.	Code	Genotype	Year 2016				
			E1 (OPT) (Mean GY ± SE)	E2 (RF) (Mean GY ± SE)	% Reduction in GY in E2	E3 (DRT) (Mean GY± SE)	% Reduction in GY in E3
1.	G1	ZH15449	113.41 ±5.50	62.17 ±2.71	45.18	54.19 ±5.56	52.22
2.	G2	ZH161039	87.54 ±22.45	74.76 ±2.20	14.60	25.41 ±3.00	70.97
3.	G3	ZH161043	67.67 ±4.32	54.35 ±3.97	19.69	15.24 ±3.81	77.48
4.	G4	ZH161045	59.70 ±11.86	37.00 ±3.49	38.03	23.24 ±2.05	61.07
5.	G5	ZH161047	84.98 ±18.69	83.04 ±1.21	2.28	30.78 ±3.78	63.78
6.	G6	ZH161051	75.49 ±7.35	51.17 ±1.89	32.22	39.37 ±3.12	47.85
7.	G7	ZH161054	56.42 ±17.78	54.41 ±7.56	3.55	25.64 ±4.03	54.56
8.	G8	ZH161060	43.11 ±17.02	33.35 ±3.45	22.64	16.09 ±0.94	62.67
9.	G9	ZH161064	70.93 ±27.68	51.00 ±11.82	28.10	23.36 ±3.50	67.07
10.	G10	ZH161068	73.08 ±14.60	53.00 ±7.31	27.48	22.41 ±4.00	69.34
11.	G11	ZH161071	54.56 ±4.11	47.25 ±17.26	13.40	33.74 ±14.99	38.17
12.	G12	ZH161076	62.23 ±1.89	52.76 ±6.62	15.22	41.70 ±3.79	33.00
13.	G13	ZH161078	68.81 ±15.38	46.32 ±5.56	32.68	40.76 ±1.94	40.77
14.	G14	ZH161079	83.81 ±3.76	44.60 ±3.65	46.78	28.54 ±4.00	65.94
15.	G15	ZH161082	76.05 ±3.96	63.94 ±11.23	15.93	26.16 ±2.61	65.60
16.	G16	ZH161089	49.29 ±4.72	37.40 ±2.20	24.12	6.54 ±0.88	86.74
17.	G17	ZH161095	68.58 ±5.04	46.73 ±11.93	31.85	9.40 ±3.76	86.29
18.	G18	ZH161100	67.49 ±14.41	48.68 ±10.86	27.88	49.28 ±6.50	26.99
19.	G19	ZH161102	60.68 ±0.21	60.68 ±0.21	0.00	58.75 ±9.47	3.18
20.	G20	ZH161120	81.23 ±4.31	73.48 ±2.41	9.53	46.43 ±4.00	42.84
21.	G21	ZH161135	57.92 ±27.17	53.46 ±16.20	7.69	38.88 ±12.66	32.87
22.	G22	ZH161271	96.64 ±2.42	59.25 ±3.70	38.70	44.88 ±2.30	53.56
23.	G23	ZH161285	108.70 ±13.66	74.29 ±7.42	31.66	60.60 ±15.17	44.25
24.	G24	ZH161289	89.44 ± 1.49	70.79 ± 11.18	20.85	44.65 ±6.20	50.07
25.	G25	ZH161303	85.18 ± 7.15	72.73 ± 8.06	14.62	45.59 ±22.09	46.48
26.	G26	ZH161330	82.72 ± 9.62	69.76 ±3.50	15.67	53.79 ±2.00	34.98
27.	G27	ZH161358	72.64 ± 6.80	70.28 ±3.95	3.24	44.82 ±4.33	38.30
28.	G28	ZH161398	89.29 ± 0.77	52.61 ± 1.12	41.08	49.28 ±18.95	44.81
29.	G29	ZH161418	108.68 ± 17.59	57.37 ± 12.81	47.21	38.29 ±0.00	64.77
30.	G30	ZH161438	87.68 ± 2.84	62.17 ± 0.80	29.09	47.24 ±2.85	46.13
		CD	36.78	22.79		23.34	
			Year 2017				
S. No.	Code	Genotype	E1(OPT) (Mean GY± SE)	E2(RF) (Mean GY± SE)	% Reduction in GY in E2	E3(DRT) (Mean GY± SE)	% Reduction in GY in E3
1.	G1	ZH15449	82.28 ± 2.015	65.37 ± 3.90	20.56	39.17 ± 7.83	52.40
2.	G2	ZH161039	63.27 ± 2.810	55.14 ± 2.20	12.85	48.34 ± 3.58	23.59
3.	G3	ZH161043	69.71 ± 14.16	40.21 ± 3.97	42.31	37.34 ± 1.69	46.44
4.	G4	ZH161045	66.79 ± 0.48	51.94 ± 10.19	22.24	47.68 ± 6.81	28.61

5.	G5	ZH161047	65.62 ± 1.65	53.37 ± 0.90	18.67	46.90 ± 5.21	28.52
6.	G6	ZH161051	68.45 ± 1.28	64.28 ± 1.89	6.10	61.05 ± 2.49	10.82
7.	G7	ZH161054	72.52 ± 0.57	70.12 ± 7.56	3.31	42.15 ± 1.75	41.88
8.	G8	ZH161060	68.05 ± 6.39	47.87 ± 11.65	29.65	46.65 ± 7.18	31.44
9.	G9	ZH161064	82.95 ± 3.505	41.00 ± 11.82	50.57	17.24 ± 4.20	79.21
10.	G10	ZH161068	59.31 ± 3.165	50.98 ± 7.34	14.03	26.74 ± 11.70	54.91
11.	G11	ZH161071	78.56 ± 1.835	54.56 ± 3.49	30.55	37.27 ± 5.10	52.56
12.	G12	ZH161076	54.24 ± 0.80	45.88 ± 6.62	15.41	44.54 ± 0.83	17.89
13.	G13	ZH161078	86.19 ± 1.13	64.77 ± 5.56	24.85	17.20 ± 1.74	80.04
14.	G14	ZH161079	83.42 ± 3.160	51.57 ± 3.65	38.19	42.65 ± 4.35	48.87
15.	G15	ZH161082	74.04 ± 4.76	54.76 ± 11.23	26.04	31.23 ± 5.00	57.81
16.	G16	ZH161089	43.50 ± 3.46	27.15 ± 2.20	37.58	19.42 ± 4.15	55.37
17.	G17	ZH161095	61.31 ± 4.15	43.68 ± 0.83	28.75	14.56 ± 0.85	76.26
18.	G18	ZH161100	87.81 ± 0.61	50.38 ± 4.93	42.63	43.43 ± 0.85	50.54
19.	G19	ZH161102	64.32 ± 0.95	53.23 ± 0.21	17.23	48.30 ± 3.54	24.91
20.	G20	ZH161120	61.76 ± 35.27	55.07 ± 2.41	10.83	33.87 ± 5.08	45.16
21.	G21	ZH161135	52.71 ± 2.08	50.05 ± 16.20	5.05	33.92 ± 17.26	35.65
22.	G22	ZH161271	64.21 ± 2.820	52.70 ± 3.70	17.93	35.98 ± 18.16	43.96
23.	G23	ZH161285	67.25 ± 11.31	49.55 ± 2.58	26.32	32.25 ± 9.07	52.05
24.	G24	ZH161289	75.12 ± 21.82	69.86 ± 11.18	7.01	47.82 ± 2.60	36.34
25.	G25	ZH161303	77.93 ± 2.83	57.37 ± 8.06	26.38	44.59 ± 2.64	42.78
26.	G26	ZH161330	67.80 ± 14.00	67.76 ± 16.78	0.06	52.87 ± 7.80	22.03
27.	G27	ZH161358	73.03 ± 5.26	46.46 ± 25.89	36.38	37.80 ± 13.74	48.24
28.	G28	ZH161398	82.10 ± 0.23	40.78 ± 1.12	50.33	35.10 ± 1.99	57.26
29.	G29	ZH161418	76.53 ± 3.44	62.16 ± 12.81	18.77	44.20 ± 0.87	42.24
30.	G30	ZH161438	68.76 ± 1.42	62.78 ± 0.80	8.69	43.34 ± 0.13	36.97
		CD	20.53	15.84		20.72	

GY = Grain yield, E1 = Environment 1; E2 = Environment 2; E3 = Environment 3; SE = Standard error at 5%, CD = Critical difference, OPT = Optimum, RF = Rainfed and DRT = Drought.

as rainfed conditions in Nepal that the average irrigated yield potential (Yp) and water-limited yield potential (Yw) was 14.2 t/ha and 10.7 t/ha, respectively, which resulted in estimated yield gap of around 3.7 t/ha between Yp and Yw for rainfed maize.

Effects of drought and rainfed on Anthesis-silking Interval (ASI)

Drought stress has been recognized as a major constraint in maize production as it significantly reduces the grain yield by affecting the water relations of plants at cellular, tissue and organ levels causing damage and adaptation reactions. The presence of genetic diversity and the identification of novel elite lines is the crucial step for conventional breeding for tolerance to abiotic stress (Lu et al. 2011). Also, there is uneven rainfall occurrence in rainfed conditions, which results in less water availability, so the drought-tolerant lines can also be screened for their tolerance to rainfed conditions. The lines identified in the present study showed less reduction in grain yield which can be used as potential donors in the development of highly tolerant drought cultivars. Moreover, the genetic gains can also be accelerated by the addition of these drought-tolerant lines into the pipeline of breeding program for drought tolerance.

Anthesis-silking interval (ASI) is the key secondary trait that gets significantly affected during adverse climates. Under optimum conditions, the male and female flowering is well synchronized. Under abiotic stresses, there is poor synchrony in ASI and therefore, it results in reproductive failure. Under optimum conditions, in 2016, ASI varied from one to four days, under drought from two to five days and under rainfed, it was observed as one day for all the genotypes (Supplementary Table S1). ZH 161045 proved to be a drought susceptible genotype with five days ASI under drought ecology with a yield reduction of 61.07% as contrary to optimum conditions. ZH 161100 and ZH 161102 with ASI of two and three days had performed well with a lower yield reduction of 26.99 and 3.18% under drought conditions. In 2017, it varied under optimum (2–5 days), rainfed (1–6 days), and drought (2–10 days) conditions. It clearly depicts that, under adverse climatic conditions, the ASI increases, as a result, grain filling and grain setting also got affected. ZH161082 and ZH161102 exhibited the ASI of 10 days under drought conditions in 2017. ZH 161082 also exhibited higher yield reduction (57.80%) in grain yield, whereas ZH 161102 (24.91%) possessed a moderate yield reduction under drought environments. Effects of drought conditions were severe thus resulted in higher ASI.

GGE biplot analysis

The GGE (genotype main effect + G × E) biplots is one of the most used statistical techniques for MET analysis. GGE biplot is a specific version of a biplot that not only provides information on genotype main effects but also on G × E interaction at the same time. In the typical multivariate stability analysis methods, only G × E interaction is considered. But in GGE biplot, genotype main effects are also well taken in consideration. Genotype and genotype × environment (GGE) has been widely used to study stability and adaptability in various plant commodities because this method justifies all three important aspects of mega environment analysis, genotype evaluation, and test site for target environment (Yan et al. 2007). Also, a number of studies have reported similar interactions in different crops such as in durum (Kendal and Senar 2015), lentil (Karimijadeh et al. 2013), maize (Oyekunle et al. 2017), maize as a silage (Kaplan et al. 2017), sorghum (Gasura et al. 2015), sweet corn (Ruswandi 1 et al. 2020) and sweet potato (Mustamu et al. 2018) for employing the GGE biplot to evaluate stable cultivars. GGE biplot has emerged to be an effective technique in recent times in crop improvement and plant breeding research procedures.

In the present study, Genotype-Environment Interaction (GGE) biplot analysis was performed in order to study the relationships among and between environments. The GGE biplot provides a graphical display and is considered as an innovative methodology for applied plant breeding (Yan et al. 2000). It is increasingly being used in G×E interaction data analysis in maize (Tonk et al. 2011; Mitrovia et al. 2012). The GGE biplots for grain yield of 30 genotypes evaluated in three environments in 2016 and 2017 are shown in Fig. 1, 2 and 3. The values of the first principal component (PC1) and the second PC2 were estimated to generate a GGE biplot graph. The first principal component (PC1) scores were used as the X-axis and the second principal component (PC2) scores were used as the Y-axis. The percentage of GGE explained by PC1 and PC2 was 53.61% and 15.88%, respectively. The biplot explained 69.49% of the total variation relative to G and GEI.

Identification of high-yielding stable hybrids

Within a single mega-environment, genotypes should be evaluated for both mean performance and stability across environments. Fig. 1 depicts the average-environment coordination (AEC) view of the GGE biplot. The single-arrowed line is the AEC abscissa (or AEA); it points to higher mean yield across environments. Thus, ZH 15449 has the highest mean yield (69.43 q/ha), followed by ZH 161289 (66.28 q/ha), ZH 161330(65.78 q/ha) and ZH 161285 (65.44 q/ha), while ZH 161089 and ZH 161095 has the lowest mean yield of 30.55 q/ha and 40.71 q/ha, respectively. The double-arrowed line is the AEC ordinate; it points to greater variability (poorer stability) in either direction. Thus, ZH 161095 was highly unstable whereas ZH 161285 was a highly stable genotype. Some of the genotypes i.e., ZH 161078, ZH 161082 and ZH 161082 were also among the good performers as well as high stability across the diverse environments having mean grain yields of 54.01, 55.77 and 54.36 q/ha, respectively. In a similar study conducted by Mitrovia et al. (2012), by employing the GGE biplot methods, 19 maize hybrids were tested on multi environmental conditions and by assessment from mean vs stability, it was observed that some of the genotypes *i.e.* G10 and G17 falls in the category of high yielders as well as high stability. Oliveira et al. (2018) also carried out a similar study to evaluate maize hybrids and selected some of the hybrids that possess high yield as well as high phenotypic stability.

Ranking of genotypes

An ideal genotype can be identified as having high mean performance and high stability across environments. An ideal genotype (the centre of the concentric circles) to be a point on the AEA (absolutely stable) in the positive direction

Table 2. Combined analysis of variance (ANOVA) for both the years (2016-2017)

Source	DF	MSS	F value	Pr (>F)	%TSS
Environment	5	7409.60	27.74	0**	20.03 %
Genotypes	29	904.09	3.38	0**	14.17 %
Env : Gen	145	507.49	1.90	0.00002**	39.79 %
PC1	33	857.05	3.22	0	
PC2	31	643.93	2.42	0.00016	
PC3	29	498.52	1.87	0.00716	
PC4	27	257.16	0.96	0.51	
PC5	25	157.65	0.59	0.93	
PC6	23	0	0	1	
Residuals	180	267.07	NA	NA	

**Significant at 1% level of significance

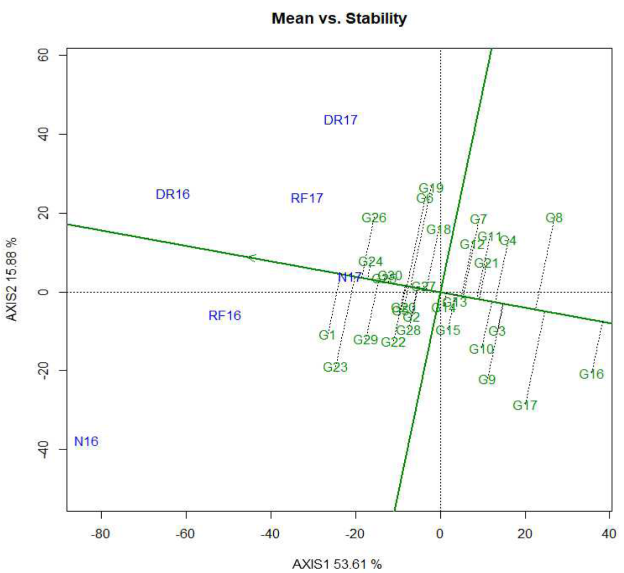

Fig. 1. Average-environment coordinate (AEC) for assessing stability of genotypes across the environments

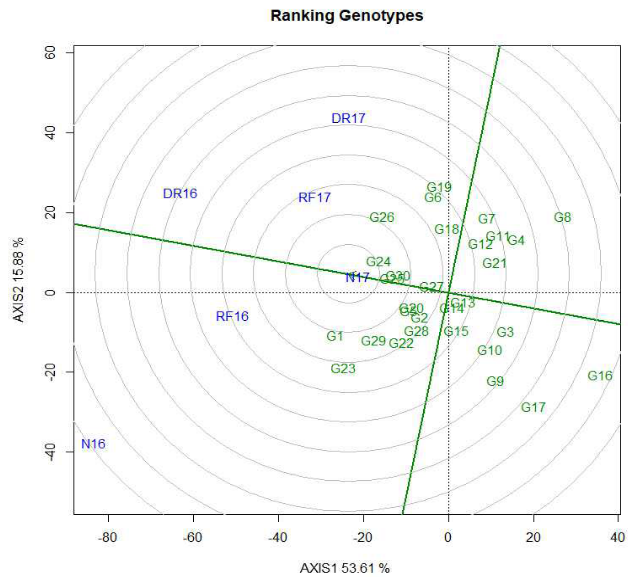

Fig. 2. The average-environment coordination (AEC) view to rank genotypes relative to an ideal genotype (the centre of the concentric circles)

and has a vector length equal to the longest vectors of the genotypes on the positive side of AEA (highest mean performance). Any genotype located in closer proximity to the ideal genotype can also be selected as the desirable one (Fig. 1). Therefore, genotypes located closer to the 'ideal genotype' are more desirable than others. In order to rank them, a line is drawn that passes through the biplot origin and the environment (Yan and Tinker, 2006). Thus, in the present study, it can be interpreted that ZH 161289 was more desirable in terms of performance followed by ZH 161330. Balestre et al. (2009) implied that in a study of testing 45 double cross hybrids, genotype 6 was observed to be the ideal and most desirable one as it showed the least distance to the average mean coordination.

Identifying winning genotypes at specific environments

Another major feature of GGE biplot is its characteristic to show which-won-where pattern which helps to identify the best performing genotypes in a defined environment. Yan et al. (2000) and Yan and Hunt (2002) suggested 'which won where' biplot to identify mega-environments. It is one of the most attractive features of GGE biplot. Fig. 3 showed the polygon view of the GGE biplot which is helpful in visualizing the 'which won where' pattern and showed different winning genotype in different environments. The genotypes which are farthest from the biplot origin are joined with a straight line forming a polygon. Perpendicular lines to each side of the polygon are drawn, starting from the biplot origin. These perpendicular lines are the equality lines between adjacent genotypes on the polygon. These equality lines divide the biplot into sectors, and the winning genotype for each sector is the one located on the respective vertex. The locations where certain genotypes have the best yield, can be considered as mega-environments for that genotype. Fig. 3 showed that genotypes ZH 161102, ZH 161330, ZH 15449, ZH 161285, ZH 161095 and ZH 161089 located at the corner of the polygon were the vertex genotypes with the longest vectors. ZH 15449(113.41 q/ha) and ZH 161285(108.7 q/ha) were the best-performing genotypes followed by ZH 161095 (68.58 q/ha) under optimum conditions in year 2016. ZH 161330 has a relatively good grain yield under drought conditions in 2016 and 2017 (53.79 and 52.87 q/ha, respectively) as well as in rainfed conditions (67.76 q/ha) in year 2017. These genotypes were the most responsive genotypes to the above-mentioned environments. These genotypes can be further tested for their performance under diverse environments in order to select the best ones. Ruswandi et al. (2022) identified genotypes MH2, MH8, MH9, MH1, MH3, and MH10 from which-won-where pattern of GGE biplot.

The GGE interaction biplots are important techniques in crop improvement. This study has important implications in determining the appropriate test location for the development of cultivars. Moreover, the breeding program in maize depends upon the extent of genetic diversity and association among inbred lines and breeding material (Bojovic et al. 2020). Maize breeders have been challenged by so many constraints such as changes in climate and need to develop high yield cultivars. The aspect of the Genotype x environment (G × E) interaction is very important in the plant breeding programmes as it affects performance of genotypes to a high extent. To resolve this, multi-environment trials (MET) has been used to identify superior and best-performing genotypes across the environments

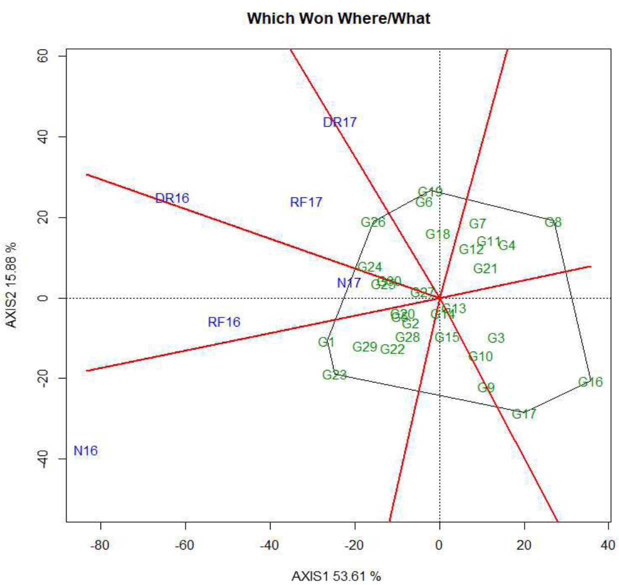

Fig. 3. Potential mega-environments and genotype performance in environments

and across the years. The genotypes that showed less reduction in grain yield (ZH 161102, ZH 161330, ZH 161051) under drought and rainfed conditions can be used as parental lines or donors in the breeding program. The most stable genotypes (ZH 15449, ZH 161285, ZH 161330, ZH 161102) identified in this study could be tested in larger plot size at multilocations so that they may be recommended for commercial cultivation suited for an appropriate environment. ZH 161078, ZH 161079 and ZH 161082 were considered as highly stable as well as good performers, thus it can be interpreted that they can perform well at the adverse climates provided that their genetic potential can be further exploited by testing at multi locations.

Supplementary material

Supplementary Table S1 is provided online, www.isgpb.org

Authors' contribution

Conceptualization of research (RK, PHZ); Designing of the experiments (RK, AKD, PHZ); Contribution of experimental materials (PHZ); Execution of field/lab experiments and data collection (RK, YK, SBS, BK, JPS, MBP); Analysis of data and interpretation (AKD); Preparation of the manuscript (RK, YK, AKD).

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Supplementary Table S1. Days to anthesis (DA), days to silking (DS) and anthesis-silking interval (ASI) of the genotypes for all the three locations

		Year 2016									Year 2017								
		Optimum (Delhi)			Rainfed (Ludhiana)			Drought (Godhra)			Optimum (Ludhiana)			Rainfed (Godhra)			Drought (Varanasi)		
S. No.	Genotype	DA	DS	ASI	DA	DS	ASI	DA	DS	ASI	DA	DS	ASI	DA	DS	ASI	DA	DS	ASI
1.	ZH15449	51	53	2	55	56	1	80	83	3	58	60	2	53	57	4	101	109	8
2.	ZH161039	52	56	4	51	52	1	83	85	2	54	55	1	55	57	2	101	109	8
3.	ZH161043	50	53	3	55	56	1	83	85	2	56	58	2	54	55	1	103	109	6
4.	ZH161045	54	57	3	57	58	1	79	84	5	54	57	3	58	59	1	105	110	5
5.	ZH161047	53	56	3	54	55	1	80	83	3	54	57	3	53	55	2	102	107	5
6.	ZH161051	51	54	3	56	57	1	80	83	3	54	55	1	54	56	2	100	106	6
7.	ZH161054	52	56	4	56	57	1	80	83	3	53	55	2	54	56	2	102	107	5
8.	ZH161060	52	53	1	52	53	1	99	102	3	50	53	3	54	56	2	101	110	9
9.	ZH161064	52	54	2	52	53	1	99	102	3	57	59	2	56	56	0	102	107	5
10.	ZH161068	50	53	3	53	54	1	81	84	3	57	58	1	54	56	2	106	109	3
11.	ZH161071	49	52	3	53	54	1	78	81	3	54	56	2	56	58	2	100	108	8
12.	ZH161076	52	54	2	55	56	1	80	83	3	53	58	5	55	57	2	101	107	6
13.	ZH161078	55	57	2	56	57	1	79	83	4	56	59	3	56	59	3	104	109	5
14.	ZH161079	54	57	3	53	54	1	82	84	2	56	58	2	55	57	2	101	110	9
15.	ZH161082	51	54	3	51	52	1	77	80	3	55	57	2	54	56	2	99	109	10
16.	ZH161089	51	54	3	54	55	1	74	76	2	59	60	1	53	59	6	102	109	7
17.	ZH161095	50	52	2	54	55	1	83	85	2	67	68	1	58	60	2	101	109	8
18.	ZH161100	50	52	2	52	53	1	80	82	2	52	54	2	53	55	2	103	107	4
19.	ZH161102	50	54	4	52	53	1	78	81	3	55	57	2	55	57	2	98	108	10
20.	ZH161120	53	55	2	55	56	1	85	87	2	53	55	2	56	58	2	99	107	8
21.	ZH161135	54	56	2	55	56	1	83	86	3	55	59	4	58	63	5	101	110	9
22.	ZH161271	53	55	2	54	55	1	87	89	2	68	69	1	53	55	2	101	110	9
23.	ZH161285	54	56	2	50	51	1	96	98	2	67	68	1	56	58	2	101	103	2
24.	ZH161289	55	58	3	51	52	1	91	93	2	57	61	4	56	58	2	102	108	6
25.	ZH161303	52	54	2	51	52	1	94	96	2	53	55	2	53	55	2	101	108	7
26.	ZH161330	54	56	2	55	56	1	92	94	2	57	59	2	61	62	1	106	109	3
27.	ZH161358	55	58	3	53	54	1	98	100	2	55	57	2	56	58	2	101	110	9
28.	ZH161398	52	55	3	53	54	1	78	80	2	58	60	2	52	55	3	104	110	6
29.	ZH161418	49	53	4	52	53	1	53	55	2	58	60	2	71	75	4	102	106	4
30.	ZH161438	55	59	4	55	56	1	53	55	2	67	68	1	90	92	2	105	108	3