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RESEARCH ARTICLE

Assessment of genotype × environment interaction and yield stability of grain maize (*Zea mays* L.) hybrids

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ABSTRACT

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Understanding the genotype × environmental interaction in the maize (*Zea mays*) breeding programs is necessary for finding high yielding and stable yield genotypes for different environmental conditions, enhancing breeding efficiency and crop productivity. To identify early-maturing maize hybrids that possess both high yield and yield stability, 11 hybrids including four promising three-way crosses and seven promising single crosses along with three single-cross hybrids (cv. Dehghan, cv. Fajr, and cv. Koosha) as control were evaluated across nine locations over two consecutive growing seasons (18 environments). The experimental design was randomized complete blocks with four replications. Phenological traits including silking, anthesis and physiological maturity dates, as well as grain yield, and yield components were measured and recorded. Combined analysis revealed significant effects of hybrid, growing season, location and their interaction on grain yield, emphasizing on the necessity of multi-environment trials to identify superior and stable yield grain maize hybrids. Grain yield showed positive correlation with all traits, except for cob percentage and kernel moisture content. The yield stability analysis using different yield stability indices showed high variation among hybrids. The hybrids were ranked based on grain yield and eight stability indices. Hybrids H, H11, H2, H4 and H5 achieved higher rank and were grouped as stable yield hybrids. The GGE biplot divided nine experimental locations into two major sectors and identified H8, H11, H10, H5 and H4 as winning hybrids adapted to specific environments. The first sector included Karaj, Miandoab, Kerman, Moghan and Sari with H11 and H8 and H4 as the winning hybrids, and the second sector comprised Shiraz, Isfahan, Kermanshah and Mashhad where H5 and H10 were the best-performing hybrids. The visualization of the ideal genotype demonstrates that H4 followed by H11 were located in close proximity to the ideal genotype. The single cross hybrid H11 (KE 76009/312 × K 1264/5-1) and the three-way cross hybrid H4 (KE 77008/1 × KSC260) performed significantly different from the control hybrids, producing the highest grain yield of 11.447 and 11.238 t ha^{-1}, respectively. The GGE biplot and complementary yield stability analyses consistently identified H11 and H4 (from the FAO group 400) as desirable hybrids with high stable grain yield, therefore suitable for being commercially released.

Keywords: maize, early maturity, stable yield genotypes, specific adaptation, GGE biplot analysis

INTRODUCTION

Iran's annual demand for maize (*Zea mays* L.) kernel is about 7.5 million tons for the livestock and poultry industry. Approximately one-fifth of this demand is produced domestically, while the remaining is met through imports from other countries. The area of maize cultivation, as grain and forage, increased from approximately 64,000 hectares in 1992 to 350,000 hectares in 2019 highlighting the importance of this crop in food security of the country. But the cultivation area of grain maize has declined in some regions, possibly due to water resources limitation and reduced rainfall in the past decade (Estakhr *et al.,* 2015; FAOSTAT, 2019).

Maize farmers grow single-cross hybrids in different parts of Iran. Maize breeding strategies are concentrated on developing of grain maize hybrids with high stable yields adapted to different environments and appropriate physiological maturity (FAO groups 200-500). Breeding for early maturity and high stable yield hybrids is the main objective in breeding programs of maize in the Seed and Plant Improvement Institute (SPII) and some provincial research centers in Iran. Late-maturing maize hybrids require more water because of their longer life cycle.

Late maturing maize hybrids may encounter cold specifically during grain filling period, hence yield reduction in most parts of Iran. Due to the shorter growth period, early-maturing maize hybrids require less irrigation water, and can be grown in areas where they are adapted and produce high stable yield (Estakhr and Dehghanpour, 2011). The introduction of early-maturing maize hybrids with high stable grain yield can save irrigation water consumption, reduce economic losses, and prevent the reduction of maize production in maize growing areas

Genotype × environment interactions (GEI) are important in evaluation of plant genotypes, as they affect yield stability and complicate the selection of desirable genotypes that are suitable for particular regions (Hebert *et al.,* 1995). The performance of crops depends on genotype (G), environment (E), and GEI (Yan *et al.,* 2007). A thorough comprehension of GEI is indispensable for the accurate assessment of yield stability and for the efficient selection processes in plant breeding programs (Sabaghnia *et al.,* 2008). Investigations into GEI facilitate the identification of factors that govern the responses of genotypes to fluctuating environmental conditions (Allard and Bradshaw, 1964).

Yield stability assessments are typically employed to identify genotypes that produce stable yield across different environmental conditions. A number of models has been proposed for statistical analysis of yield stability, each elucidating distinct dimensions of GEI, thereby indicating that no singular methodology can sufficiently account for genotype performance across environments. Notable examples encompass the ecovalence, which quantifies the contribution of each genotype to the total sum of squares of GEI (Wrick, 1962), and the variance of genotype stability i ($\sigma^2 i$), representing variation in its performance across environments, following the exclusion of the main effects of environmental means (Shukla, 1972).

Other noteworthy statistics include the regression coefficient (b_i), which indicates the genotype's response to the environmental index derived from the mean yield of all genotypes within each environment (Finlay and Wilkinson, 1963). The coefficient of variation (CVi) introduced by Francis and Kannenberg (1978), along with mean yield and environmental variance, aid in evaluating the sensitivity of a genotype to environmental variations. Plaisted and Peterson (1959), suggested the component of variance of genotype-by-environment interactions (θ_i) to assess interactions among possible genotype pairs (Plaisted, 1960). Additionally, Kang's rank-sum (KR) statistic integrates both yield and σ^2_i as criteria for selection (Kang, 1988). Ghaed-Rahimi *et al.,* (2014), implemented various statistical analyses, including the CVi (Francis and Kannenberg, 1978), Wrick's ecovalence (Wrick, 1962), Shukla's variance (Shukla, 1972), and the regression coefficient of Eberhart and Russell (1966), to study genotype by environment interactions and yield stability in bread wheat (*Triticum aestivum* L.) as well as antioxidant variations under drought stress conditions.

The analysis of genotype main effects and genotype × environment interaction through biplot methodology (GGE biplot) serves as an analytical approach to study the interactions between genotype and environmental factors via graphical representation of multi-environment trials (MET), aimed to identifying stable yield cultivars. This analytical framework facilitates a visual exploration of the relationships among genotypes, testing environments and genotype × environment interactions (Yan *et al.,* 2000). Tahmasebi *et al.,* (2014) employed the GGE biplot analyses to evaluate the interaction of genotype and environment within the Seri M82/Babax wheat population and identity key criteria for selection of high stable yielding bread wheat genotypes under heat and drought stress.

GGE biplot analysis and additive main effects and multiplicative interactions (AMMI) analyses were utilized to discern stable yield genotypes and to dissect GEI in sugar beet (*Beta vulgaris* L.), maize and plantago (*Plantago* sp.) (Adu *et al.,* 2019; Shahriari *et al.,* 2018; Hassani *et al.,* 2018; Shiri, 2013). Collectively, these researchers employed sophisticated statistical methodologies to dissect the interaction of genotype by environment and to detect the most stable and high-performing genotypes across a spectrum of environmental conditions.

In grain maize breeding programs in Iran, newly developed hybrids undergo evaluation in multi-environment trials conducted across major maize growing areas for at least two growing seasons. The evaluation includes grain yield and yield stability of new hybrids, and selection and release of superior hybrids as new grain maize cultivars.

The main objective of the present study was to evaluate the GEI for grain yield and its stability of new early-maturing maize hybrids across nine maize growing regions in Iran.

MATERIALS AND METHODS

Fourteen early and medium-maturing maize hybrids, including four promising three-way crosses and seven promising single crosses selected from the 2013 and 2014 semi-final yield trails of grain maize breeding programs along with three commercial single-cross hybrids from FAO200 and FAO400 groups (cv. Dehghan, cv. Fajr, and cv. Koosha) were evaluated for grain yield and its stability in a multi-environmental trial (MET) in nine experimental field stations. The summarized information of grain maize hybrids is presented in Table 1.

Table 1. Summarized information of grain maize hybrids used in this study

No.	Hybrid	Pedigree	Hybrid type
1	H1	KE 77005/5 × KSC400	Three way cross
2	H2	KE 77008/1 ×KSC400	Three way cross
3	H3	KE 78012/221 × KSC400	Three way cross
4	H4	KE 77008/1 × KSC260	Three way cross
5	H5	KE 77008/1 × K 1264/5-1	Single cross
6	H6	KE 77008/1 × K 1263/1	Single cross
7	H7	KE 77004/2 × K 1264/5-1	Single cross
8	H8	NK 79 × K 1264/5-1	Single cross
9	H9	KE 75016/321 × K 1264/5-1 (KSC350)	Promising Single cross
10	H10	KE 76005/111 × K 1264/5-1 (KSC290)	Promising Single cross
11	H11	KE 76009/312 × K 1264/5-1 (KSC405)	Promising Single cross
12	H12	KE72012/12 × K 1263/1(KSC 400) (cv. Dehghan)	Single cross (check)
13	H13	K 1264/5-1 × K615/1(KSC 260) (cv. Fajr)	Single cross (check)
14	H14	K 1263/17 × S61 (KSC201) (cv. Koosha)	Single cross (check)

Experiments were carried out in 2016 and 2017 at nine stations of the agricultural and natural resources research and education centers of different provinces, located in different geographical and agro-ecological regions of Iran including; Shiraz, Isfahan, Karaj, Sari, Kerman, Moghan, Mashhad, Kermanshah and Miandoab (Table 2).

Experiments were conducted using randomized complete block design with four replications. The hybrids' seeds were planted on four beds of 6.08 meters length and 75 centimeters and hill spacing of 32 centimeters. The planting date at each location was between late May and late June (Estakhr and Choukan, 2011; Estakhr and Dehghanpour, 2011; Estakhr and Hiedari, 2012). Then plots were thinned, at the four-leaf stage, to maintain two plants in each hill, therefore, plant density was approximated 83,000 plants per hectare. Irrigation, weed control and management, and fertilizer applications were performed uniformly in all the plots at each location.

Throughout the growing seasons, phenological traits, including; days from planting to silking, days from planting to pollination, and days from planting to physiological maturity for each hybrid were recorded. Data collection occurred when 50% of the plants within each plot reached to these growth stages. In the post-pollination stage, both plant height (measured distance from the soil surface to the initial branch of the tassel) and ear height (measured distance from the soil surface to the upper ear node) were measured and recorded on ten randomly selected plants in each plot (Estakhr *et al.,* 2015).

Ear yield (kg $plot^{-1}$) was determined by weighing the dehusked harvested ears obtained from the two central rows (9.12 m^2) of each plot. The grain moisture of harvested plants and the cob percentage (calculated as cob weight multiplied by 100 divided by ear weight), were quantified, and grain yields were derived using Equation (1):

Table 2. Geographical and climatic information of the experimental locations

Province	City	Longitude	Latitude	Altitude (m)	Region in Iran	Climate type	Absolute maximum temperature (°C)	Absolute minimum temperature (°C)	Mean annual precipitation (mm)
Fars	Shiraz	52.43º E	29.46º N	1600	Southwest	Cold -temperate	43.2	-14.0	343.2
Isfahan	Isfahan	51.51 ºE	32.30º N	1545	Center	Cold- temperate and dry	40.6	-10.6	138.0
Alborz	Karaj	50.55º E	35.49º N	1270	North and center	Cold and temperate	42.0	-20.0	243.0
Mazandaran	Sari	52.58º E	36.32º N	15	North	Warm- temperate and humid	42.5	-5.2	977.0
Kerman	Kerman	57.01º E	30.16º N	1750	Southeast	Cold-temperate and dry	41.5	-15.1	117.0
Ardebil	Moghan	47.32º E	39.41º N	400	Northwest	Cold-semi-arid	40.0	-8.0	317.0
Khorasan	Mashhad	59.38º E	36.16º N	999	Northeast	Cold and dry	43.0	-23.0	210.0
Kermanshah	Kermanshah	47.06º E	34.20º N	1307	West	Cold-temperate	42.7	-12.4	475.0
West Azarbayjan	Miandoab	46.00º E	36.57º N	1290	Northwest	Cold-temperate	36.0	-20.0	289.0

$$GY=EY\times\frac{(100\text{-}CP)}{100}\times\frac{(100\text{-}GMP)}{(100\text{-}14)}\times\frac{10}{9.12} \quad (1)$$

Where GY indicates grain yield (t ha^{-1}) with 14% moisture, EY represents ear yield (kg m^{-2}), CP shows the cob percentage, GMP refers to grain moisture content (%) at the harvest time. The measurements of ear diameter, cob diameter, grain length (calculated as half of ear diameter minus cob diameter), thousand grain weights, the grain number in row, and the row number in ear were systematically measured and recorded following the harvest of ten randomly selected ears.

Data analysis

Combined analysis of variance (ANOVA) and mean comparisons using the Least Significant Difference (LSD) test, at the 5% probability level, for all locations and years were performed using the Statistical Analysis System (SAS) version 9.1. In addition, a correlation plot was generated to illustrate the relationships among the traits. Stable yield hybrids were identified using grain yield stability analysis. To assess grain yield stability the following stability indices were implemented:

Wricke's ecovalence, Wi^2 (Wrick, 1962), represents the contribution of each genotype to the sum of squares attributable to the genotype-environment interaction. The ecovalence (Wi) of the ith genotype is defined as its interaction with environments, which is squared and aggregated across environments. Consequently, genotypes exhibiting lower values demonstrate reduced deviations from the mean across environments, thereby indicating higher grain yield stability. Shukla's variance of stability (Shukla, 1972), refers to the yield stability variance of genotype i (σ^2_i) as its variance across environments after removing of the main effects of environmental means. Based on this statistical indices, genotypes characterized by minimal values are deemed to be of higher yield stability.

The deviation variance from regression, denoted as S^2d_i (Eberhart and Russell 1966), represents a widely employed index for the selection of stable yield genotypes, with genotypes exhibiting S^2d_i=0 deemed to be of the highest stable yield. The regression coefficient or slope, bi (Finlay and Wilkinson,1963), the coefficient of variation, CVi (Francis and Kannenberg, 1987), and stability indices associated with the variance of genotype-environment interaction, such as the mean variance component θ_i (Plaisted and Peterson 1959), the GEI variance component $\theta_{(i)}$ (Plaisted, 1960), and the Kang ranking (KR) (Kang, 1988), were also used in the analysis. Genotypes that are characterized by low CVi, low environmental variance (EV), and high mean yield would be identified as high stable yield genotypes. Also genotypes with elevated θ_i values are regarded as exhibiting greater yield stability (Plaisted, 1960).

Hybrids were systematically ranked considering mean grain yield and yield stability indices. Kang's rank-sum (KR) statistic integrates both yield and σ^2_i as criteria for selection. This index assigns a weight of 1 to yield and yield stability statistics to facilitate the identification of high- stable yield genotypes. The genotype that achieves the highest yield and the lowest σ^2_i is assigned the rank of 1. Then the ranks of yield and yield stability variance are compiled for each genotype, with those possessing the lowest rank-sum being regarded as the most favorable genotypes (Kang, 1988). Subsequently, the sum of ranks, the ranks mean, and the ranks standard deviation for each hybrid were computed, thereby facilitating the identification of more stable yield maize hybrids. Grain yield stability analyses were performed utilizing STABILITYSOFT, a new online software application (Pour-Aboughadareh *et al.,* 2019).

GGE biplot analyses were performed based on Yan *et al.,* (2000), and Yan and Tinker (2005), method. The GGE biplot shows both the performance and yield stability of genotypes across environments by combining genotype effects and GEI. This analysis is recognized as an efficacious method that employs principal component analysis (PCA) to evaluate multi-environment trials. This analytical approach permits a graphical representation of the associations among the tested environments and genotypes. The analysis of genotype-environment interaction (GEI) was performed using Genstat software version 15 (Payne *et al.,* 2012), utilizing the original dataset. In addition, a correlation plot was generated to illustrate the relationships among the traits.

RESULT AND DISCUSSION

The ANOVA showed significant differences among the hybrids in almost all the characteristics across locations (Table 3). However, it should be noted that the rankings of these hybrids and their traits varied across different locations (Table 4). The highest (13.607 t ha^{-1}) mean GY was at Shiraz and the lowest (7.653 t ha^{-1}) at Moghan and Sari (7.349 t ha^{-1}). In certain environments, the two-year average GY of the hybrids exhibited similarities. For instance, Isfahan and Kerman, as well as Kermanshah and Mashhad, had similar GY (Table 3). The other traits were also significantly different across test environments.

Table 3. Combined analysis of variance for studied traits of 14 maize hybrids across nine location and two growing seasons

		Mean of squares											
S. O. V.	d.f.	EH	PH	GNR	RN	DSM	DM	DS	GL	TGW	CP	GMC	GY
Location (L)	8	13938.75**	46658.72**	887.34**	11.58**	5320.67**	11170.36**	1793.61**	32.16**	55566.87**	159.57**	2312.25**	515.63**
Year (Y)	1	748.31*	5542.74**	0.49	1.88	171.68**	55.25*	32.14**	58.36**	39599.07**	70.88**	820.08**	126.95**
L × Y	8	1808.56**	3421.23**	261.62**	26.35**	1894.20**	1532.48**	414.31**	26.38**	42966.19**	187.30**	333.28**	65.16**
Rep (L× Y)	54	137.71	328.97	10.61	0.80	13.72	12.03	3.37	0.77	593.83	1.76	6.63	3.92
Hybrid (H)	13	3276.67**	3820.37**	161.20**	133.87**	122.80**	313.85**	128.65**	24.17**	12098.62**	63.95**	102.36**	24.00**
H × L	104	270.42**	445.02**	17.35**	2.23**	28.84**	35.33**	7.32**	1.43**	1718.49**	3.72**	11.10**	4.49**
H × Y	13	198.98**	238.66	8.38	20.53**	39.22**	34.36**	6.39**	4.38**	1708.91**	2.78**	14.08**	2.01**
H × Y × L	104	96.72*	227.43**	12.15**	1.63**	31.01**	25.68**	5.04**	0.95**	1188.20**	2.79**	3.99**	2.73**
Error	702	73.21	140.58	6.95	0.85	5.43	5.97	1.74	0.56	399.18	1.00	2.70	1.22
C. V. (%)		8.0	5.6	7.0	5.6	4.2	2.2	2.5	6.9	6.7	6.9	8.5	10.7

* and **: Significant at the 0.05 and 0.01 probability levels, respectively.

PH, plant height; EH, ear height; RN, row number; GNR, grain number per row; DSM, days from silking to physiological maturity; DM, days from planting to physiological maturity; DS, days from planting to silking; GL, grain length; TGW, thousand grain weight; CP, cob percent; GMC, grain moisture content; GY, grain yield.

Table 4. Mean comparison of different traits of maize hybrids studied at different locations

Location	EH (cm)	PH (cm)	GNR	RN	DSM (day)	DM (day)	DS (day)	GL (mm)	TGW (g)	CP (%)	GMC (%)	GY (t ha^{-1})
Shiraz	105.4	211.8	37.8	16.6	56.1	107.1	51.1	11.37	326.9	12.4	12.6	13.607
Isfahan	92.7	186.7	37.7	16.7	60.6	118.8	58.2	11.64	264.8	15.2	24.7	9.432
Sari	116.0	238.8	32.4	16.3	39.5	86.3	46.8	10.09	287.5	15.0	17.9	7.349
Kerman	91.0	188.3	35.1	15.8	58.5	114.0	55.5	10.48	273.7	13.5	22.1	9.207
Karaj	121.6	242.4	40.8	16.7	51.9	104.4	52.5	10.48	302.7	14.8	16.2	11.821
Moghan	104.0	203.0	36.1	16.8	56.5	106.1	49.5	10.59	331.9	14.6	27.1	7.653
Mashhad	106.2c	207.2	37.6	16.2	62.6	116.1	53.6	10.93	290.0	15.4	18.8	10.789
Miandoab	121.7	230.5	41.6	16.3	57.2	116.5	59.4	11.00	301.5	12.8	18.2	12.614
Kermanshah	103.7	204.7	38.8	16.5	60.4	113.5	53.1	11.54	307.3	15.7	16.4	10.909
Mean	106.92	212.6	37.5	16.5	55.9	109.2	53.3	10.90	298.5	14.4	19.3	10.376
LSD (5%)	3.14	4.86	0.87	0.24	0.99	0.93	0.49	0.24	6.53	0.36	0.69	0.53

PH, plant height; EH, ear height; RN, row number; GNR, grain number per row; DSM, days from silking to physiological maturity; DM, days from planting to physiological maturity; DS, days from planting to silking; GL, grain length; TGW, thousand grain weight; CP, cob percent; GMC, grain moisture content; GY, grain yield.

Days to physiological maturity of the hybrids were relatively similar (about 116 days) at Mashhad and Miandoab while that in Sari was different from the other locations (Table 4). The lowest GMC (%) at harvest was at Shiraz and it was significantly different from the other locations. Due to the increase in drying costs, there is a real demand for grain maize hybrids with faster grain dry down properties that can be harvested with low grain moisture content. Environmental conditions, including temperature and humidity, affect the rate of grain dehydration and grain dry down (Zhang *et al.,* 2024). Variations in these conditions across different locations of this experiment led to differences in GMC, as the important and effective characteristic of grain quality, at harvest (Table 4).

In a previous study it was shown that the mean moisture content of maize grain after harvest was 2.2% higher than that recorded before harvest (Li *et al.,* 2021). Furthermore, this notable increase in grain moisture content was exclusively observed when the pre-harvest grain moisture content exceeded 23.9%. In contrary, there was no significant difference between the pre- and post-harvest samples when the moisture content prior to harvest was below 23.9% (Li *et al.,* 2021). In our investigation, the GMC at the most of locations was determined to be 19.3%, thereby indicating its suitability for harvest and quality assessment. In Moghan and Isfahan, the moisture content of grain exceeded 23.9%. The two-year average GMC of the maize hybrids across all locations was less than 23.9% (Table 4).

The combined analysis of variance revealed that the effect of location was significant for all traits, indicating variability among the test environments (Table 3). The effect of year was also significant for most of the studied traits, except for row number (RN) and grain number per row (GNR). Additionally, the interaction between hybrid and location was significant at the 1% probability level, indicating that the response of the evaluted maize hybrids varied across different environments. The variation among the hybrids for studied traits and the potential for the selection of stable yield genotypes has resulted from the significant effects of genotype and the GEI (Crossa, 1990; Dehghani *et al.,* 2008; Ghaed-Rahimi *et al.,* 2014). The significant effects of hybrid, year, location and their interactions (H × Y, H × L and H × Y × L) for grain yield revealed substantial genetic variability among the hybrids and strong influence of temporal and spatial environmental factors as well as their interactions. These results emphasize the necessity of multi environmental trials to reliably identify superior and stable yield hybrids (Table 3).

Hybrids H11 and H4 yielded 11.447 and 11.238 tons per hectare of grain with 14% moisture content, respectively (Table 5). H11 and H4 had higher grain yield, which were more than the yield of all control cultivars (cv. Dehghan, cv. Fajr and cv. Koosha). Following these two hybrids, H10, H8 and H2 hybrids performed superior compared with the control cultivars. CvKoosha and Fajr control cultivars along with hybrids H3 and H9 which produced a grain yield of 9.7 tons per hectare with 14% moisture content showed a lower yield compared to other hybrids (Table 5).

The difference in the days to physiological maturity between H14 (earliest hybrid with 105 days), and H8 (the latest-maturing hybrid with 113 days), was approximately four days in Sari and extended to 14 days in Karaj (data not shown). Notably, in this experiment, even a single day variation in the physiological maturity of the hybrids was significant (Table 5). These hybrids developed through the national maize breeding programs in Iran from early-maturing lines and were categorized within the FAO250 to FAO450 groups, which necessitate maturation duration of 100–120 days to attain physiological maturity across diverse regions in Iran. The results of our study, particularly those pertaining to the duration from planting to physiological maturity (109.2) and the GMC at the harvest time (19.3%), confirm these findings (Table 5). In Iran, about 50 percent of maize grain is produced from second cropping following wheat and barley harvest, and it is recommended that farmers adopt early-maturing maize cultivars for second cropping to prevent autumn cold damage in grain filling stage (Estakhr *et al.,* 2015). Furthermore, early-maturing cultivars require less water than late-maturing cultivars, due to their shorter life cycle (Estakhr *et al.,* 2015; Rahimi Jahangirlou *et al.,* 2021).

Grain yield of the evaluated hybrids showed positive correlation with all traits except cop percent and grain moisture content (Fig. 1). The highest positive correlation of the grain yield was estimated with grain number per row The highest positive correlation was between days to physiological maturity and days to silking, and the highest negative correlation was between grain yield and grain moisture content (Fig. 1).

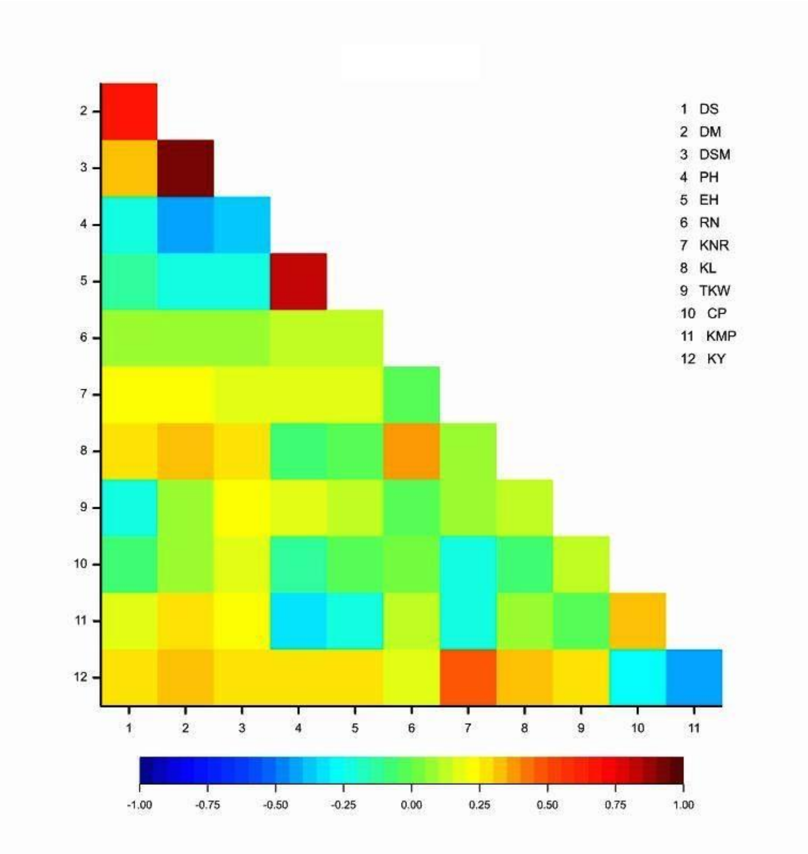

Fig. 1. Correlation plot for the relationship between different trait. DS: days to silking; DM: days to physiological maturity, DSM: days from silking to physiological maturity, PH: plant height; RN: row number; KNR, grain number per row; KL, grain length; TKW: thousand grain weight, KMP: grain moisture content; CP: cob percent, and KY: grain yield

Biplot analysis revealed detailed correlation patterns among traits and hybrids (Fig. 2). Acute angel between grain yield, grain number per row, thousand grain weight and row number vectors indicated strong positive correlations among these traits, particularly between grain yield and grain number per row (Fig. 2). In contrary, cob percent and grain moisture content exhibited wide angles in relation to grain yield, suggesting negative association between these traits. Cob percentage and grain moisture content showed an approximate 180-degree angles with plant height and ear height, confirming strong negative relationship (Fig. 2), similar to previous report for different maize hybrids (Estakhr *et al.,* 2015).

Other investigations identified grain number er row, ear diameter, and 1000 grain weight as key yield-determining traits. Plant height, cob length and cob diameter and 1000 grain weight showed strong positive correlation with maize grain yield, though cob diameter proved less reliable than other grain yield components (Raut *et al.,* 2017; Yahaya *et al.,* 2021). Path analysis indicated that the most substantial effect on grain yield was attributed to 1000 grain weight, followed by the grain number per row, ear length, and ear diameter. The majority of traits had positive indirect influences through 1000 grain weight, row number and grain number per row(Rafiq *et al.,* 2010; Kovačević *et al.,* 2024). Consistent with our correlation coefficient findings, the results from path analysis in a different study indicated that 1000 grain weight possesses the strongest positive direct effect on grain yield, however direct effects were negative for cob diameter (Rafiq *et al.,* 2010; Kovačević *et al.,* 2024). Aman *et al.* (2020), similarly reported significant positive correlations between grain yield and ear height, plant height, grain number per row and 1000 grain weight.

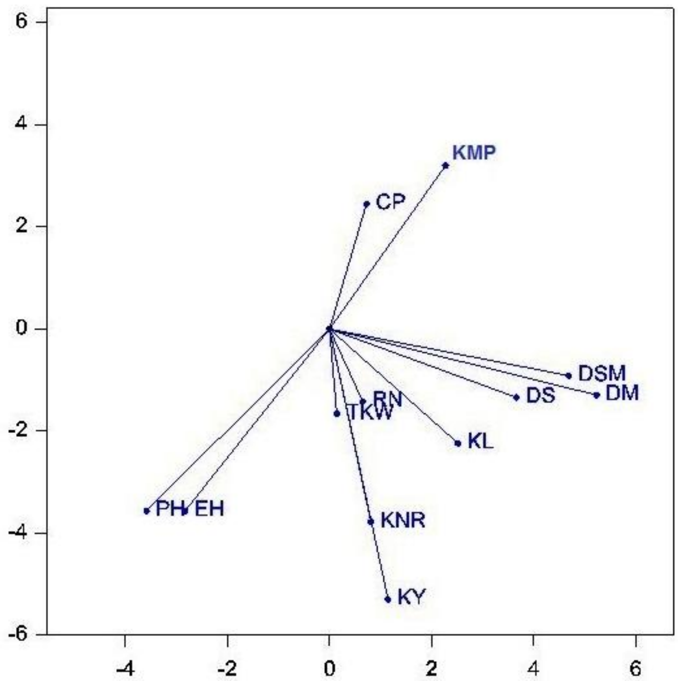

Fig. 2. Biplot for the relationship between different traits in maize hybrids. DS: days to silking, DM: days to physiological maturity, DSM: days from silking to physiological maturity, PH: plant height, RN: row number, KNR: grain number per row; KL: grain length, TKW, thousand grain weight; KMP: grain moisture content, CP: cob percent, KY, grain yield

Grain stability analysis

Grain stability analysis using various stability indices was performed to assess the stability of grain yield of early grain maize hybrids (Table 5). Based on Wrick's ecovalence (Wrick's, 1962), a hybrid exhibiting a lower value, which signifies reduced deviation from the average across all environments, is regarded as more stable yiled genotype. Hence, the hybrid which had the lowest value of ecovalence was assigned the highest rank in terms of grain yield stability. Hybrids demonstrated low ecovalence indicated less changes across environments, and as a result, are considered grain yield stable.

Using Wrick's ecovalence (1962), the hybrids identified with highest stable grain yield were H1, H6, and H14, with respective values of 7.87, 9.25, and 9.71 (Table 5). These hybrids did not attain the highest rank regarding mean grain yield, securing positions 8th, 10th, and 14th, respectively (Table 6). In accordance with the ecovalence methodology, the hybrids identified with the most unstable grain yield were H13 and H3, with values of 22.02 and 19.24, respectively. These two hybrids ranked 9th and 12th for mean grain yield (Tables 5 and 6).

Using Shukla stability variance index (σ^2_i), hybrids that showed the lowest values of this index were of higher stable grain yield and ranked higher. The highest stable grain yield hybrids were H1 (σ^2_i =0.47) and H6 (σ^2_i =0.56), respectively. Regarding the Kang ranking index (KR), which integrates the mean grain yield (Y) of the hybrid along with the Shukla stability index (σ^2_i), the hybrid that attained the maximal yield in conjunction with the minimal σ^2_i were assigned the higher ranks. Accordingly, the hybrids exhibiting the greatest grain yield stability were H11 (KR = 6) and H1 (KR = 9), respectively. In accordance with the Kang,s rank index, the hybrids designated with the least grain yield stability included; hybrid H3 as well as the control cultivars (H12, H13, and H14) (Table 5).

Regression coefficient (bi), identifies hybrids of high superior performance, adaptability and yield stability, and is characterized by coefficients approaching the value of one. If the regression coefficients of a hybrid does not exhibit significant deviation from the value of one, it can be inferred that such a hybrid is widely adapted across all environments (Kang 1988). In contrary, if the regression coefficient exceeds value of one, it signifies an increased degree of adaptability with favorable environments. However, if the regression coefficient is below value of one, it indicates an enhanced level of adaptation to adverse environments. In our study, the ranking is established based on the degree of deviation from the value of one. Thus, H10 has been assigned the first rank. Additionally, hybrids; H1, H6, H14, H9, and H11 have been recognized as the higher grain yield stable hybrids based on two stability indices: θ_i, representing the mean variance component as delineated by Plaisted and Peterson (1959), and $\theta_{(i)}$, indicating of the variance of GEI as proposed by Plaisted (1960).

Therefore, variations in stable grain yield hybrids arise when distinct indices are utilized. Previous studies have similarly indicated that the rankings of maize cultivars vary according to the different yield stability indices employed (Changizi *et al.,* 2014). In one study, the efficiency of different models and statistical approaches for studying yield stability across different irrigation were assessed graphically and mathematically (Ghaed-Rahimi *et al.,* 2014). The findings suggested that just one statistical model is not sufficient for the studying genotype by environment interactions, and a synthesis of multiple statistical models proves to be more reliable in GEI analysis (Ghaed-Rahimi *et al.,* 2014). Nevertheless, through the computation of the aggregate index rankings and mean rankings for the hybrids (grain yield and eight indices), it can be concluded that hybrids with the lowest mean rank using all indices are regarded as hybrids with higher stable yield.

The range of sum of ranks varies from 22 (in H1) to 109 (in H3), while the mean ranks range from 2.4 (in H1) to 12.1 (in H3). Hybrids H1 and H11, with sum of ranks of 22 and 40 respectively, demonstrate the highest rank and are classified as hybrids with higher stable grain yield. However, hybrids H3 and H13, with sum of ranks 109 and 105, respectively, show the lowest rank and are considered hybrids with unstable grain yield. Hence, H1 hybrid was recognized with highest grain yield stability, despite being ranked eighth for mean grain yield across all test environments (18 environments) and was not among the top three hybrids in any specific environment (Table 7). The findings of our study indicate that the online software that introduced by Pour-Aboughadareh *et al.* (2019) called STABILITYSOFT, serves as an invaluable tool for agronomists and plant breeders who manage substantial volumes of quantitative data and need accessible software to analyze genotype × environment interactions (GEI) and precisely compute yield stability indices.

Considering the mean grain yield of all hybrids across all environments (10.376 tons per hectare), with grain moisture content of 14% (Table 5), and grain yield of hybrids in each environment (Table 7), it becomes evident that grain yield certain hybrids exceeded the overall mean grain yield. For example, hybrids; H11, H4, H10, H8, H2 and H5 had grain yield exceeded the total mean grain yield. Notably, hybrids H11(designated as KSC405) which is derived from the lineage KE 76009/312 × K 1264 / 5-1, with hybrid H2 derived from the lineage KE 77008/1 × KSC400, and hybrid H5, derived from KE 77008/1 × K 1264/5-1, demonstrated considerable grain yield stability.

These hybrids had very good uniformity, complete ear inoculation, fully developed ear husk, robust plant stems and excellent stay green characteristics. Additionally, these hybrids also exhibited uniform ear size and ripening time, were disease-free, and resistant to plant lodging. The main criteria for the selection of grain maize hybrids includes; mean grain yield and yield stability, which are instrumental for releasing as new grain maize cultivars. A maize hybrid is considered of stable high grain yield when it performs consistent across diverse environmental conditions (Shojaei *et al.,* 2021; Djurovic *et al.,* 2014; Changizi *et al.,* 2014). Gaed-Rahimi *et al.* (2014) reported that the most advantageous of bread wheat cultivars for cultivation under a broad spectrum of environmental conditions are characterized by both high grain yield and yield stability, which is in agreement with our findings,.

The hybrid H11 demonstrated superior performance across four distinct environments (specifically, Shiraz and Moghan in the first year, and Sari and Miandoab in the second year) and ranked among the top three hybrids in 12 environments including; the first year in Shiraz, Sari, Kerman, Karaj, Moghan, and Kermanshah, as well as the second year in Isfahan, Sari, Kerman, Karaj, Miandoab, and Kermanshah. The hybrid H4 demonstrated the highest grain yield in three environments and was classified among the top three hybrids in eight environments (Table 7). These two hybrids were identified as the outstanding selections concerning the aforementioned traits, and with H2 and H1, have been nominated for investigation under farmer's agronomic conditions, and are of potential to be commercially releases as new grain maize cultivars for target environments.

Table 5. Grain yield stability indices for grain maize hybrids in 18 environments (9 locations in two growing seasons, 2016 and 2017)

Hybrid	Pedigree	GY (t ha^{-1})	W_i^2	σ^2_i	S^2d_i	b_i	CVi	$\theta_{(i)}$	θ_i	*K*R
H1	KE 77005/5 × KSC400	10.183	7.87	0.47	1.11	0.968	22.30	0.910	0.72	9
H2	KE 77008/1 × KSC400	10.695	13.76	0.87	1.94	1.043	23.39	0.879	0.91	12
H3	KE 78012/221 × KSC400	9.755	19.24	1.25	2.68	0.924	23.78	0.850	1.09	25
H4	KE 77008/1 × KSC260	11.238	15.58	1.00	2.13	1.086	23.20	0.869	0.97	12
H5	KE 77008/1 × K 1264/5-1	10.670	13.39	0.85	1.62	1.154	25.41	0.881	0.90	12
H6	KE 77008/1 × K 1263/1	9.980	9.25	0.56	1.12	1.129	26.22	0.902	0.77	12
H7	KE 77004/2 × K 1264/5-1	10.352	14.30	0.91	1.78	1.146	26.14	0.876	0.93	16
H8	NK 79 × K 1264/5-1	10.766	17.32	1.12	2.46	1.029	23.35	0.860	1.02	16
H9	KE 75016/321 × K 1264/5-1 (KSC350)	9.762	10.89	0.67	1.01	0.789	19.28	0.894	0.82	15
H10	KE 76005/111 × K 1264/5-1 (KSC290)	10.862	15.67	1.00	2.23	1.023	22.86	0.869	0.97	14
H11	KE 76009/312 × K 1264/5-1 (KSC405)	11.447	11.08	0.69	1.42	1.116	22.82	0.893	0.83	6
H12	KSC 400 (KE72012/12 × K1263/1)	9.753	13.98	0.89	1.93	0.925	23.12	0.878	0.92	21
H13	KSC 260 (K1264/5-1 × K615/1)	10.073	22.02	1.44	2.25	0.729	18.82	0.835	1.17	23
H14	KSC201 (K 1263/17 × S61)	9.722	9.71	0.59	1.34	0.939	22.93	0.900	0.78	17
	Mean	10.376								

GY: mean grain yield 18 environments, W_i^2: Wrick ecovalence, σ^2_i: Shukla stability variance, s^2d_i: deviation variance from regression, bi: regression coefficient, CVi: environmental changes coefficient, θ_i: mean variance component of Plaisted and Peterson, $\theta_{(i)}$: Plaisted's GE variance, KR: Kang's ranking,

Table 6. Hybrids ranking based on yield stability indices

Hybrid	Pedigree	GY	W_i^2	σ^2_i	s^2d_i	CVi	*K*R	$\theta_{(i)}$	θ_i	b_i	Sum of ranks	Standard deviation	Average of ranks
H1	KE 77005/5 × KSC400	8	1	1	2	3	2	1	1	3	22	2.2	2.4
H2	KE 77008/1 × KSC400	5	7	7	9	10	3	7	7	4	59	2.2	6.6
H3	KE 78012/221 × KSC400	12	13	13	14	11	14	13	13	6	109	2.5	12.1
H4	KE 77008/1 × KSC260	2	10	10	10	8	3	10	10	8	71	3.2	7.9
H5	KE 77008/1 ×K 1264/5-1	6	6	6	6	12	3	6	6	12	63	3.0	7.0
H6	KE 77008/1 × K 1263/1	10	2	2	3	14	3	2	2	10	48	4.7	5.3
H7	KE 77004/2 × K 1264/5-1	7	9	9	7	13	9	9	9	11	83	1.9	9.2
H8	NK 79 × K 1264/5-1	4	12	12	13	9	9	12	12	2	85	3.9	9.4
H9	KE 75016/321 × K 1264/5-1 (KSC350)	11	4	4	1	2	8	4	4	13	51	4.1	5.7
H10	KE 76005/111 × K 1264/5-1 (KSC290)	3	11	11	11	5	7	11	10	1	70	3.9	7.8
H11	KE 76009/312 × K 1264/5-1 (KSC405)	1	5	5	5	4	1	5	5	9	40	2.4	4.4
H12	KSC 400 (KE72012/12 × K1263/1)	13	8	8	8	7	12	8	8	7	79	2.2	8.8
H13	KSC 260 (K1264/5-1 × K615/1)	9	14	14	12	1	13	14	14	14	105	4.3	11.7
H14	KSC 201 (K 1263/17 × S61)	14	3	3	4	6	11	3	3	5	52	4.0	5.8

GY: mean grain yield 18 environments, W_i^2: Wrick ecovalence, σ^2_i: Shukla stability variance, s^2d_i: deviation variance from regression, bi: regression coefficient, CVi: environmental changes coefficient, θ_i: mean variance component of Plaisted and Peterson, $\theta_{(i)}$: Plaisted's GE variance, KR: Kang's ranking.

Table 7. Mean grain yield (t ha^{-1}) of grain maize hybrids in different locations in two growing seasons (2016 and 2017)

	Shiraz		Isfahan		Sari		Kerman		Karaj		Moghan		Mashhad		Miandoab		Kermanshah	
Hybrid	Y1	Y2	Y1	Y2	Y1	Y2	Y1	Y2	Y1	Y2	Y1	Y2	Y1	Y2	Y1	Y2	Y1	Y2
H1	14.61	11.89	7.94	8.98	7.80	6.99	9.18	9.59	11.37	11.19	7.92	7.42	10.07	10.43	14.47	12.85	10.86	9.74
H2	15.61	10.48	10.22	10.71	7.38	6.18	11.07	10.14	12.40	13.15	8.19	6.96	11.70	10.11	14.39	12.92	11.08	9.84
H3	14.43	9.45	6.57	10.37	6.31	6.34	9.82	10.13	12.04	11.40	8.29	7.24	9.77	9.88	13.66	9.29	11.51	9.09
H4	15.28	14.06	8.64	12.16	8.46	7.10	10.51	9.64	11.84	12.50	7.55	8.65	11.44	10.20	15.58	14.76	11.80	12.12
H5	16.45	12.12	9.70	10.64	8.30	4.44	9.90	9.30	12.32	12.49	7.48	7.30	13.06	10.99	12.44	12.70	11.64	10.81
H6	16.26	10.81	7.04	10.80	7.39	5.83	7.63	9.32	12.05	12.22	7.20	6.88	11.31	10.86	11.85	11.92	10.66	9.63
H7	15.91	11.16	7.30	9.33	7.58	6.86	8.99	9.49	11.80	11.58	7.55	7.49	11.11	9.44	15.38	13.94	10.11	11.30
H8	16.78	12.15	7.30	11.15	9.21	7.83	8.37	8.64	13.48	12.07	8.89	9.50	11.18	10.38	15.02	12.09	10.06	9.69
H9	14.76	10.71	8.70	9.84	8.55	7.80	8.72	8.25	10.83	9.87	6.75	7.18	10.65	9.21	11.05	11.02	11.48	10.36
H10	16.14	11.84	8.27	11.14	8.41	6.32	9.11	8.59	12.84	11.41	8.68	8.77	11.48	11.98	13.98	10.60	12.36	13.58
H11	18.06	12.30	8.84	11.55	8.55	8.81	10.70	10.10	13.08	12.51	8.93	7.51	11.14	10.61	14.27	14.90	12.20	11.98
H12	14.43	12.64	9.47	9.54	6.95	5.93	9.31	7.85	11.14	11.77	6.40	7.21	10.40	10.67	10.72	10.68	11.36	9.08
H13	14.70	12.33	9.70	9.01	8.66	7.79	8.62	8.84	10.95	11.27	7.29	7.87	12.41	10.40	10.83	9.46	10.00	11.17
H14	14.52	11.13	9.05	10.14	7.19	6.82	8.01	7.97	11.68	9.73	6.17	6.99	10.67	10.55	12.38	10.06	12.02	9.91
LSD (5%)	1.57	1.81	1.64	1.53	1.29	1.1	2.24	2.05	1.5	1.51	1.04	1.02	1.44	1.65	1.28	2.58	1.13	1.10

Y1: First year, Y2: Second year

GGE biplot analysis

The GGE biplot analysis indicated that 60.99% of the total variations was attributed PC1 and PC2 (43.94% and 17.05%, respectively) caused by G + GEI based on grain yield of 14 grain maize hybrids across 18 environments (Fig. 3). The polygon view of the GGE biplot clearly discriminated the test environments and identified the winning hybrids for each sector. The hybrids located at the vertices of the polygon were H5, H10, H11, H8, H7, H3, H9, and H14 (Fig. 3)**.** Among these, H5, H10, H11, and H8 were associated with specific environments and thus represented the winning genotypes in their respective sectors, while H3, H7, H9, and H14**,** although positioned at the vertices, were not associated with any environment, and therefore did not represent winners in any environment.

The nine test environments were divided into two major sectors. The first sector included; Karaj, Miandoab, Kerman, Moghan and Sari with H11 and H8 and H4 as the winning hybrids, demonstrating their superiority in these locations. Notably, the Karaj environment fell directly on H11, indicating that this hybrid had the highest grain yield in Karaj. The second sector included; Shiraz, Isfahan, Kermanshah and Mashhad, where H5 and H10 were the best-performing hybrids. Although Sari that was placed inside the polygon can be considered as a distinct sector that was closer to H2, which indicating its relative superiority in this location. It is noteworthy that all the aforementioned hybrids performed superior to the control hybrids (H12, H13, and H14), which in the scatter plot were situated in the lower left quadrant.

These results suggest that it might be possible to reduce the number of test locations by eliminating some similar environments, based on the patterns observed in the biplot for early-maturing grain maize hybrids. Similar to our findings, the GGE biplot analysis discerned ideal experimental sites for selecting superior early-maturing grain maize hybrids in six locations in Ghana and eight locations in Nigeria (Oyekunle *et al.,* 2017).

Results from complementary grain yield stability analyses using various stability indices (Wricke's ecovalence, and Shukla's variance and etc.) and grain yield confirmed that hybrids; H11, H2, H4, H5, and H1 had the higher stable grain yield across environments. Although the polygon view of the GGE biplot identified H8, H11, H10, H5 and H4 as winning hybrids in some specific environments, results from other stability analyses consistently ranked H4, H5, and H11 hybrids among the higher stable grain yield genotypes across environments. This indicated that H4, H11, and H5 not only performed well in certain environments but also exhibited wide adaptation and grain yield stability across the test locations**.**

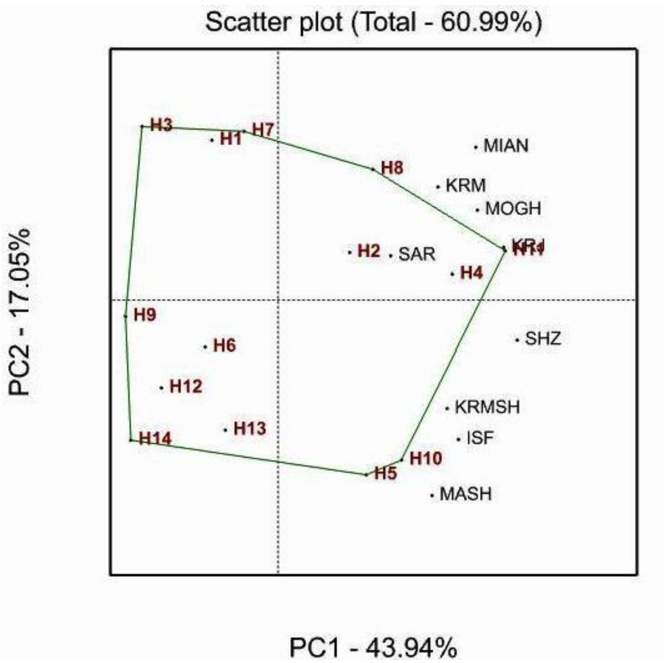

Fig. 3. GGE biplot polygon for grain maize hybrids (H1-H14) and environments based on grain yield of hybrids. Environmental codes; MIAN, KRM, MOGH, KRJ, SAR, SHZ, KRMSH, ISF, and MASH represent the research field stations; Miandoab, Kerman, Moghan, Karaj, Sari, Shiraz, Kermanshah, Isfahan and Mashhad, respectively

Predicated ranks of the 14 maize hybrids using mean of grain yield and yield stability indices across nine environments in two growing seasons (Fig. 4). The Average Environment Coordinate (AEC) is conceptualized as a line traversing the biplot origin, determined by the scores mean of PC1 and PC2 for all environments (Yan and Kang, 2002). The proximity of a point to a concentric circle signifies a higher mean grain yield. The grain maize yield stability is represented by a line that is perpendicular to the AEC and passes through the origin. Therefore, the axis indicated by an arrow and a circle is known as the stability axis, with any hybrid in close vicinity to this axis demonstrating higher stability.

The subsequent axis shows the mean grain yield of the hybrids, where hybrids positioned to the left of this line exhibit grain yields that are inferior to the overall mean grain yield. In other words, the horizontal axis represents the mean of environmental conditions, while the origin symbolizes yield stability; thus, each hybrid that is situated in proximity to this axis is likely to exhibit greater grain yield stability. A biplot representation of average environmental coordinates, as utilized within the GGE biplot, represents a suitable approach in the assessment of yield stability, which was employed by Shojaei *et al.* (2022), in their analysis of different early and late-maturing maize genotypes across multi-environments in Iran,

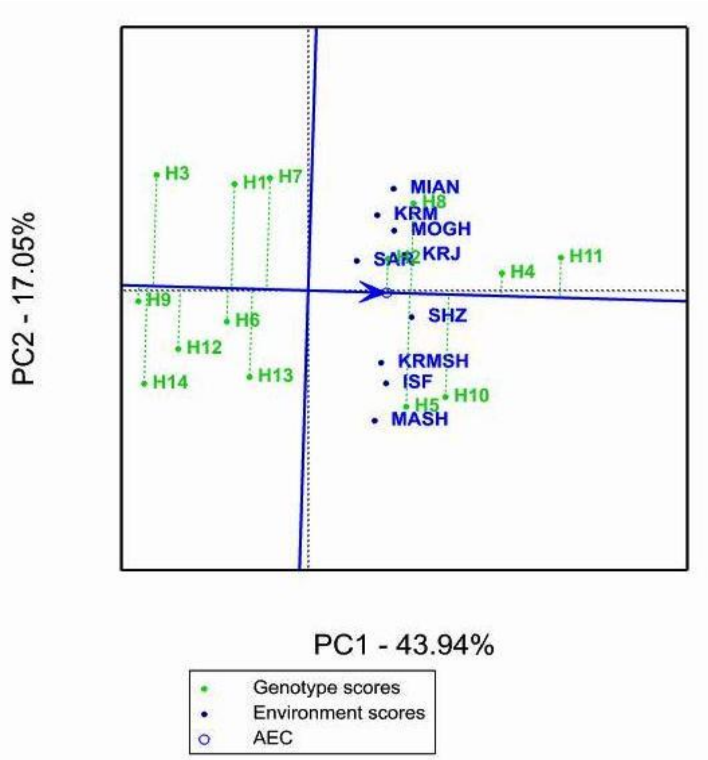

Fig. 4. Biplot of the average-environment coordination (AEC) for simultaneously selection of grain yield and yield stability of grain maize hybrids (H1-H14) in nine environments in two growing seasons. Environmental codes; MIAN, KRM, MOGH, KRJ, SAR, SHZ, KRMSH, ISF, and MASH represent the research field stations; Miandoab, Kerman, Moghan, Karaj, Sari, Shiraz, Kermanshah, Isfahan and Mashhad, respectively

which led to selection of the KSC705 hybrid for its superior performance and grain yield stability. As depicted in Fig. 4, hybrids H11 and H4 were identified as hybrids demonstrating high grain yield and yield stability. Hybrids H10, H5, and H8 had low grain yield stability despite producing high grain yield. Hybrid H2 also had good grain yield stability. Considering grain yield and its stability, hybrids; H4 (KE 77008/1 × KSC260), H11 (KE 76009/312 × K 1264/5-1 or KSC405), and H2 (KE 77008/1 × KSC400) outperformed the commercial control hybrids H12 (KSC400 or cv. Dehghan), H13 (KSC260 or cv. Fajr), and H14 (KSC201 or cv. Koosha).

The GGE biplot analysis helped identifying mega environments for selection and the discrimination of test environments in India, revealing the existence of two rainfed mega-environments suitable for early and late maturity grain maize hybrids (Kumar *et al.,* 2024). The concentric circles within the GGE biplot diagram for genotype-focused scaling contributed to the identification of a suitable genotype of sugar beet for a specific trait (Hassani *et al.,* 2018). The average environment coordination (AEC) perspective showed that the G29 genotype was identified as the most suitable genotype in terms of root yield, because it was the closest genotype to the ideal genotype (Hassani *et al.,* 2018).

The position of 14 grain maize hybrids compared to the ideal genotype are shown in Fig. 5. The hybrid that demonstrate the highest mean yield with high grain yield stability across all environmental conditions is defined as the ideal genotype. The ideal genotype is a theoretical concepts that are represented by a diminutive circle with a narrow point. To facilitate the comparison of other genotypes against the ideal genotype (optimal genotype), concentric circles are integrated into the GGE biplot to ascertain the distance between the examined genotypes to the ideal genotype (Yan, 2001; Yan and Kang, 2002). Hybrids that reside within the central region of the circles or maintain the shortest distance from this hypothetical genotype are deemed superior genotypes, exhibiting high grain yield and yield stability. The visualization of the ideal genotype (Fig. 4) demonstrates that H4 followed by H11 are located in close proximity to the ideal genotype. A number of studies have utilized the GGE biplot method to identify superior hybrids, genotypes or cultivars in some crops (Gauch *et al.,* 2008; Shiri 2013; Tahmasebi *et al.,* 2014; Hassani *et al.,* 2018; Shahriari *et al.,* 2018; Tahmasebi *et al.,* 2021; Eze *et al.,* 2020; Ruswandi *et al.,* 2022).

The correlation biplot based on GGE analysis explained 60.99% of the total variation, with PC1 (43.94%) and PC2 (17.05%) as the main contributors. Environments Kerman, Karaj, Moghan and Miandoab had acute angles, indicating strong positive correlations and similar discriminatory patterns, while Mashhad, Kermanshah, Isfahan and Shiraz formed another correlated group (Fig 5). The long vectors of Kerman, Miandoab and Mashhad suggest that these environments were the most discriminating, whereas Sari contributed less to genotype differentiation.

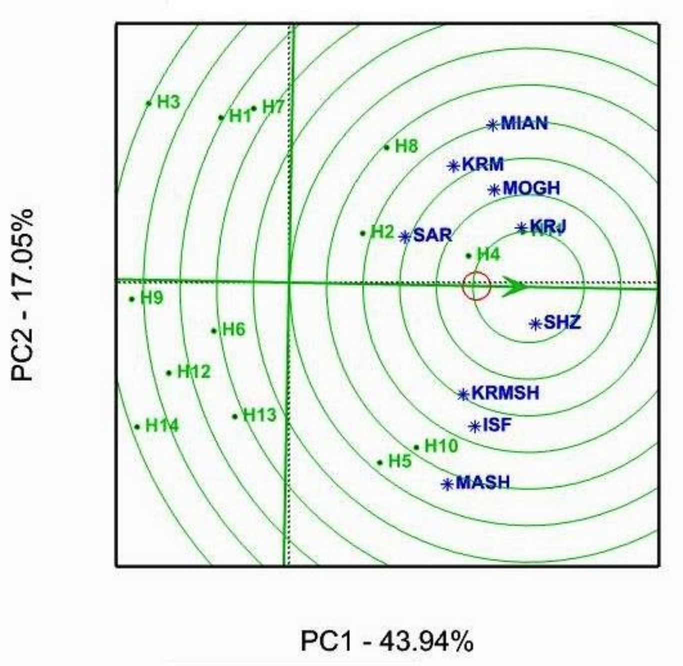

Fig. 5. Biplot of nine maize hybrids (H1-H14) in comparison with ideal genotype based on grain yield and yield stability. Environmental codes; MIAN, KRM, MOGH, KRJ, SAR, SHZ, KRMSH, ISF, and MASH represent the research field stations; Miandoab, Kerman, Moghan, Karaj, Sari, Shiraz, Kermanshah, Isfahan and Mashhad, respectively

Regarding grain maize hybrids, those hybrids that located close to each other (e.g., H4 and H11, H5 and H10, H1 and H7) exhibited similar responses across environments. Hybrids positioned along the vectors of specific environment showed specific adaptation; H5 and H10 with Mashhad, Isfahan and Kermanshah, H11 and H4 with Karaj and Shiraz, and H2 with Sari, suggesting high performance in those locations. In contrast, H6 and H9 similar to H12, H13 and H14 (control hybrids) and H1, H3 and H7 were positioned in the opposite direction of most environments or located away from environment vectors, suggesting poor adaptation or tended to perform poorly across test sites (Fig. 6).

The hybrids selected in this study (H4 and H11) that had higher grain yield and yield stability in comparison with the control hybrids (H12, H13, and H14) have the potential to be commercially released as new early-maturing grain maize cultivars, particularly H4, which is a three-way cross hybrid derived from a single cross parent (KSC260). Furthermore, certain hybrids, such as H1 and H2, which had high stable grain yield (Table 6), may serve to enrich germplasm in the national grain maize breeding programs in Iran, and H2, which demonstrates notable stability in the GGE biplot analysis.

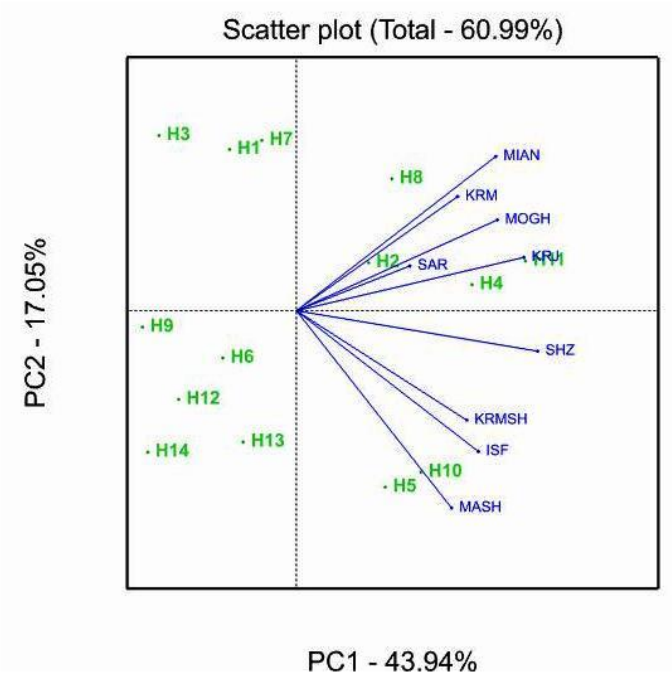

Fig. 6. Correlation biplot of test environments based on GGE analysis. Environmental codes; MIAN, KRM, MOGH, KRJ, SAR, SHZ, KRMSH, ISF, and MASH represent the research field stations; Miandoab, Kerman, Moghan, Karaj, Sari, Shiraz, Kermanshah, Isfahan and Mashhad, respectively.

CONCLUSION

The main aim of this research was to assess the genetic potential for grain yield and yield stability of 14 grain maize hybrids for selecting promising early maturity grain maize hybrids for shorter growing in different regions of Iran. The test environments in this study were heterogeneous, featuring varying growing conditions and geographical and agro-ecological conditions. The mean grain yield of the superior maize hybrids in this study was 10.376 t ha^{-1}. Using of these hybrids can enhance grain maize production in Iran, where the mean grain yield of commercial hybrids is around 8 t ha^{-1}.

The findings of this study highlighted the necessity of specific adaptation The significant interaction of genotype by environment for grain yield and yield components of the new hybrids accentuated the critical need for comprehensive testing across different environments and several growing seasons prior to releasing promising hybrids to the maize growing communities. These findings suggest the possibility of reducing breeding experiment costs by eliminating similar environments based on observed patterns in the biplot.

Our findings confirmed the observation of previous researchers, indicating a single statistical method is insufficient for stability analysis and integration of various statistical indices should be used for this purpose. The cumulative index ranking of each genotype and the average rankings for genotypes were computed. Genotypes exhibiting the lowest mean rank for all indices are regarded as the most stable. A comparison of days to physiological maturity among the new grain maize hybrids and the control cultivars, from FAO groups 200 to 400, indicated that all hybrids are classified within the 300 to 450 FAO groups. These groups, which mature earlier than the commercial maize cultivars from 600 and 700 FAO groups consume less water and are more suitable for cultivation in Iran.

Grain maize is typically planted after wheat and barley harvest, in June, in most of the grain maize growing areas in Iran. Late-maturing hybrids often face cold damage from early October onward, resulting in increased harvested grain moisture content, and the necessity of consuming more energy to reduce the grain moisture content to 14% and reduced grain yield and quality. However, these early-maturing grain maize hybrids from 200 to 400 FAO groups, which take approximately 105 to 115 days to reach physiological maturity, don't suffer from cold and allow for harvesting grain with proper moisture content level below 20%, leading to improved grain quality.

Based on different analyses, it was determined that the three-way cross hybrid, H4 (KE 77008/1 × KSC260), and the single cross hybrid, H11 (KE 76009/312 × K 1264/5-1) were the superior hybrids, because they had high stable grain, suitable grain moisture content at harvest in most regions. These hybrids, which have optimal growing cycle, can be utilized to achieve high stable grain yield and quality with consistent production across different growing seasons and regions in Iran. Therefore, hybrids; H4 and H11 high stable grain yield across diverse environments, were designated for release as new commercial grain maize cultivars. Other high stable grain yield hybrids such as H2, H5, and H1 may serve as valuable genetic resources for being used in the national grain maize breeding programs. However, H5 and H10 with specific adaptation can be recommended for being grown in specific mega-environments. These results implies that, in future, it would be feasible to reduce the number of test environments and costs by excluding certain similar environments.

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CONFLICT OF INTEREST

The authors declare that they have no competing interests.

USAGE OF ARTIFICIAL INTELLIGENCE

We declare that some Artificial Intelligence tools were used for grammar checks and improving some parts of the article's text.

REFERENCES

Adu, G. B., Badu-Apraku, B., Akromah, R., Haruna, A., Amegbor, I. K. and Amadu, M. K. 2019. Grain yield and stability of early-maturing single-cross hybrids of maize across contrasting environments. J. Crop Improv. 33(6): 776-796. DOI:10.1080/15427528.2019.1661055

Allard, R. W. and Bradshaw, A. D. 1964. Implication of genotype environment interactions in applied plant breeding. Crop Sci. 4: 403-508. DOI: 10.2135/cropsci1964.0011183X000400050021x.

Aman, J., Bantte, K., Alamerew, S. and Sbhatu, D. B. 2020. Correlation and path coefficient analysis of yield and yield components of quality protein maize (*Zea mays L.*) hybrids at Jimma, western Ethiopia. Int. J. of Agron. 2020(1): 1-7. DOI: 10.1155/2020/9651537.

Changizi, M., Choukan, R., Heravan, E. M., Bihamta, M. R. and Darvish, F. 2014. Evaluation of genotype-environment interaction and stability of corn hybrids and relationship among univariate parametric methods. Can. J. Plant Sci. 94: 1255-1267. DOI: 10.4141/CJPS2013-386.

Crossa, J. 1990. Statistical analyses of multi-location trials. Adv. Agron. 44: 55-85. DOI: 10. 1016 /S0065-2113(08)60818-4.

Dehghani, H., Sabaghpour, S. H. and Sabaghnia, N. 2008. Genotype × environment interaction for grain yield of some lentil genotypes and relationship among univariate stability statistics. Span. J.of Agric. Res. 6: 385-394.

Djurovic, D., Madic, M., Bokan, N., Stevovic, V., Tomic, D. and Tanaskovic, S. 2014. Stability parameters for grain yield and its component traits in maize hybrids of different FAO maturity groups. J. Cent. Europ. Agric. 15(4): 199-212. DOI: 10.5513/JCEA01/15.4.1530.

Eberhart, S. A. and Russell, W. A. 1966. Stability parameters for comparing varieties. Crop Sci 6: 36-40. DOI: 10.2135/cropsci1966.0011183X000600010011x.

Estakhr, A. and Choukan, R. 2011. Effect of planting date on grain yield and its components and reaction to important maize viruses in Fars Province in some exotic and Iranian maize hybrids. Seed Plant Prod. J. 27: 313-333. DOI: 10.22092/SPPJ.2017.110440.

Estakhr, A. and Dehghanpour, Z. 2011. Determination of the suitable planting date for new early maturity maize hybrids in second cropping in temperate regions in Fars province. Seed Plant Prod. J. 26: 169-191.

Estakhr, A. and Heidari, B. 2012. Combining ability and gene action for maturity and agronomic traits in different heterotic groups of maize inbred lines and their diallel crosses. J. Crop Sci. Biotechnol. 15: 219-223. DOI: 10.1007/s12892-012-0030-1.

Estakhr, A., Heidari, B. and Ahmadi, Z. 2015. Evaluation of kernel yield and agronomic traits of European maize hybrids in the temperate region of Iran. Arch. Agron. and Soil Sci. 61(4): 475-491. DOI: 10.1080/03650340.2014.941822.

Eze, C. E., Akinwale, R. O., Michel, S. and Bürstmayr, H. 2020. Grain yield and stability of tropical maize hybrids developed from elite cultivars in contrasting environments under a rainforest agro-ecology. Euphytica, 216:1-13. DOI: 10.1007/s10681-020-02620-y.

FAO. 2012. FAOSTAT. Food and Agriculture Organization of the United Nations. Food and Agriculture Data Network. Available from: http://faostat.fao.org.

Finlay, K. W. and Wilkinson, G. N. 1963. The analysis of adaptation in a plant breeding programe. Aust. J. Agric. Res. 14:742–754.

Francis, T. R. and Kanenberg, L. W. 1978. Yield stability studies in short season maize. A descriptive method for grouping genotypes. Can. J. Plant Sci. 58(4) 1026-1034. DOI: 10.4141/cjps78-157.

Gauch, H. G., Piepho, H. P. and Annicchiarico, P. 2008. Statistical analysis of yield trials by AMMI and GGE: Further considerations. Crop Sci. 4 8(3): 866-889. DOI: 10.2135/cropsci2007.09.0513.

Ghaed-Rahimi, L., Heidari, B. and Dadkhodaie, A. 2014. Genotype× environment interactions for wheat grain yield and antioxidant changes in association with drought stress. Arch. Agron. and Soil Sci. 61(2): 153-171. DOI: 10.1080/03650340.2014.926004.

Hassani, M., Heidari, B., Dadkhodaie, A. and Stevanato, P. 2018. Genotype by environment interaction components underlying variations in root, sugar and white sugar yield in sugar beet (*Beta vulgaris L.*). Euphytica 214: 1-21. DOI: 10.1007/s10681-018-2160-0.

Hebert, Y., Plomion, C. and Harzic, N. 1995. Genotypic × environment interaction for root traits in maize, as analyzed with factorial regression models. Euphytica 81: 85-92.

Kang, M. S. 1988. A rank-sum method for selecting high-yielding, stable corn genotypes. Cereal Res. Commun. 16: 113–115.

Kovačević, A., Pavlov, J., Stevanović, M., Delić, N., Mutavdzic, D. and Živanović, T. 2024. Direct selection parameter estimates and path coefficient analysis for grain yield and quantitative traits in maize (*Zea mays L.*). Roman. Agric. Res. 41: p.4101.DOI: 10.59665/rar4101.

Kumar, B., Choudhary, M., Kumar, P., Kumar, S., Sravani, D., Vinodhana, N. K., Kumar, G. S., Gami, R., Vyas, M., Jat, B. S. and Dagla, M. C. 2024. GGE biplot analysis and selection indices for yield and stability assessment of maize (*Zea mays L.*) genotypes under drought and irrigated conditions. Indian Journal of Genet. Plant Breed. 84(02): 209-215. DOI: 10.31742/ISGPB.84.2.8 .

Li, L. L., Ming, B., Xue, J., Gao, S., Wang, K. R., Xie, R. Z., Hou, P. and Li, S. K. 2021. Difference in corn kernel moisture content between pre-and post-harvest. J. Integr. Agric. 20(7): 1775-1782. DOI: 10.1016/S2095-3119(20)63245-2.

Oyekunle, M., Haruna, A., Badu-Apraku, B., Usman, I. S., Mani, H., Ado, S. G., Olaoye, G., Obeng-Antwi, K., Abdulmalik, R. O. and Ahmed, H. O. 2017. Assessment of early-maturing maize hybrids and testing sites using GGE biplot analysis. Crop Sci. 57(6): 2942-2950. DOI: 10.2135/cropsci2016.12.1014

Payne, R. W., Murray, D. A., Harding, S. A., Baird, D. B. and Soutar, D. M. 2012. Genstat® for Windows™, 15th Edition, Introduction. VSN International, Oxford.

Plaisted, R. I. and Peterson, L. C. 1959. A technique for evaluating the ability of selection to yield consistently in different locations or seasons. Am. Potato Res. J. 36: 381–385. DOI: 10.1007/BF02852735.

Plaisted, R. L. 1960. A shorter method for evaluating the ability of selections to yield consistently over locations. Am. Potato Res. J. 37: 166–172. DOI: 10.1007/BF02855271

Pour-Aboughadareh, A., Yousefian, M., Moradkhani, H., Poczai, P. and Siddique, K.

H. 2019. STABILITYSOFT: A new online program to calculate parametric and non-parametric stability statistics for crop traits. Appl, in Plant Sci. 7(1). DOI: 10.1002/aps3.1211

Rafiq, C. M., Rafique, M., Hussain, A. and Altaf, M. 2010. Studies on heritability, correlation and path analysis in maize (*Zea mays L.*). J. Agric. Res. 48(1): 35-38.

Rahimi Jahangirlou, M., Akbari, G. A., Alahdadi, I., Soufizadeh, S., Kumar, U. and Parsons, D. 2021. Phenotypic traits, grain yield and yield components of maize cultivars under combinations of management practices in semi-arid conditions of Iran. Int. J. Plant Produc. 15: 459-471. DOI: 10.1007/ s42106-021-00151-7.

Raut, S. K., Ghimire, S. K., Kharel, R., Kuwar, C. B., Sapkota, M. and Kushwaha, U. K. S. 2017. Study of yield and yield attributing traits of maize. Amer. J. of Food Sci. Health 3(6): 123-129.

Ruswandi, D., Syafii, M., Wicaksana, N., Maulana, H., Ariyanti, M., Indriani, N. P., Suryadi, E., Supriatna, J. and Yuwariah, Y. 2022. Evaluation of high yielding maize hybrids based on combined stability analysis, sustainability index, and GGE biplot. BioMed. Res. Int. 2022:1-12. DOI: 10.1155/2022/3963850.

Sabaghnia, N., Sabaghpour, S. H. and Dehghani, H. 2008. The use of an AMMI model and its parameters to analysis yield stability in multi-environment trials. J. Agric. Sci. 146: 571-581.

Shahriari, Z., Heidari, B. and Dadkhodaie, A. 2018. Dissection of genotype × environment interactions for mucilage and seed yield in Plantago species: Application of AMMI and GGE biplot analyses. PloS One, 13(5). e0196095. DOI: 10.1371/journal.pone.0196095.

Shiri, M. 2013. Grain yield stability analysis of maize (*Zea mays L.*) hybrids in different drought stress conditions using GGE biplot analysis. Crop Breeding Journal 3(2): 107-112. DOI: 10.22092/cbj.2012.100456

Shojaei, S. H., Mostafavi, K., Bihamta, M. R., Omrani, A., Mousavi, S. M. N., Illes, A., Bojtor, C. and Nagy, J. 2022. Stability on maize hybrids based on GGE biplot graphical technique. Agron. 12(2): 394: 1-10. DOI: 10.3390/ agronomy 12020394.

Shojaei, S. H., Mostafavi, K., Omrani, A., Omrani, S., Nasir Mousavi, S. M., Illés, Á., Bojtor, C. and Nagy, J. 2021. Yield stability analysis of maize (*Zea mays* L.) hybrids using parametric and AMMI methods. Scientifica 2021. 1-9. DOI: 10.1155/2021/5576691

Shukla, G. K. 1972. Some statistical aspects of partitioning genotype-environmental components of variability. Heredity 29: 237-245. DOI: 10.1038/hdy.1972.87.

Tahmasebi, S., Esmaeilzadeh Moghaddam, M., Tabib Ghaffar, M., Sayyahfar, M., Lotfi Ayeneh, G. and Akbari Moghaddam, H. 2021. Dissection of genotype× environment interaction and assessment of adaptability and grain yield stability of spring bread wheat genotypes. Crop Breeding Journal, 11(2): 11-24. DOI: 10.22092/CBJ.2022.357170.1072

Tahmasebi, S., Heidari, B., Pakniyat, H. and Jalal Kamali, M. R. 2014. Independent and combined effects of heat and drought stress in the Seri M82 × Babax bread wheat population. Plant Breeding 133(6): 702-711. DOI: 10.1111/pbr.12214.

Wrick, E. 1962. Uber eine mehode zur Erfassung der Okologischen streubreite in feld versuchen. A. Pflanzenauecht 47: 92-95.

Yahaya, M. S., Bello, I. and Unguwanrimi, A. Y. 2021. Correlation and path-coefficient analysis for grain yield and agronomic traits of maize (*Zea mays L.*). Sci. World J. 16(1): 10-13.

Yan, W. 2001. GGE biplot- a windows application for graphical analysis of multi-environment trial data and other types of two-way data. Agron. J. 93: 1111-1118. DOI: 10.2134/agronj2001.9351111x.

Yan, W., Hunt, L. A., Sheng, Q. and Szlavnics, Z. 2000. Cultivar evaluation and mega-environment investigation based on the GGE biplot. Crop Sci. 40: 597-605. DOI: 10.2135/ cropsci2000 .403597x.

Yan, W. and Kang, M. S. 2002. GGE biplot analysis: A graphical tool for breeders, geneticists, and agronomists. CRC press. 286 pp.

Yan, W., Kang, M. S., Ma, B., Wood, S. and Cornelius, P. L. 2007. GGE biplot vs. AMMI analysis of genotype-by-environment data. Crop Sci. 47: 643-655.

Yan, W. and Tinker, N. A. 2005. An integrated biplot analysis system for displaying, interpreting and exploring genotype× environment interaction. Crop Science 45(3): 1004-1016. DOI:10.2135/cropsci2004.0076.

Zhang, H., Gou, X., Ma, L., Zhang, X., Qu, J., Wang, X., Huang, W., Yan, S., Zhang, X., Xue, J. and Xu, S. 2024. Reveal the kernel dehydration mechanisms in maize based on proteomic and metabolomic analysis. BMC Plant Biol. 24(1): 1-15. DOI: 10.1186/s12870-023-04692-z.