Evaluation of multi-environment grain yield trials in maize hybrids by GGE-Biplot analysis method

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Abstract

Experiments were conducted in 2014 and 2015 at locations from Sakarya, Adana, Sazak, Ceyhan, Yuregir, Bursa, Antalya, Samsun, and Izmir. PR31G98, PR31A34, Kalumet, P 3167, Adasa16, 72MAY99, PAN34015, P1429, ZP873, MAS71B, MAS78T, Sagunto, SY Hydro, PL 772, LG30600, P1758, P2088, Kebeos and Kamperos hybrid dent corn cultivars were used as plant material. Experiments were conducted in a randomized block design with four replications. The primary objective of the study was to determine the stability of 19 hybrid dent corn cultivars in 16 environments with the aid of GGE-Biplot analysis. According to variance analysis concerning grain yield data, genotype × environment interaction was found to be significant. Considering the total variation in grain yields, the environment represented 82.32% of total variation. Genotype and genotype × environment interaction constituted 9.33% and 8.36% in total variation, respectively. GGE-biplot analysis explained 65.91 % of the total variation. Experimental environments were distributed over four mega-environments. E8 with a close position to average environment coordinate (AEC) and high vector length was identified as the environment with the largest capability of representing the different environments and largest genotype separation power. Despite the high grain yield scores of G8, G17 and G18 genotypes, G8 with a close position to AEC was identified as the most stable genotype.

Abbreviations

G-Genotype, E-Environment, GEI-Genotype × environment interaction, GGE-Genotype + Genotype by environment interaction, AEC-Average environment coordinate, PCA-Principal component analysis, PC-Principal component, ME-Mega-environment, VCU-Value for cultivation and use, DUS-Distinctness, uniformity and stability

Introduction

Maize has diverse uses and high unit-area yields and has become one of the most significant worldwide agricultural products. According to data from 2017, 5.9 million tons of maize were produced from 639,000 ha cultivated lands of Turkey (TUIK, 2017). When the statistics for the sowing area and production quantities from the 2001 to 2017 period were assessed, remarkable increases in yields were found. While Turkey had an average yield of 0.40 ton ha^{-1} with 2.2 million ton production from 550,000 ha sowing area in 2001, the value reached 0.92 ton ha^{-1}in 2017. With a 16% increase in sowing area, a 130% increase was achieved in yields. The greatest increase in sowing areas was observed in irrigated farming lands of the Southeastern and Central Anatolia regions. Use of hybrid maize cultivars with high yield potentials had great contributions to such increased yield levels (Bayramoglu and Bozdemir, 2018).

Newly developed and/or foreign-registered hybrid maize cultivars are taken for value for cultivation and use (VCU) tests under main or second crop conditions in Turkey. Silage hybrid maize, sweet corn (*Zea mays* L. *saccharata* Sturt.), and popcorn (*Zea mays* L. *everta* Sturt) candidate varieties are tested separately. Parents of hybrid maize varieties are registered only through distinctness, uniformity, and stability (DUS) tests (MAF, 2018). However, VCU and DUS tests of hybrid maize varieties are conducted concurrently. VCU experiments in maize cultivation regions are set up in a multi-location manner. In multi-location experiments with many genotypes (G), G and G × environment (E) interactions (GEI) are the basic sources of variation and different statistical methods are employed in such experiments (Djurovic *et al.*, 2014). Instead of using several parametric indicators to investigate the effects of G, E, and GEI, the graphical method, the GGE-Biplot, is commonly used in such cases (Khalil *et al.*, 2011; Mortazavian *et al.*, 2014; Kaplan *et al.*, 2017). Biplot analysis reveals important information about the relationships of significant environmental data proven by variance analysis and allows visual assessment of the separation capabilities of the Gs (Yan *et al.*, 2010). For phenotypic performance assessment of the Gs in multi-environment experiments, GEI (in cases in which the analysis of variance [ANOVA] revealed the existence of GEI) should also be taken into consideration.

In Turkey, mostly single hybrid cultivars are used in maize cultivation. Besides high yields, stability of the cultivars should also be taken into consideration (Tonk *et al.*, 2011). Multi-environment experiments are the essential methods used to identify the stability of the genotypes. However, multi-environment experiments are costly processes. Repeated GGE-biplot analysis allows identification of unnecessary environments (Yan and Kang, 2003). Biplot analysis reveals important information about representative capabilities of test environments and separation powers of the Gs (Yan and Tinker, 2006). Studies on maize and other plant species by AMMI and GGE-biplot analysis to identify the environment best representing experimental environments and the genotypes with the greatest separation power have been conducted (Dehghani *et al.*, 2009; Kaya *et al.*, 2006; Ilker *et al.*, 2009). Mitrovic *et al.* (2012) used hybrid maize cultivars under different climate conditions and indicated that a large difference between AMMI and GGE-biplot analyses could not be found, and both methods could be used successfully in multi-E studies. Muftuoglu *et al.* (2019) generated the G-trait biplot graph for visual presentation of the relationships among the investigated traits in cluster bean. Xu *et al.* (2017) pointed out the significance of quality attributes besides yield in registration experiments and recommended biplot analysis for assessment of such attributes.

Turkey has diverse ecologies and recent changes in climate parameters significantly influence G stabilities in changing environments. Maize is among the plant species with the greatest number of registration applications by private companies. Therefore, identification of stability in addition to yield performance are crucial issues in cultivar selection and recommendation (Ilker *et al.*, 2009).

G and E are of great importance with respect to yield and quality (Orhun, 2020; Kahriman *et al.*, 2016). Due to extreme climate conditions especially in recent years,, determining the responses of Gs under different environmental conditions has increased the importance of this response. Biplot analyses have been used frequently by researchers in recent years to analyze grain yield of maize genotypes (Oyekunle *et al.*, 2017), quality characteristics (Orhun, 2020), and perform disease studies (Kumar *et al.*, 2017). In Turkey, registration of

Table 1 - Information about 19 hybrid maize genotypes and 16 environmental locations

Code	Genotype	Origin of genotype	Date of registration in Turkey	FAO maturity groups	Code	Growing season	Location
G1	PR31G98	USA	2002	700-750	E1	2014	Sakarya
G2	PR31A34	USA	2011	650-700	E2	2015	Sakarya
G3	Kalumet	Italy	2011	700	E3	2014	Adana
G4	P 3167	USA	1997	750	E4	2015	Adana
G5	Adasa16	Turkey	2016	650-700	E5	2014	Sazak-Adana
G6	72MAY99	Turkey	2016	650	E6	2015	Sazak-Adana
G7	PAN34015	France-Italy	2016	650	E7	2015	Ceyhan-Adana
G8	P1429	USA	2016	650	E8	2014	Yuregir-Adana
G9	ZP873	Turkey	2016	650-700	E9	2014	Bursa
G10	MAS71B	France	2016	700	E10	2015	Bursa
G11	MAS78T	France	2016	700-750	E11	2014	Antalya
G12	Sagunto	Spain	2016	700	E12	2015	Antalya
G13	SY Hydro	Italy	2016	650-700	E13	2014	Samsun
G14	PL 772	Turkey	2016	650-700	E14	2015	Samsun
G15	LG30600	Italy	2016	650-700	E15	2014	Izmir
G16	P1758	Italy	2016	650-700	E16	2015	Izmir
G17	P2088	USA	2016	650-700			
G18	Kebeos	Italy	2016	700-750			
G19	Kamperos	Italy	2016	650-700			

Table 2 - Meteorological data at experimental locations*

Locations	Months	Average temperature (oC)			Total rainfall (mm)			Average relative humidity (%)		
		2014	2015	Long term	2014	2015	Long term	2014	2015	Long term
Izmir	March	13.2	11.3	12.0	106.4	108.4	81.7	60.8	73.0	65.2
	April	16.9	14.4	16.1	132.2	31.4	47.7	61.0	54.8	61.8
	May	20.8	21.6	20.8	15.3	28.8	28.3	57.3	52.6	58.7
	June	25.0	23.8	25.6	48.5	52.3	12.3	53.3	58.0	52.8
	July	27.8	28.2	28.2	1.0	0.0	4.2	50.4	44.9	50.2
	August	28.4	28.7	28.0	3.8	35.4	5.9	53.3	50.1	52.3
	September	23.9	25.3	24.0	10.6	7.1	20.0	57.4	59.6	56.8
	October	18.9	19.4	19.1	91.1	83.5	48.4	65.4	67.9	63.4
Samsun	March	10.2	8.8	8.2	40.8	76.0	64.4	70.6	74.1	73.6
	April	12.0	10.7	11.2	24.4	95.7	54.5	76.7	69.1	78.1
	May	17.0	16.1	15.4	48.1	30.4	53.5	75.0	74.3	79.1
	June	21.3	21.1	20.3	62.3	80.3	49.8	68.0	70.3	75.1
	July	24.6	23.7	23.4	55.0	43.2	36.4	66.1	66.5	72.3
	August	25.7	25.6	24.0	19.9	16.0	44.5	65.0	63.8	71.8
	September	21.5	23.2	20.5	74.5	28.9	47.9	67.9	70.4	73.1
	October	17.2	17.5	16.5	66.6	72.3	84.1	71.8	72.2	74.2
Antalya	March	14.7	14.3	12.8	230.5	146.9	97.0	61.7	62.9	60.9
	April	17.1	16.0	16.3	31.3	22.2	52.4	70.8	58.2	63.6
	May	20.2	21.3	20.5	88.1	18.8	32.2	72.0	67.1	67.3
	June	25.4	23.9	25.3	6.2	17.2	9.3	58.4	66.2	61.5
	July	27.7	28.3	28.4	0.0	0.0	2.4	68.9	61.3	60.1
	August	29.2	29.2	28.3	1.6	0.0	2.7	66.3	61.9	59.9
	September	25.7	26.4	25.1	79.4	73.6	14.4	61.3	67.8	57.6
	October	21.7	22.6	20.4	95.7	130.8	71.9	56.8	58.9	54.6
Bursa	March	10.7	9.1	8.7	64.2	87.4	70.3	69.7	79.5	70.1
	April	14.5	11.5	13.1	124.6	128.5	65.5	71.2	70.7	68.5
	May	18.3	19.3	17.7	108.9	50.7	47.1	72.2	66.3	66.5
	June	22.3	21.4	22.3	118.3	53.7	40.5	71.0	75.2	61.5
	July	25.5	25.5	24.7	5.1	0.0	18.5	64.9	61.2	59.1
	August	25.8	26.4	24.7	51.0	6.8	14.2	68.0	62.1	60.8
	September	20.7	23.6	20.6	140.9	108.5	44.4	76.7	73.7	66.0
	October	16.4	16.4	15.6	77.3	108.1	79.5	80.3	84.2	73.6
Adana	March	15.6	14.6	13.7	47.7	135.1	64.4	63.2	64.9	65.1
	April	19.0	16.9	17.8	22.1	21.5	51.0	65.5	61.2	66.4
	May	22.0	22.5	21.9	34.9	65.7	47.6	67.7	64.8	66.7
	June	25.6	25.0	25.8	89.8	4.8	23.7	68.0	69.6	67.5
	July	28.4	28.4	28.5	3.5	0.4	12.5	70.6	69.8	70.6
	August	29.3	30.0	29.0	0.2	10.9	12.4	70.9	63.4	70.1
	September	26.3	28.4	26.5	95.4	130.0	22.6	64.6	64.8	64.7
	October	21.3	23.4	22.0	54.9	32.1	46.7	64.9	63.7	60.5
Sakarya	March	11.4	9.3	8.9	93.4	46.7	74.3	72.2	78.3	72.2
	April	14.8	12.1	13.1	25.0	117.7	59.5	72.3	69.1	71.3
	May	18.9	19.0	17.5	111.2	63.8	56.7	72.5	73.1	72.0
	June	22.2	21.1	21.7	120.5	283.5	74.7	74.7	80.5	70.3
	July	24.8	24.2	23.8	66.0	39.2	52.0	75.9	75.2	72.2
	August	25.3	25.4	23.8	70.7	34.3	44.4	77.3	75.4	73.6
	September	20.9	23.5	20.1	169.3	103.0	49.7	80.2	79.2	74.4
	October	16.9	16.6	15.8	69.4	165.2	89.4	81.7	87.3	78.1

*Meteorological data recorded at city center

Table 3 - Analysis of variance for grain yields of 19 hybrid maize cultivars in 16 environments

Source of variation	Degrees of freedom	Sum of squares	Mean square	F	SS[1] (%)
Replication	48	142.84	2.98 **	1.58	
Environment	15	10750.55	716.70 **	380.52	82.32
Genotype	18	1217.94	67.66 **	35.92	9.33
Genotype × Environment	270	1091.25	4.04 **	2.15	8.36
Error	864	1627.31	1.88		
Corrected total	1215	14829.88			
CV (%) = 9.19					

[1]Proportional distribution (Total sum of squares of E, G and GEI)
**Significant at $p<0.01$

maize genotypes and grain yield criterion is of primary importance. Quality and other characteristics are the next set of important criteria.

This study was conducted to determine the stability of 19 dent corn cultivars with the aid of GGE-Biplot method based on grain yield results from samples from the 2014 and 2015 growing seasons obtained from some locations of Turkey in which maize cultivation is commonly practiced.

Material and methods

Experimental locations

Experiments were conducted in Sakarya, Adana, Sazak, Ceyhan, Yuregir, Bursa, Antalya, Samsun, and Izmir in 2014 and 2015, Yuregir in 2014, and Ceyhan in 2015. Experimental locations are presented in Figure 1.

Plant materials

Experiments were conducted with 19 hybrid maize cultivars in a randomized block design with four replications. Since many Gs and Es were used, codes were used for G and E in tables and figures. The hybrid maize cultivars used in present experiments were coded as the FAO 650-750 maturity group and are suitable for main crop cultivation. The present cultivars originated mainly from Turkey, United States, Italy, France, and Spain. The codes and information about the cultivars and experimental environments are given in Table 1.

Fig. 1 - Experimental locations highlighted on Turkey map

Agronomical trials

Cultivars were sown in four rows of each plot. Inner two rows were harvested, and yields were converted into t ha^{-1}. Unit area grain yield was calculated based on 15% grain moisture as indicated by MAF (2018). Plant rows were 5 m long, row spacing was 70 cm, and in-row plant spacing was 18 cm. Sowing was performed at the end of winter freeze when the soil temperatures reached 10–12 °C (between the end of March and middle of May). Based on soil analyses results, 200–250 kg ha^{-1} N, 80–120 kg ha^{-1} P_2O_5, and K_2O fertilization was performed. All of the P_2O5 and K_2O fertilizers and a some of the N fertilizer were applied at sowing, and the remaining N fertilizer was applied in further stages as a dressing. If two seeds placed in seedbed germinated, singling out was performed at the first hoeing. If two of the seeds did not germinate, two plants were then left in the nearest seedbed to maintain plant density. The first hoeing was performed when the plants reached 15–20 cm in height and had four leaves, the second hoeing was performed when the plants reached 40–50 cm in height and had 6–8 leaves. Irrigation was performed based on climate and soil conditions of the locations.

Meteorological data

Monthly average temperatures, monthly total precipitations, and monthly average relative humidity values of the experimental locations are provided in Table 2 (TSMS, 2016). Monthly average temperatures and relative humidity of the experimental locations were generally close to long-term averages. In the Samsun location, total precipitation was lower than the long-term averages of the first year and slightly over the long-term averages of the second year. In the other locations, total precipitations were greater than the

Table 4 - Mean yields of 19 hybrid maize cultivars in experimental environments (t ha^{-1})

Genotypes	Environments																
	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15	E16	Mean
G1	16.65	15.75	19.43	17.24	14.91	16.83	16.54	17.02	18.06	16.35	12.70	10.81	12.01	11.33	10.04	21.18	15.43 de
G2	16.22	13.41	18.47	17.23	14.67	16.23	17.52	15.50	17.43	16.96	13.36	10.06	10.71	11.97	9.35	22.08	15.07 ef
G3	16.13	14.44	19.16	18.06	14.35	16.83	16.39	17.22	18.97	16.57	13.41	7.99	9.82	11.85	13.30	21.72	15.39 de
G4	13.12	14.70	16.57	16.53	12.64	17.10	14.27	13.58	15.68	15.47	12.46	8.85	10.24	10.68	10.36	19.19	13.84 h
G5	12.60	15.31	15.77	16.36	11.92	16.22	14.98	15.52	15.14	14.63	11.48	8.45	10.67	11.38	9.12	17.36	13.56 h
G6	13.80	14.00	16.07	15.88	12.34	14.32	16.25	14.11	15.51	15.61	11.48	8.29	9.38	10.43	10.97	19.34	13.61 h
G7	14.27	14.93	17.66	17.42	14.30	15.91	16.29	14.05	18.11	15.95	10.26	7.51	10.55	10.97	12.35	20.34	14.43 g
G8	17.90	16.59	20.50	19.52	16.80	16.74	16.95	19.41	20.20	17.08	13.09	12.12	11.93	13.02	11.10	20.91	16.49 a
G9	15.31	13.29	15.99	16.74	12.36	15.52	15.11	13.54	17.78	14.38	10.33	9.55	9.30	10.35	10.42	18.97	13.68 h
G10	15.33	12.94	18.12	17.87	13.12	18.04	15.45	15.82	15.50	15.31	13.40	9.79	8.68	10.82	11.68	19.29	14.45 g
G11	18.29	13.57	19.40	19.36	14.91	18.62	16.84	18.21	17.02	14.84	13.32	11.05	13.61	12.37	11.75	20.06	15.83 cd
G12	14.24	12.06	17.40	16.30	13.51	14.84	15.34	12.24	16.89	16.09	12.57	10.26	9.16	9.82	10.38	19.36	13.78 h
G13	16.67	15.84	19.20	16.13	15.40	16.75	17.10	15.98	16.40	16.75	13.23	10.85	10.34	11.66	10.86	23.25	15.40 de
G14	15.26	12.06	17.06	17.84	14.15	16.18	15.91	15.74	16.07	16.17	10.54	6.62	9.43	9.90	8.66	20.08	13.85 h
G15	17.84	15.60	18.73	19.20	15.39	18.72	16.71	17.45	17.80	17.30	11.51	9.90	11.92	11.83	10.64	20.48	15.69 cd
G16	15.04	16.12	17.24	15.92	15.11	13.21	15.67	16.49	17.24	16.61	10.51	9.61	13.06	12.91	8.89	20.03	14.60 fg
G17	17.61	16.94	20.11	17.27	14.88	17.72	17.04	19.32	18.15	18.21	14.51	10.54	12.92	12.85	11.31	22.40	16.36 ab
G18	17.07	17.72	18.30	17.75	15.66	19.45	16.55	17.51	19.97	18.34	13.74	10.19	12.84	13.43	10.87	21.85	16.33 ab
G19	17.48	16.58	17.89	17.37	16.17	19.49	16.62	17.58	19.05	17.40	13.03	9.82	12.27	11.58	12.35	20.77	15.96 bc
Mean	15.83 F	14.83 G	18.06 B	17.37 C	14.35 H	16.78 D	16.19 EF	16.12 EF	17.42 C	16.32 E	12.36 I	9.59 L	10.99 K	11.53 J	10.76 K	20.46 A	14.93

Least Significant Difference (LSD) of environments : 0.476 (for alpha 0.05)

Least Significant Difference (LSD) of genotypes : 0.437 (for alpha 0.05)

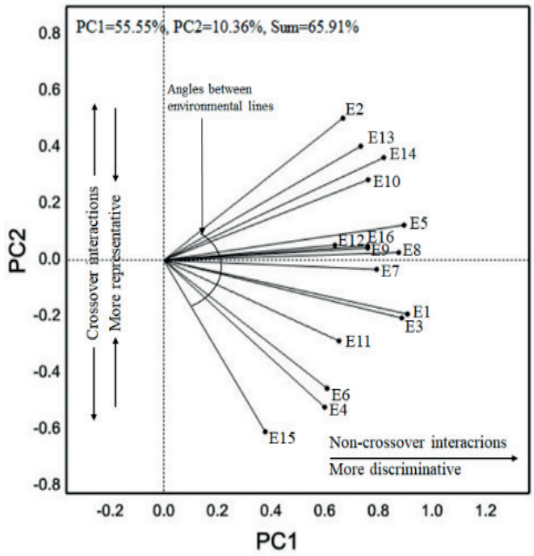

Fig. 2 - Positions of 16 experimental environments on biplot graph and vector images to biplot origin

long-term averages in both years of the experiments. For precipitation and temperature, distribution within a month or extreme values should also be taken into consideration. In some cases, total rainfall seen over a couple months may occur several hours, and such intense or heavy rainfalls may present serious problems to agricultural practices. A similar case may also be experienced with respect to temperatures. Minimum and maximum temperatures out of the range of long-term averages and low relative humidity may generate problems during the pollination period. In recent years, extreme meteorological events have been seen in coastal zones with common maize cultivation.

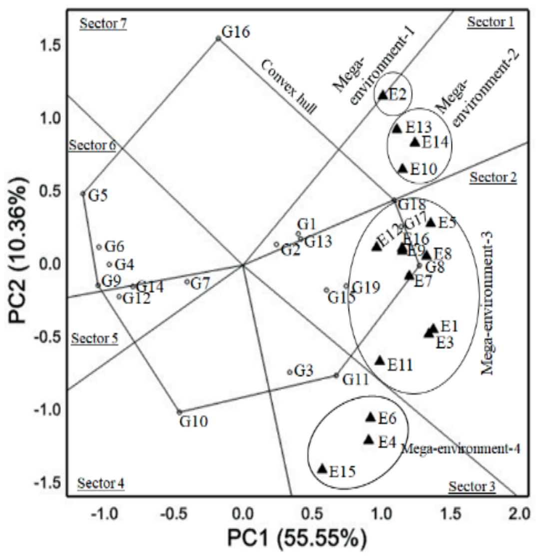

Fig. 3 - Positions of 16 experimental environments on biplot graph and vector images to biplot origin

Statistical analyses

Variance analysis was conducted for grain yield data. Gs and Es were grouped with the based on the least significant difference (LSD) method. GEI interaction was analyzed with the aid of the GGE-biplot method by GenStat (Genstat, 2009) statistical analysis software, and results were visually presented in graphs. The GGE-biplot based on the principal component analysis (PCA) model (G- and E-focused scaling) provided an effective means for visualizing grain yield performance and stability of the tested cultivars.

Results and discussion

Grain yield variance analysis

Results of variance analysis applied to grain yields of 16 environments are provided in Table 3. E, G, and GEI were found to be significant at the 0.01 level. Of total variation (E + G + GEI), 82.32% consisted of E, 9.33% of G, and 8.36% of GEI. Gauch and Zobel (1997) reported that about 80% of total variation consisted of E. Ahmadi *et al.* (2012) and Dehghani *et al.* (2009) also reported similar findings. Mean yields of the experimental locations and genotypes and difference groupings are given in Table 4. E averages varied between 9.59 and 20.46 t ha^{-1}. Environments were placed into 13 different groups. Genotypes were placed into eight different yield groups. The largest performance (16.49 t ha^{-1}) was achieved with G8, and the lowest grain yield (13.56 t ha^{-1}) was obtained from G5. The other G had grain yields between these two genotypes.

GGE-biplot analysis

With the GGE-biplot analysis of grain yields from 19 hybrid maize cultivars in 16 environments, 65.91% of total variation was explained (Figure 2). Of this explained variation, 55.55% and 10.36% were distributed on the PC1 and PC2 axes, respectively. Positive PC1 values from 16 experimental environments indicated the existence of non-crossover GEI. On the other hand, environments had negative and positive values on the PC2 axis. As can be seen in Figure 2, all environments had vectors with about a 90° angle range. The largest angle was observed between E2 and E15. Smaller angles between the environments indicate similar performance of the genotypes (Yan, 2014). Lengths of E vectors indicate G separation power of the E (Yan and Tinker, 2006). E12 had the shortest vector length (Figure 2). Such a case indicates that E12 had the lowest G separation power. In Figure 2, Gs were not presented so as to make the Es prominent and used them in assessments. In Figure 3, genotypes and environments were analyzed together to explain which-won-where model

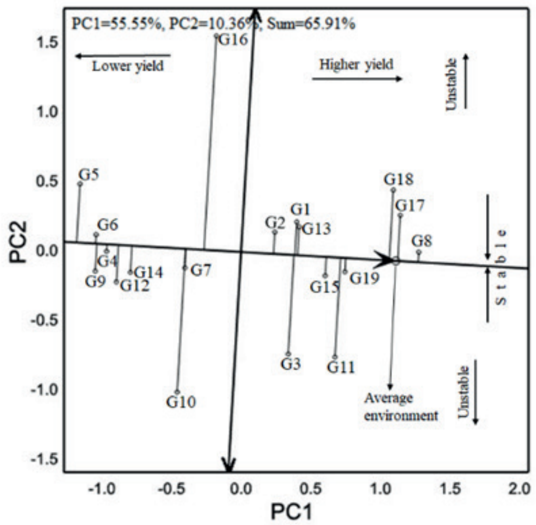

Fig. 4 - Vector images of 19 hybrid maize cultivars on GGE-biplot graph with respect to average environment coordinate (AEC)

of GGE-biplot. The vectors furthest from the origin of the biplot were connected, and a seven-sided polygon was obtained. The graph was then divided into seven sectors by orthogonal lines stretching to polygon sides from the origin of the biplot. Es were placed into four sectors and grouped within four mega-environments (ME). E2 was placed into ME-1, E10, E13, and E14 were placed into ME-2, E4, E6, and E15 were placed into ME-4, and the rest were placed into ME-3. G8 was the vertex variety of ME-3 in which majority of the varieties were found. Vertex genotypes of the sectors were the genotypes with the greatest vector length from the origin and these genotypes had a greater response to changing conditions (Yan, 2014). Boshev *et al.* (2014) indicated that the GGE-biplot method is an efficient tool for recommending maize hybrids for certain growing regions based on hybrid characteristics and growing conditions.

Average Environment Coordinate PCA analysis

In Figure 4, the average environment coordinate (AEC) was generated based on E point and biplot origin. Assessments were made about G stability based on orthogonal vectors of the genotypes to AEC. The genotypes over the AEC ordinate or with high PC1 values were ordered as G8>G17>G18>G19>G11> G15>G13>G1 ≈ G3>G2. G8 had the largest grain yield average and was positioned close to the AEC apsis, in other words, it had a short vector length and thus was identified as highly stable. Considering the cultivars with positive PC1 scores and values over the average score, it was observed that G3 and G11 had the longest vector lengths to AEC. Such a case indicates low G stability or instability. Considering the cultivars with negative PC1 scores and values below the average score, it was observed that G16 and G10 were the furthest G to the AEC apsis. The actual data of G16 with the longest vector (Table 4) revealed that while the genotype had the lowest performance in E6, it had the second largest grain yield in E13.

Ideal Genotype and environment-focused scaling PCA analysis

On the G-focused biplot graph, G8 was placed into ideal genotype zone (Figure 5). While G8 was placed into the smallest circle, G4–6 and G9 were placed into the largest circle. Enlarging circles indicate movement

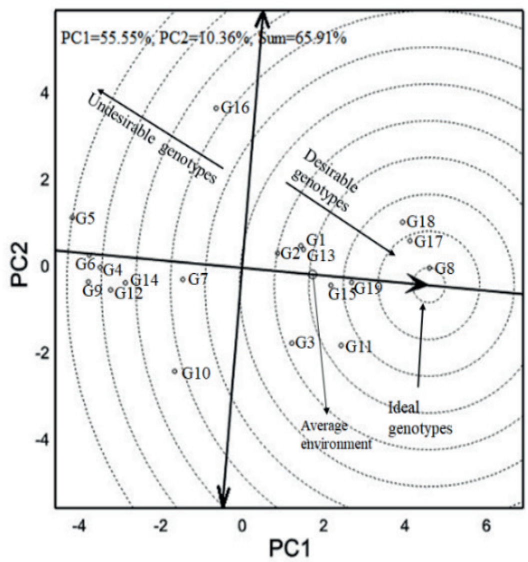

Fig. 5 - Position of the genotypes on ideal genotype-focused GGE-biplot graph

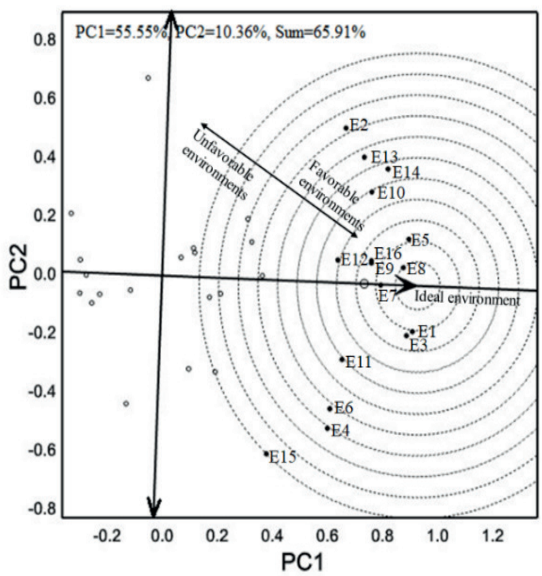

Fig. 6 - Position of environments on ideal environment-focused GGE-biplot graph

away from the ideal genotype and thus show the low-performance Gs. Following G8, G17 and G18 were the closest ones to ideal G zone, but they were not positioned to the AEC apsis as closely as G19 and G15 were. The E-focused biplot graph is presented in Figure 6. E8 was the closest E to an ideal environment zone. E8 had a high vector length to the biplot origin and was close to the AEC apsis. E15 with the lowest PC1 value (the shortest vector length) was the furthest E from the ideal E circle; thus, it can be indicated that the E had the least G separation power.

Conclusions

Performance and stability of genotypes in multi-environment trials is important in variety registration systems. Therefore, multi-environment experiments should be conducted, and experimental findings should be accurately and efficiently assessed. In this study, grain yields of 19 hybrid dent corn genotypes were investigated at 16 Es. All the experimental Es had positive PC1 values and thus exhibited non-crossover GEI. Experimental environments formed four mega-Es. The majority of experimental Es were placed into ME-3. G8 exhibited the largest performance, and with a close position to AEC, it was identified as the most stable cultivar. Position further from AEC of some Gs with high grain yield performance indicated that these Gs were not stable in their response to different Es. In this study including many Gs and experimental Es, GGE-biplot analysis revealed significant visual information about the performance and stability of Gs in different Es

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