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YIELD STABILITY STUDIES IN INDIGENOUS AND EXOTIC MAIZE HYBRIDS UNDER GENOTYPE BY ENVIRONMENT INTERACTION

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Abstract

Identification of superior maize hybrids for targeted environment is very complex due to the existence of lager genotype-by-environment interaction (GEI). This study considered G × E interaction of nine genetically diverse, indigenous and exotic maize hybrids with eleven environments of Pakistan for grain yield in two consecutive spring seasons (2017 and 2018) under randomized complete block design in split plot arrangement with two replicates. Combined analysis of variance showed that environments, genotypes and their interactive effects were significant (p<0.01) for grain yield. Average grain yield of the maize hybrids ranged from 8369 kg ha^{-1} for YH-5140 to 11066 kg ha^{-1} for FH-1046. The first two principal components (PC1 and PC2) were used to produce two-dimensional genotype + genotype × environment interaction (GGE) biplot that accounted for 62.3% and 18.69%, respectively. Results showed a crossover type of interaction between hybrids and environments, with differential performance of maize hybrids across test environments. The "which won where" GGE biplot proposed the presence of two maize mega-environments with two wining hybrids i.e., FH-1046 and YH-5482. The "mean vs. stable" biplot suggested that FH-1046 was the most productive hybrid but was less stable, whereas YH-1898 was the most stable hybrid across the test environments. The "discriminativeness vs. representativeness" biplot showed that Depalpur was the most ideal test environment while Jhang was the most discriminative location. Highly productive but less stable maize hybrids across test environments are proposed for cultivation in those test environments/locations wherever they performed outstandingly.

Key words: Test environments, Principal component analysis, GGE-biplots, Grain yield, *Zea mays* L.

Introduction

Maize is a predominant cereal crop in many areas of the world. It is an important source of starch, protein, oil, iron, alcoholic beverages, food sweeteners, cosmetics, biofuel, vitamin B and essential fatty acids such as linoleic acid, sitosterol and vitamin E (Langade *et al.*, 2013). According to the Anon., (2019), average per capita daily consumption of maize is 49 g, with developing countries being the major consumers. Maize is the major source of calories for 230 million people across the globe.

In Pakistan, maize is cultivated in two different growing seasons i.e., spring and summer crops. The spring maize is planted under the low temperatures of January–February, and its reproductive phase grows under the high temperatures of May–June. In contrast, summer maize is sown under the medium to high temperatures of July–August and completes its vegetative phase under the medium temperatures of September–October. However, the reproductive phase of summer crop is completed under the low temperatures of December, and compared with spring maize it takes 10–15 days more to attain its physiological maturity because of the low temperatures during the grain filling and maturation phases. Hence, two different sets of environmental conditions prevail from germination to maturity for the spring and summer maize crops. The area under spring maize is continuously increasing because it has higher productivity than summer maize. In 2018–19, maize was sown on an area of 1.318 million hectares and 6.309 million tons production was obtained, with a yield of 4787 kg ha^{-1} (Anon., 2019).

In Pakistan, maize is predominantly used for feed and fodder in the poultry and dairy industries, respectively. It is also used in wet and dry milling industry, and direct human consumption as roasted grains or cobs. However, according to the Anon., (2019), the average grain yield of maize per unit area in Pakistan (4.29 tons ha^{-1}) is quite low than that of USA (11.08 metric tons ha^{-1}), Canada (10.02 metric tons ha^{-1}), Turkey (10.00 metric tons ha^{-1}), European Union (7.51 metric tons ha^{-1}), Argentina (6.15 metric tons ha^{-1}) and China (6.11 metric tons ha^{-1}). The main reasons for the lower grain yield in Pakistan are high temperature, low availability of irrigation water, unavailability of quality seeds, insect pests (especially maize borer, shoot fly, termites) and diseases like stalk rot and early seedling diseases, fusty crop management, supra or sub-optimal rates of inputs (Yousaf *et al.*, 2017). Selection of appropriate and productively stable maize hybrids for cultivation in a specific environment could increase the per acre grain yield of maize. This could be achieved by screening maize hybrids in different locations to examine their genotype + genotype × environment (G × E) interaction and yield stability (Khalil *et al.*, 2010; Maqbool *et al.*, 2019).

Large genotype by environment interaction generally occurs under normal as well as stress conditions; hence, performance of a variety in one test location during one growing season differs from its performance in other periods or sites within same region (Sibiya *et al.*, 2012). This crossover performances arises owing to differential phenotypic expression of genotypes under different environmental conditions (Falconer & Mackay, 1996). Moreover, variation in genotypic sensitivities to target environments might be the other reason of G × E interaction. Under non-significant G × E interaction, evaluated genotypes are satisfactory indicators of stable genotypic performance under various environments (Miti, 2007). However, significant G × E interaction show that hybrids are not stable and hybrids selected from one set of environmental changes may perform in a different way in another set of changes. Thus, G × E interaction could aid in shaping a breeding approach. Information regarding G × E is also helpful for plant breeders in choosing suitable locations for selection (Yan & Tinker, 2005).

The genetic diversity among various maize genotypes for morpho-physiological and grain quality parameters is considered pivotal for crop improvement (Grzesiak, 2001). Development of high yield and stable crop varieties is the ultimate objective of most breeding programs. An ideal genotype has high mean yield and a low fluctuation in yield (stability) across environments (Annicchiarico, 2002). Farmers require maize hybrids that are stable across different environmental conditions with high grain yield potential under favorable conditions (Kenga, 2001). Therefore, plant breeders should develop hybrids that are capable of enduring unpredictable environmental changes.

Newly developed maize hybrids should be assessed for a number of years under at various sites before their release (Badu-Apraku *et al.,* 2012; Ndhlela, 2012). Varietal Selection is often inefficient in multi-location trials owing to large G × E interaction and relative rankings of varieties that make it hard to fix the dominance of any single variety (Adu *et al.,* 2013; Badu-Apraku *et al.,* 2011). However, various statistical models can help in selection of varieties for a target environment by providing information on their level of adaptability and stability in a specific environment. Models can also help breeders in equally important task of identifying genotypes that perform better across the environments. Researchers use different models for stability analysis; for example, joint regression analysis, additive main effects and multiplicative interaction (AMMI) and G × E interaction (GGE) biplot analysis (Ndhlela, 2012; Adu *et al.,* 2013; Eberhart & Russell, 1966). Among these, GGE biplot analysis is the more extensively used statistical model for genotypic evaluation of multi-environment trials (METs) because it integrates genotype main effect with the G × E effect (Badu-Apraku *et al.,* 2012). It can also help in clustering environments and identifying more representative ones for varietal evaluation (Cooper *et al.,* 1997). Genotypic comparisons and ranking are also possible through mean yields and stability indices (Yan, 2001).

In Pakistan, maize is grown in different agro-ecological zones, hence studies investigating performance of different genotypes (local and exotic) and its interaction with environment is indispensable for further breeding program. Therefore, the present study was carried out with the objectives; a) to evaluate the local and multinational maize hybrids for grain yield under genotype by environment interaction effects, and b) to identify the high yielding maize hybrids with stability across test environments.

Materials and Methods

Experimental material: Experimental material comprised nine single cross maize hybrids of indigenous and exotic origin (Table 1). Seeds of indigenous maize hybrids were obtained from the Maize and Millets Research Institute, Yusafwala, Pakistan. Exotic maize hybrid seeds were obtained from regional offices of Pioneer and Monsanto seeds located in Sahiwal, Pakistan. Among indigenous hybrids, three hybrids (YH-1898, FH-1046 and FH-949) were approved control hybrids while four elite maize hybrids (YH-5140, YH-5482, FH-793 and FH-1292) were under evaluation. Most of the indigenous hybrids were of a temperate-tropical nature but both of the exotic maize hybrids (P-1543 and DK-9108) were mainly of tropical origin.

Experimental sites: A total of nine single cross maize hybrids were evaluated at eleven different geographical locations in the core maize growing areas of Punjab, Pakistan as a part of on-farm maize yield trials, to check the adoptability and productivity of indigenous maize hybrids in comparison with exotic hybrids during two consecutive spring seasons (2017 and 2018). The longitude, latitude, altitude and soil types of these sites are depicted in Table 2. All these environments had different cropping systems (e.g. maize-potato-maize, or cotton-maize).

Experimental design and data acquisition: The maize hybrids were laid out applying randomized complete block design (RCBD) in duplicate under a split plot arrangement. Maize hybrids were sown on 75 cm wide ridges with 15 cm plant spacing. Each experimental unit was 10 m long and contained four rows of hybrid. Two seeds per hills were planted and at three to four leaf stage plants were thinned to ensure optimum plant population. Standard agronomic practices were carried out at all locations. At maturity, whole plots were harvested, fresh cobs were weighed and later grain yield was adjusted at 15% moisture using the following formula:

$$\text{Grain yield (kg ha}^{-1}\text{)} = \frac{\text{Fresh ear weight (kg/plot) x (100-MC) x 0.8 x 10000}}{\text{(100-15) x area harvested/plot}}$$

where:
MC = Grain moisture contents (%) at the time of harvest
0.8 = Coefficient for shelling
10,000 m^2 = Corresponds to 1hectare (area of hectare plot)
15% = Grain moisture percentage required for seed storage

Statistical analysis

All the recorded data were subjected to combined analysis of variance (ANOVA) to find out differences among maize hybrids, environments and their G x E interaction using Statistix 8.1 statistical package (Gomes and Gomes,1984). Maize hybrids were given the major importance while test environments were given the minor importance. Furthermore, G × E interaction was performed through GGE biplot analysis, to identify maize hybrids suitable for a given environments as well as under various environment (Mafouasson *et al.,* 2018).

Table 1. Names and sources of maize hybrids used in the study.

Hybrids	Origin	Hybrid	Origin
P-1543	Pioneer, Pakistan	YH-5140	MMRI, Yusafwala
DK-9108	Monsanto, Pakistan	FH-1292	MRS, AARI, Faisalabad
FH-793	MRS, AARI, Faisalabad	YH-5482	MMRI, Yusafwala
FH-949	MRS, AARI, Faisalabad	YH-1898	MMRI, Yusafwala
FH-1046	MRS, AARI, Faisalabad		

MMRI, Yusafwala = Maize and Millets Research Institute, Yusafwala, Sahiwal, Pakistan MRS, AARI, Faisalabad = Maize Research Station, Ayub Agricultural Research Institute, Faisalabad, Pakistan

Table 2. The salient features of eleven studied test environments.

Location	Latitude	Longitude	Altitude (meter)	Soil Type
Faisalabad	30.950396°N	72.830602°E	167	Loamy
Sargodha	32.134845°N	72.687585°E	188	Silt Loamy
Jhang	31.290256°N	72.291879°E	154	Clay Loamy
Okara	30.681556°N	73.638651°E	171	Loamy
Mamu Kanjan	30.831403°N	72.809388°E	164	Loamy
Samundri	31.063314°N	72.937453°E	171	Clay loamy
Kamalia	30.717208°N	72.620233°E	153	Clay loamy
Arifwala	30.287040°N	73.051347°E	153	Clay loamy
Depalpur	30.681732°N	73.637631°E	171	Loamy
Toba Take Singh	30.961737°N	72.474813°E	159	Clay Loamy
Khanewal	30.287936°N	71.950938°E	135	Clay Loamy

Table 3. Mean squares for grain yield under genotype by environment interaction study in maize.

Source	DF	Sum of squares (SS)	Mean squares	F-calculated
Replications (R)	1	324284	324284	
Environments (E)	10	448300000	44830000	540.39**
Error (R × E)	10	829558	82955.8	
Genotype (G)	8	121736588	15220000	546.85**
G x E Interaction	80	88260000	1103291	39.64**
Error (R × E × G)	88	2449570	27836.0	
Total	197	661900000		

Table 4. Mean yield (kg ha^{-1}) of nine maize hybrids across eleven environments.

Hybrids/ Locations	Faisalabad	Sargodha	Jhang	Okara	Mamun Kanjan	Samundri	Kamalia	Arifwala	Depalpur	TT Singh	Khanewal	Mean
P-1543	12153	11801	10398	11874	9713	8061	8801	7099	7818	7161	7067	9268
DK-9108	11950	11908	11836	12228	11217	8522	9108	9011	9658	9008	8801	10295
FH-793	11448	12684	9143	11427	12606	7411	7905	8203	8580	7984	8084	9588
FH-949	**12987**	12992	12081	11710	12481	8688	9422	9228	9308	9095	8210	10564
FH-1046	12361	**14094**	**13468**	**12541**	**13108**	9232	9190	9573	**9995**	8758	9412	11066
YH-5140	10658	10361	9015	10446	10348	7353	7005	7396	7056	6325	6093	8369
FH-1292	11776	10083	9546	10110	11919	7711	8010	7613	7689	7638	8956	9186
YH-5482	12019	11610	9248	10359	10609	**9704**	**10035**	**10124**	9552	**9859**	**10069**	10290
YH-1898	11689	11786	11487	11314	11844	8818	8078	9526	9684	8678	9192	10190
Mean	11893	11924	10691	11334	11538	8389	8617	8641	8815	8278	8431	9868

Values in bold and underline are highest grain yield (Kg ha^{-1}) of maize hybrids at each test environment

Results

Analysis of variance: Results obtained from combined analysis of variance across 11 environments for 9 hybrids showed that both main effects and their interaction significantly ($p<0.01$) affected the grain yield (Table 3). For grain yield, the environments accounted for 67.7% of the total variation in the sum of squares (SS) while contribution of genotypes (G) and genotype by environment (G × E) interaction were 18.4% and 13.3%, respectively.

Genetic variability among maize hybrids across environments: Grain yield performance of 9 maize hybrids was estimated on the basis of their mean grain yield over environments (Table 4). Mean grain yield ranged from 8278 kg ha^{-1} in Toba Tek Sing to 11,924 kg ha^{-1} in Sargodha, Pakistan. However, among hybrids average grain yield ranged from 8369 kg ha^{-1} (YH-5140) to 11066 kg ha^{-1} (FH-1046). Hybrids FH-1046 and YH-5482 were found as the most productive across different environments having grain yield 11066 and 10295 kg ha^{-1}, respectively. However, FH-1046 was the highest yielding hybrid across five different environments i.e., Sargodha, Jhang, Okara, Mamu Kanjan and Depalpur, Pakistan. Similarly, YH-5482 was also the most productive hybrid in five environments i.e., Samundri, Kamalia, Arifwala, Toba Tek Singh and Khanewal, Pakistan.

Selection of ideal hybrid across 11 test environments (which won where biplot): The GGE polygon biplot graph of nine maize hybrids across 11 environments is presented in Fig. 1. PC1 and PC2 scores were highly significant, explaining 62.3% and 18.69% of the total variations, respectively. Collectively, PC1 and PC2 explained 80.99% of the total variations for genotype main effects and genotype × environment interaction for grain yield. The GGE polygon biplot graph exhibited the "which won where" situation of maize hybrids (Fig. 1). The vertex of the GGE polygon graph were the marker hybrids, located farthest from the origin of biplot in different directions, in a way that all other hybrids were confined in the resultant polygon. The "which won where" GGE biplot was separated into four different segments and two mega environments, revealing three apex hybrids i.e., FH-1046, YH-5482 and YH-5140). The 1st mega environment, comprising of five environments i.e., Faisalabad, Sargodha, Jhang, Okara and Mamu Kanjan while FH-1046 was the highest yielding hybrid in this mega environment. The second mega environment comprised of six environments i.e., Samundri, Kamalia, Arifwala, Depalpur, Toba Tek Singh and Khanewal along with YH-5482 as the most productive hybrid. Three maize hybrids i.e., FH-793, P-1543 and YH-5140 were not fallen in any of the mega environment, indicating that either these hybrids were not the best hybrids in any environment, or they were the lowest productive hybrids in some or all of the test environments. Vertex hybrids were more responsive than the hybrids within the polygon (Fig. 1).

Average yield performance and stability of maize hybrids: Performance and yield stability of 9 maize hybrids was tested over 11 environments through GGE biplots using an average environment coordination (AEC) (Fig. 2) (Yan, 2001). In this biplot, a line (i.e., the AEC) passes through the biplot origin and average environment circle (ideal environment), and represents the highest average grain yield. Another line that passes through the biplot origin and is perpendicular to AEC (with a double arrow) denotes the stability of maize hybrids. Any line that pass away from the biplot origin on either side of this axis showed higher G × E interaction and lower stability of hybrids for grain yield (Yan & Hunt, 2002).

It was further shown that YH-1898 was intermediately productive hybrid with an excellent yield stability across the environments, whereas FH-1046 had the highest grain yield but low stability. Exotic maize hybrid DK-9108 was also among intermediately productive hybrids with higher yield stability than FH-949 (which showed average yield and stability). An indigenous hybrid, YH-5482, was highly productive but least stable hybrid. Similarly, exotic maize hybrid P-1543 had a higher yield but was less stable than the indigenous hybrids FH-793 and YH-5140.

Comparison of hybrids relative to an ideal hybrid: Ranking of maize hybrids based on their yield performance and stability comparative to an ideal hybrid is given in Fig. 3. An Ideal hybrid can be used as a reference to identify the most stable and productive hybrid. With the ideal hybrid (i.e., the most productive and stable) at the center, concentric circles were drawn to demonstrate the distance between the ideal and the studied hybrids. Fig. 3 showed that four maize hybrids i.e., YH-1898, DK-9108, FH-949 and FH-1046 which were found as superior hybrids (i.e., located near to the center of the concentric rings). All these hybrids were high yielding; FH-1046 was the most productive and thus the most desirable, followed by FH-949 and DK-9108.

Representativeness and discriminativeness based ranking of test environments: Discriminating capability and representativeness of tested environments is displayed in Fig. 4. An ideal environment refers to an environment that have maximum discriminativeness for hybrids. The results revealed Jhang as the most discriminative as well as most representative environment, being distant from biplot origin (discrimination) and having the shortest projection on the AEC. The environment Jhang appears to be similar to Sargodha, Okara and Mamu Kanjan based on the small cosine of the angle between them. However, another group of environments i.e., Samundri, Kamalia, Arifwala, TT Singh and Khanewal, also had high discriminating power but not greater than Jhang. Furthermore, Jhang and its associated environments (Sargodha, Okara and Mamu Kanjan) had a strong positive association with the most favorable genotype (FH-1046). Ranking of environments, as presented in Fig. 5, suggested that Depalpur should be the most ideal environment due to its closeness to the center of the concentric circles, followed by Arifwala, TT Singh and Jhang etc. However, Depalpur was further from the ATC Y-axis than Jhang, which was present in the third circle, indicating that the Jhang environment was more important than Depalpur.

Relationships among eleven test environments: The relationships among test eleven environments are shown in Fig. 6. All the test environments had different vector lengths; the different lengths represent the discriminating ability of these environments and the cosine of the angle displays the magnitude of correlation between them. More the length of the vector, more discriminating the environment, and smaller the cosine of the angle, stronger the association between environments. Thus, Fig. 6 shows that Jhang is the most discriminating test environment, followed by Sargodha, Khanewal, TT Singh and Depalpur. However, there was a strong association between Jhang and Sargodha, and between Khanewal and TT Singh. Test environment Depalpur had weak association for other discriminating environments (Jhang, TT Singh and Khanewal). Therefore, test environments Jhang, Khanewal and Depalpur were the best for the genetic differentiation of hybrids.

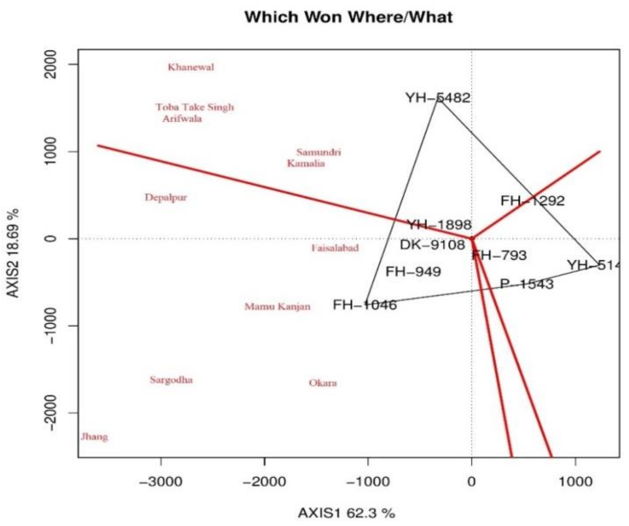

Fig. 1. Genotype + Genotype × Environment interaction biplot showing hybrids performance in each environment.

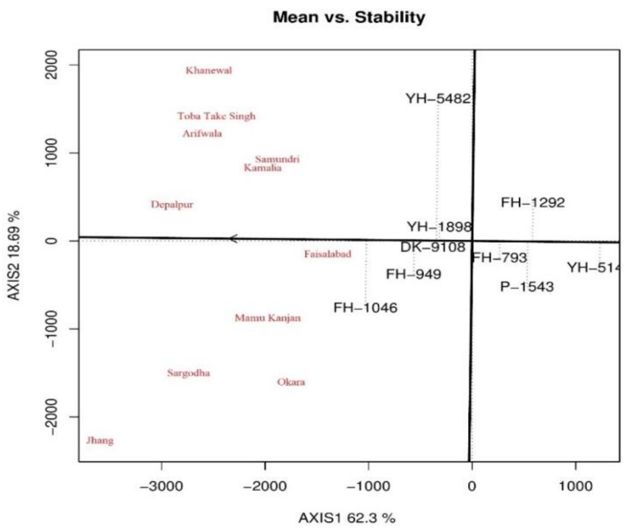

Fig. 2. Average tester coordination (ATC) view of the GGE biplot. Environments are denoted by 'E' AXIS1 and AXIS2 are PC1 and PC2, respectively.

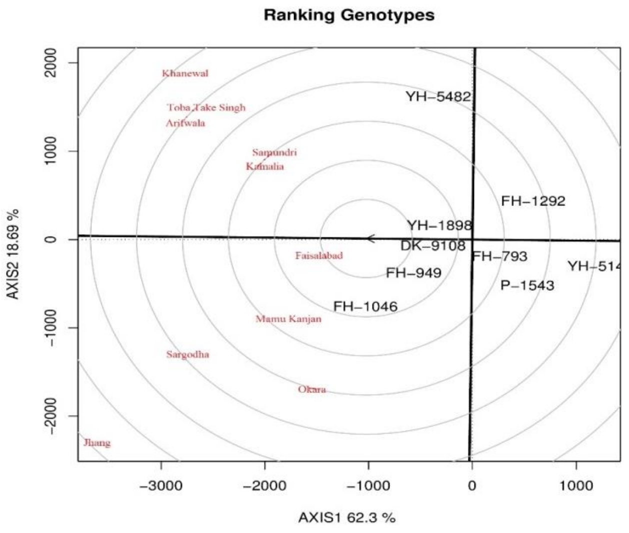

Fig. 3. GGE biplot of ideal genotype and comparison of thegenotypes with the ideal genotype.

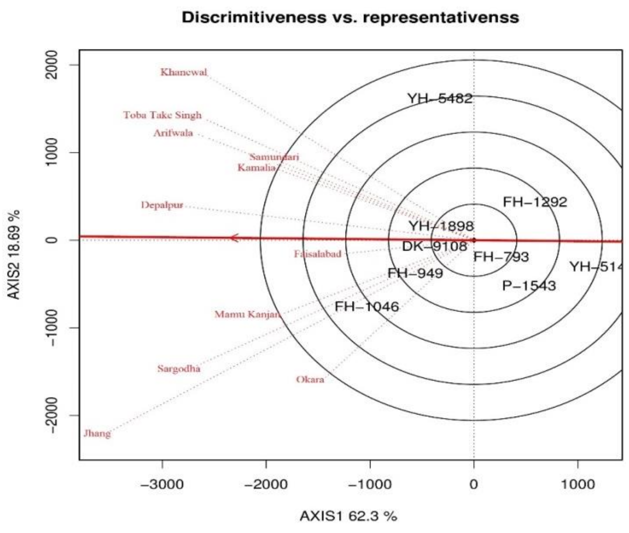

Fig. 4. The "discriminating power vs. representativeness" view of the GGE biplotfor 9maize hybrids tested at 11 test environments.

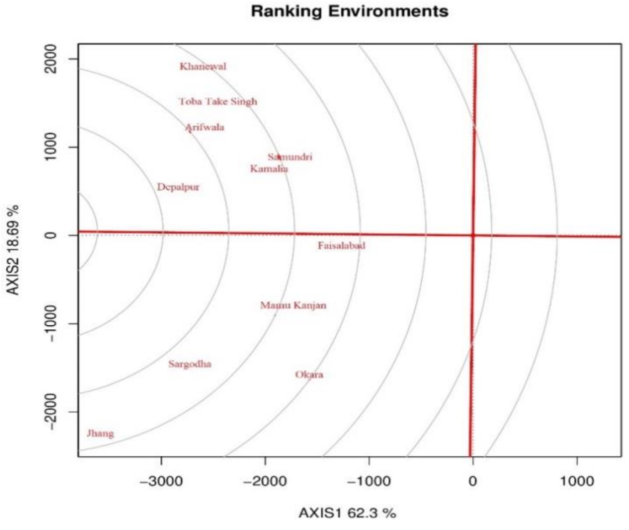

Fig. 5. GGE biplot of environments ranking and comparison of the environments with the ideal environment.

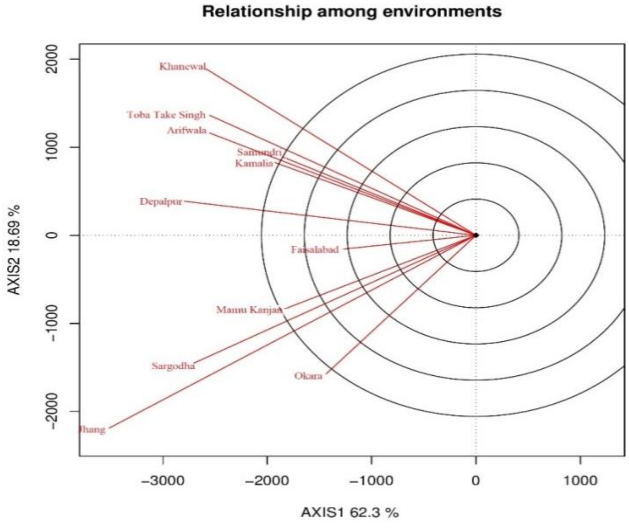

Fig. 6. Vector view of GGE biplot for relationships among environments.

Discussion

In this study, environments created more variation than genotypic main effects and genotype × environment interaction, suggesting the prevalence of high variability among test environments. Similar results were also described by Badu-Apraku *et al.,* (2012) who revealed that the role of test environments was much more than any other source of variation, including genotypic in multi-location experiments. Highly significant differences for genotype × environment interaction for grain yield in maize indicates the use of genotype + genotype × environment interaction (GGE) biplot analysis to evaluate single cross maize hybrids for their performance and yield stability. Our results were in line with Ghani *et al.,* (2017), Saeed *et al.,* (2018) and Shehzad *et al.,* (2020) who showed the presence of highly significant variations among maize hybrids under heat stress conditions.

The GGE biplot analysis revealed that PC1 and PC2 explained the maximum variation in the data by 62.3% and 18.69%, respectively; together, these axes explained 80.99% of total variation, suggesting that the PC1 and PC2 biplot effectively approached the data. The GGE biplot for nine hybrids was separated into three segments and two mega environments from where the selection of hybrids should be performed for the deployment to the similar types of environment as proposed by Yan & Tinker (2005).

Previous studies suggested that ideal genotypes must be high yielding (i.e., have high PC1 scores) and highly stable (i.e., have low PC2 scores) (Yan, 2001). Similarly, the ideal test environment should have a high PC1 score (which shows environmental discriminability of the genotypes on the basis of their genotypic main effects) and a low or absolute PC2 score (which describes the representativeness of the overall environment). A polygon view of the biplot graph for the "ideal" genotype showed that the hybrids present at the vertex were the highest yielding hybrids in their sector (Yan & Tinker, 2005). Hence, the biplot identified three vertex hybrids (FH-1046, YH-5482 and YH-5140) falling under three sectors. Among these vertex hybrids, two hybrids (FH-1046 and YH-5482) fell under two different mega environments. YH-5482 performed well under the second mega environment, which had more rainfall and lower temperatures than the first mega environment (in which FH-1046 had a higher yield than other hybrids). Maize and potato are the most cultivated crops in the first mega environment whereas wheat, rice and sugarcane are the primary crops in the second mega environment. The results demonstrate that most productive hybrids from each mega environment could be recommended for cultivation in similar environments. However, further evaluation is required under more diverse environments over more seasons.

An ideal hybrid should have maximum grain yield along with higher stability across test environments. Therefore, it must be on AEC in a positive direction and should have maximum vector length. The GGE biplot showed that YH-1046 had the highest average grain yield (11,066 kg ha^{-1}) because it had the highest projection on the performance line (i.e., AEC), followed by FH-949 (10,562 kg ha^{-1}), DK-9108 (10,295 kg ha^{-1}) and YH-5482 (10,290 kg ha^{-1}). These hybrids were not stable in various environments. However, in selecting genotypes suitable for maize production across the environments, an ideal genotype would have high performance in terms of grain yield and stability. FH-1046 and FH-949 were not suitable because of their poor stability. However, YH-5482 could be selected for production across environments, because it met the necessary characteristics of high grain yield and stability, as suggested by Badu-Apraku *et al.,* (2012). The YH-5482 hybrid was the most suitable, followed by FH-949, DK-9108 and YH-1898. Yousaf *et al.,* (2020) also reported higher productivity and stability of YH-5482, FH-949 and FH-1046 under heat stress conditions. The overall performance of two indigenous maize hybrids (FH-1046 and YH-5482) in Pakistan was far better than that of two exotic maize hybrids (DK-9108 and P-1543) that were susceptible to the spring heat. Maize hybrids YH-5140 and FH-1292 were the worst performing hybrids in all locations studied.

Identification of ideal test environment for efficient selection of superior maize hybrids is considered very essential for crop improvement under diverse environmental conditions. An ideal testing location/site or environment should be able to discriminate among hybrids and must be demonstrative of all test environments (Yan & Kang, 2003). The discriminativeness of an environment or site represents its capacity to differentiate among different hybrids, while the representativeness illustrates its competence to represent other test environments (Yan *et al.,* 2007). The vector length of a test environment, which approximates the standard deviation, measures the magnitude of the environment's ability to discriminate among genotypes (i.e., the differentiation power). Shorter vector length of an environment indicates weak differentiation power (Yan & Holland, 2010). Hence, the locations with short vector length i.e., Faisalabad, Okara, Mamu Kanjan, Samundri and Kamalia may be regarded and treated as unique locations. In contrast, the locations with longer vector length i.e., Sargodha, Jhang and Depalpur were more powerful in differentiating maize hybrids. Environments or locations with longer vector length and smaller angle with AEC are ideal for selection of superior hybrids. In this study, Depalpur was the most discriminating and representative test environment owing to its long vector length and small angle with AEC abscissa.

Environments could be grouped into three types on the basis of their discriminating ability among hybrids and representativeness of test locations as suggested by Yan *et al.,* (2007). *Type 1* environments have a short vector length, and thus provide little or no information on the genotypes; these cannot be used as test environments. *Type 2* environments have a longer vector length and a smaller angle with AEC abscissa, and are considered the most suitable for the selection of superior genotypes. *Type 3* environments have a longer vector length coupled with larger angles with the AEC abscissa; therefore, they cannot be exploited in selection of superior hybrids but could be useful in identifying unstable hybrids. According to this classification, Faisalabad, Okara, Mamu Kanjan, Samundri and Kamalia were type-1 environment and thus were not suitable for use as test environments. These locations could be dropped, to reduce field testing costs without losing valuable information. Depalpur and Jhang were type-2 environments and are therefore appropriate for the section of superior genotypes owing to their high discriminativeness and representativeness. Sargodha, Toba Take Sing and Khanewal were type-3 environments and thus could not be applied in selection of first-rated hybrids but could be used in rejecting unstable genotypes. The findings of current study were similar to the results obtained by Oyekunle *et al.*, (2017) and Mafouasson *et al.,* (2018) who also used GGE biplot analysis in dissecting the genotype × environment interaction among single cross maize hybrids in the test locations of Nigeria and Cameron, respectively. Both the studies found GGE biplot helpful in the selection of ideal genotypes and test sites. The superior hybrids found in this study were also found to be the most promising hybrids by Yousaf *et al.*, (2017) and Yousaf *et al.,* (2018). Hence, these hybrids could be released for general cultivation in the core maize growing areas of Pakistan.

Conclusion

Significant ($p<0{\cdot}01$) differences were observed between maize hybrids, environments and their interaction. The GGE-biplot analysis disclosed the existence of two mega environments with two winning hybrids (FH-1046 and YH-5482). In these two hybrids, FH-1046, was the most productive hybrid but had low stability across the environments; in contrast, YH-5482 was an average productive maize hybrid but was most stable across the test environments. The locations i.e., Jhang and Depalpur were the most discriminative test environments. However, Depalpur was the closest to the AEC line, making it the ideal environment for hybrid comparison. The GGE-biplot methodology was found effective in identification and recommendation of maize hybrids for specific growing regions, taking into account the specificities of hybrids and growing environments.

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