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Examination of genotype × environment interactions by GGE biplot analysis in spring durum wheat

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Abstract

A study was conducted to examine the effects of genotype × environment interaction (GEI) on grain yield, its components, and quality characteristics using genotype main effect (G) plus genotype × environment interaction (GE) (GGE) biplot analysis. Significant differences were observed among cultivars in grain yield, yield components, and quality traits and the relationship between yield components was used to identify three groups. Positive correlations were found between quality parameters and yield components, whereas correlations of quality parameters with yield and yield components were negative. The GGE biplot indicated that E6 (single irrigated location at Diyarbakir) was an ideal environment for all traits and E5 (rainfed locations at Diyarbakir) was a highly efficient model for quality parameters. The biplot analysis showed that Zenit was the best cultivar in terms of yield and quality and Zühre was efficient for quality parameters only and hence these two genotypes can be recommended to Southeastern Anatolia Region in Turkey.

Key words: Cultivar, multi-environments, yield, quality parameters, classification

Introduction

Durum wheat (*Triticum durum* Desf.) is produced in all agro-ecological zones of southeastern Anatolia. This region is known as the wheat basin due to the presence of the Karacadað basin, to which durum wheat is well adapted. As a result, both productivity and quality are more efficient in this region compared with other regions. Many determinants of the quality and yield of durum wheat are determined by the agro-ecological conditions of various sub-regions (Mizrak 1986).

Crop breeders have aimed to develop genotypes characterized by superior grain yield, quality, and other desirable traits over a wide range of environmental conditions. The complexities of genotype × environment interaction (GEI) make selection difficult to identity the best performing and most stable genotypes (Yau 1995). It has been reported that the yield performance of wheat is highly influenced by GEI effects (Naroui et al. 2013). Therefore, the aim of the present study was to determine the yield, yield components, and quality characteristics of durum wheat in three sub-regions of southeastern Anatolia using the GGE biplot method.

Materials and methods

Plant material and experimental design

Ten durum wheat cultivars were evaluated in two rain-fed environments (E) located at Diyarbakir (E1) and Hani (E4), one irrigated environment at Diyarbakir (E2), and one support-irrigated environment at Kiziltepe (E3) during 2010-2011, and in two rain-fed locations at Diyarbakir (E5) and Hazro (E8), one irrigated location at Diyarbakir (E6), and one support-irrigated location at Kiziltepe (E7) during the 2011-2012 growing seasons. The experiments were conducted in a randomized block design with four replications. The seeding rate was 450 seeds m^{-2}. The plot size was 7.2 m^{-2} (1.2 × 6 m) consisting of six rows spaced 20 cm apart. Sowing was performed using a Wintersteiger drill. The basal dose of fertilizer for all the plots comprising 60 kg N ha^{-1}, 60 kg P ha^{-1} and 60 kg N ha^{-1} was applied to plots during early stem elongation. Irrigation was commenced after anthers appeared (Zadox 7) during the 2011-2012 season. However, due to excessive rainfall in April, irrigation was performed

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when the plants showed slight yellowing (Zadox 8) during the 2010-2011 season at the Diyarbakir irrigated location. Support irrigation was done twice for germination after sowing time and prior to heading time at the Kiziltepe support-irrigated location during the 2010-2011 and 2011-2012 seasons. The humidity and temperature during the 2010-2011 season were nearly 1.5% higher than the averages during 2011-2012. Harvesting was done using a Hege 140 harvester in an area of 6 m^2 in each plot. Table 1 shows the code name, origin and registration date of the wheat cultivars used in the experiment and Fig. 1 indicates the average precipitation by season.

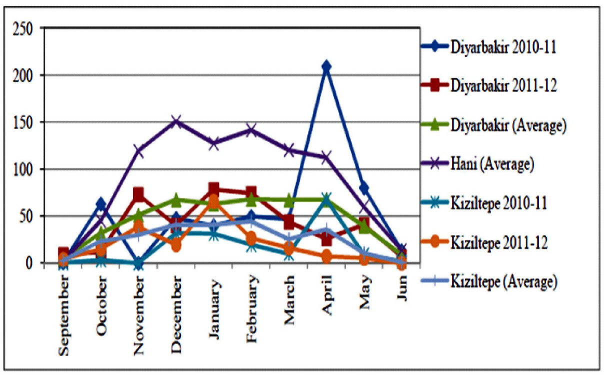

Fig. 1. The value of average and seasons (2010-11, 2011-12) describing precipitation (mm)

Statistical analysis (GGE)

The data were analyzed using JMP Statistical Discovery Software from SAS to determine whether GEI effects were significant. Differences between groups were determined using combined analysis of variance (ANOVA). Means were separated using the least significant differences (LSD), with significance set at $P < 0.05$. The data were graphically analyzed for interpretation of GEI using the GGE biplot software (Yan 2001).

Result and discussion

The combined ANOVA revealed significant differences among the environments for all traits ($P < 0.01$, $P < 0.05$) as shown in Table 2. Additionally, highly significant differences ($P < 0.01$, $P < 0.05$) were recorded among the genotypes for all of the investigated traits (Table 3). The biplot performance of each cultivar under each environment in terms of grain yield and the comparison among genotypes based on mean and yield instability accounted for 52.77% (28.52% and 24.25% for principal components (PC) 1 and 2, respectively) of the total variation (Figs. 2 and 3). The biplot of the environmental relationships by traits and the comparison of environments by traits based on mean and instability accounted for 59.03% (33.00% and 26.03% for PC1 and PC2, respectively) of the total variation (Figs. 4 and 5). The biplot of genotypic relationships by trait and the comparison of genotypes by traits based on mean and instability accounted for 63.29% (44.78% and 18.52% for PC1 and PC2, respectively) of the total variation (Figs. 6 and 7). These results confirmed that durum wheat parameters were affected by G, GE, and GEI as also suggested by Bendjama et al. (2014).

Table 1. Details of durum wheat cultivars used in the experiments

Code	Name of cultivar	Origin of cultivar	Year of registeration	Recommendation of cultivars under different environments
G1	Artuklu	GAPIARTC	2008	E4, E5 and E8
G2	Aydin 93	GAPIARTC	1993	E1, E4, E5 and E8
G3	Eyyubi	GAPIARTC	2008	E1, E2, E3, E4, E5, E6, E7 and E8
G4	Güneyyildizi	GAPIARTC	2010	E2, E3, E6 and E7
G5	Harran 95	GAPIARTC	1995	E1, E4, E5 and E8
G6	Saricanak 98	GAPIARTC	1998	E1. E2, E3, E5. E6 and E7
G7	Svevo	TASAKOALC	2001	E1, E2, E3, E5, E6 and E7
G8	Şahinbey	GAPIARTC	2008	E1, E2, E3, E5, E6 and E7
G9	Zenit	TASAKOALC	2001	E1. E2, E3, E5, E6 and E7
GI0	Zühre	GAPIARTC	2010	E1. E2, E3, E5, E6 and E7

G: Cultivar, GAPIARTC :GAP International Agricultural Research and Training Center; TASAKOALC: TASAKO Agricultural Liability Company

Table 2. Combined analysis of variance for grain yield, yield components and quality criteria data of eight environments

Environment	GY ($kgha^{-1}$)	HD (date)	SS (m^2)	ES (m^2)	MT (date)	PH (cm)	LS (cm)	NSS (number)	NGS (number)	YS (g)	VIT (%)	TGW (g)	HW (kg/hl)	PC (%)	SC	SDS (ml)	WG
E2	6093d	124d	570c	415d	168c	103b	6.9c	19.7b	53b	2.4 ab	90c	49.6a	82.3d	14.3c	22.0ab	8.0a	28.9b
E3	8282b	111f	577c	470c	161g	106a	6.9bc	20.1b	50c	2.4ab	84d	50.0a	85.4a	12.8d	20.7c	4.4e	24.9c
E4	3627f	128b	354e	249f	170b	87e	6.1e	19.8b	56a	2.2c	82e	45.5c	83.9bc	12.2e	20.1d	5.2d	23.0d
E5	6991c	128b	819b	676b	162f	102b	6.5d	18.2c	49c	2.0d	100a	36.3f	82.2d	15.8a	22.2a	7.3b	32.3a
E6	8981a	127b	1009a	867a	172a	107a	7.0ab	20.7a	47d	2.1c	99a	45.4c	85.8a	14.7b	21.1c	4.9d	29.3b
E7	5587e	122e	503d	444c	152h	90d	7.2a	19.3b	50c	2.3b	99a	48.2b	83.3c	14.5b	21.7ab	6.3c	25.2c
E8	2644g	130a	343e	280e	165e	69f	6.9bc	20.1b	40e	1.7e	100a	39.6e	84.3b	14.6b	21.6b	7.7a	29.5b
Mean	6059	124	593	486	165	95	6.7	19.9	49.2	2.2	87.4	44.6	83.8	14	21.4	6.4	27.3
LSD	21.36	2.49	20.63	17.6	0.56	1.88	0.17	0.49	1.66	0.03	0.14	1.14	0.82	0.21	0.48	0.38	0.73
F	**	**	**	**	**	**	**	*	*	**	**	**	**	**	**	**	**
C. V. (%)	7.9	7.2	7.8	8.2	0.8	4.4	5.8	5.5	7.7	7.5	3.2	5.8	2.2	3.5	5	5.1	6.1

Table 3. Combined analysis for variance of grain yield, yield components and quality criteria of 10 durum wheat cultivars

Genotypes	GY ($kgha^{-1}$)	HD (date)	SS (m^2)	ES (m^2)	MT (date)	PH (cm)	LS (cm)	NSS (no.)	NGS (no.)	YS (g)	VIT (%)	TGW (g)	HW (kg/hl)	PC (%)	SC	SDS (ml)	WG
Artuklu	5906ce	124bd	572d	459de	165bd	103b	7.1b	19.9b	51.5b	2.3a	94c	44.5cd	84.2bc	13.7d	20.3g	5.6d	27.5cd
Aydin	5802ef	126a	586cd	487bc	166ac	106a	6.3e	20.5a	50.9b	2.1d	92d	42.3fg	85.0ab	14.2b	20.9f	5.2d	28.1ac
Eyyubi	5984ce	124cd	572d	488bc	164e	98c	6.8c	19.9b	51.0b	2.3ac	92cd	45.8bc	84.9ab	13.5de	19.8g	7.2b	26.6e
Güneyyildizi	6115bd	125bc	613b	488bc	165d	97c	6.7cd	19.0c	50.2bc	2.2cd	96b	44.2de	83.7c	14.2b	22.2c	7.0b	27.7bc
Harran	5891de	125b	587cd	490bc	166ac	91e	6.8c	20.5a	49.8bc	2.2bc	87e	46.9b	82.1e	14.0c	21.5de	6.2c	26.7de
Sariçanak 98	6506a	124cd	585cd	477cd	165cd	89f	6.6d	20.7a	54.7a	2.3ab	88e	43.4df	85.5a	13.3e	21.1ef	4.2e	25.3f
Svevo	6133bc	121e	643a	530a	163f	94d	6.0f	17.7d	44.6d	2.0e	99a	42.9ef	83.8c	14.6a	23.1b	7.9a	28.8a
Sahinbey	6291ab	124d	568d	443e	166ab	93de	6.9c	20.3ab	45.8d	2.2ac	93cd	50.5a	82.8de	13.6d	19.1h	4.5e	26.2e
Zenit	5581f	124d	611b	492bc	166ab	88f	7.5a	20.7a	45.4d	2.0e	97b	43.8de	82.6e	14.3b	24.4a	7.8a	27.6bc
Zühre	6381a	124d	597bc	504b	165bd	94d	6.8c	19.8b	48.5c	2.0e	99a	41.4g	83.6cd	14.1bc	21.8cd	7.8a	28.3ab
LSD	23.36	0.73	23.07	19.67	1.75	2.1	0.3	0.16	1.86	0.08	1.5	1.27	0.92	0.24	0.53	0.42	0.81
F	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**
C. V. (%)	7.9	7.2	7.8	8.2	0.8	4.4	5.8	5.5	7.7	7.5	3.2	5.8	2.2	3.5	5	5.1	6.1

GY = Grain yield, HD = Heading date, SS = Stalks per square meter, ES = Ear per square meter MT = Maturation time PH = Plant height, LS = Length of spike, NSS = Number of spikelet spike, NGS = Number of grains spike, YS = Yield of spike, VIT = Vitreous, TGW = Thousand grain weight, HW = Hectoliter weight, PC = Protein content, SC = Semolina color, SDS = Mini sedimentation and WG = Wet gluten

Grain yield of cultivars in each environment

Graphically, the GGE biplot allows PC1 and PC2 to be readily displayed in a two-dimensional biplot so that each genotype × environment interaction is visualized (Farshadfar et al. 2013). Both the genotypic and environmental vectors as shown in Fig. 2, illustrating the specific interactions of each genotype with each environment (i.e., the performance of each genotype in each environment). In this respect, Fig. 2 is useful for ranking the genotypes based on their performance in any environment and ranking environments in terms of the relative performance of any genotype. When the relative positions of two genotypes or environments differs by less than 90°, the two are considered different based on the respective variable (Hagos and Abay 2013). Thus, the genotypes Artuklu and Svevo can be seen as differing in their genetic make-up with respect to grain yield. When genotypes are located in different areas on the biplot, the cosine of the vector is an obtuse angle between genotypes far from each other. Cultivar Svevo showed above average results, as indicated by acute angles, for four environments (E1, E2, E7 and E8), and Güneyyildzi, Saricanak and Zühre had above average results for E3, E4, E5 and E6. On the other hand, Artuklu, Eyyubi, Harran95, Sahinbey and Zenit had below average performance in all test environments. Cultivars located near the center of the biplot contributed less to G and/or GE, whereas cultivars having longer vectors showed the greatest contribution of G and/or GE as indicated by Letta et al. (2008). The cultivars Svevo and Zühre, which had the longest vectors, contributed most to positive outcomes, whereas other genotype such as Saricanak 98 had short vectors and contributed less. Thus, these genotypes aligned with specific environments. Although G made major contributions to grain yield, because some of these have opposite directions in the biplot, the genetic contributions may be very different (Jalata 2011). A genotype that results in both high mean yield and high stability, termed an ideal genotype, should possess both high mean performance and high stability across environments. Thus, the cultivar Svevo which is located near the center of the average environment axis (AEA), was more desirable than other genotypes. The cultivar Artuklu was the poorest genotype because it is located far from the ideal genotype and consistently showed the poorest outcomes, as seen in Fig. 3. According to these results, Saricanak was highly stable, whereas Güneyyildzi and Zühre were desirable genotypes because they had above average yield and stability relative to the environment.

On the other hand, six cultivars, namely, Artuklu, Audin 93, Eyyubi, Harran 95, Sahinbey and Zenit had the lowest average yields; therefore, they were undesirable genotypes across the environments. The proximity of a given genotype to the virtual ideal genotype represents the degree to which it can be considered an ideal genotype (Karimizadeh et al. 2013). Hence, Svevo and Zühre are suggested to be ideal genotypes. However, other reports have suggested a different view. This method can be compared to the additive main effects and multiplicative interaction (AMMI) model, which facilitates identification of more stable genotypes using AMMI procedures (Sabaghnia et al. 2008a). The GGE biplot method provides considerable flexibility, allowing plant breeders to simultaneously select for yield and stability (Sabaghnia et al. 2013). GEI and yield stability analyses are important for their consideration of both varietal stability and suitability for cultivation across seasons and ecological circumstances (Adjabi et al. 2014). The results of the present study further indicate that both AMMI and the GGE biplot are informative methods for exploring the stability and adaptation pattern of genotypes in practical plant breeding and in subsequent variety recommendations as suggested earlier by Mortazavian et al. (2014).

Discriminating ability and representation of environments for grain yield

Discriminating ability and representativeness are the most important parameters of the GGE biplot when evaluating an environment. These measures provide valuable and unbiased information about the tested genotypes (Yan and Kang 2003). In Yan and Thinker (2006) model, a long environmental vector had high discriminating ability, and a short one had low discrimination. Therefore, as shown in Fig. 3, test locations E1 and E8 were identified as the most discriminating environments and E7 and E2 as the least discriminating. Another equally important measure of a test environment is the degree to which it is representative of the target environments. The distance between two environments indicates their dissimilarity in discriminating among genotypes. On this basis, the eight tested locations fell into two apparent groups: E1, E2, E7, and E8 were one group, and E3, E4, E5, and E6 formed the other. The biplot indicated that some environments were more similar; however, we selected environments that were farther apart as the focus of this study. If two test locations

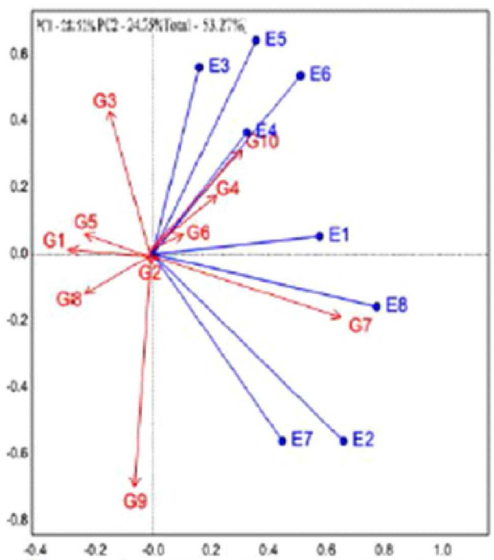

Fig. 2. GGE biplot model showing relationships among test environments and genotypes based on yield

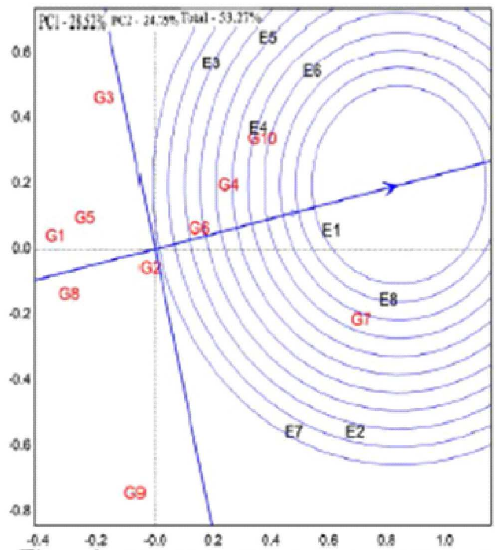

Fig. 3. GGE biplot discriminating ability and representativeness of environments for grain yield

are consistently highly correlated across years, one can be eliminated from the analysis without losing much genotype information (Farshadfar et al. 2013; Sujay et al. 2014). In the biplot graph, a majority of environments have environmental vectors of similar length. Thus, seven of the eight test environments were highly discriminating with regard to durum wheat performance (yield), with E4 being the only exception. Previous research has indicated that the length of a location vector can be used to estimate the standard deviation within each location (Sabaghnia et al. 2013). A testing environment that shows an acute angle with the average-environment coordination (AEC) axis on the biplot is considered representative of the other testing environments, whereas the reverse is true for a testing environment that shows an obtuse angle with the AEC axis (Abate et al. 2015). Hence, E1 and E8 were identified as the most representative testing environments, i.e., the most able to provide unbiased information about the performance of the tested genotypes, whereas E3 and E5 were identified as the least representative. An ideal test environment has enhanced power to discriminate genotypes in terms of the genotypic main effect and is also representative of the overall environment. However, this type of environment may not exist under real conditions. Therefore, we portrayed ideal environments as representing a small circle located in the center of concentric circles, indicated by an arrow (Fig. 3). Hence, among the testing environments, E1 and E8, which fell near this ideal environment, were identified as the most desirable testing environments in terms of being the most representative of the overall environment and having the power to discriminate among genotypes. GEI and yield stability analyses are important for appreciating variations in stability and suitability for cultivation across seasons and ecological conditions (Adjabi et al. 2014).

The relationship among environmental traits

The relationship among environmental traits, shown in Fig. 4, may be most relevant to production agronomists who are interested in knowing which environments are more favorable (or unfavorable) for production in terms of a particular (or general) trait (Yan and Thinker 2006). The biplot showed positive correlations among HD (heading date), SDS (mini sedimentation), SC (semolina color), VIT (vitreous), and PC (protein content), as indicated by the acute angles between their respective vectors (vector angles <90°). Five traits, namely, LS (length of spike), ES (No. of ears per square meter), SS (stalks per square meter), GY (grain yield), and PH (plant height), were highly correlated with one another, and MT (maturation time), NSS (number of spikelet/spike), NGS (number of grains/spike), TGW (thousand grain weight), YS (grain yield/spike), and HW (hectoliter weight) were correlated with one another. Also, relationships of environments with traits were observed. The biplot showed relationships (vector angles <90°) of E5 with three traits (HD, SDS, SC), of E8 with two traits (HD, SDS), of both E6 and E7 with five traits (LS, ES, SS, GY, and PH), and of both E2 and E3 with six traits (MT, NSS, NGS, TGW, YS, and HW). By contrast, E1 and E4 were not found to be significantly related to any traits because these two environments were not positioned relative to specific traits on the biplot. The relationships of environments with traits indicated that E5 was suitable for use in improving quality and E6 for improving grain yield in durum wheat. Previous researchers (Koutis at al. 2012) reported that GGE biplot analysis was more informative than ANOVA for distinguishing special features in specific cultivars as expressed in different environments.

Comparison of environments by traits based on mean and stability

The environment that has both high mean yield and high stability is called an ideal environment (Fig. 5). Accordingly, environments located closer to the ideal environment on the biplot are regarded as more favorable than others (Farshadfar et al. 2013). Any environment not located at the center of AEA is not considered absolutely stable. E6 is considered a favorable environment for the study of durum wheat because it is located near the center of AEA. Moreover, E2, E3, E5, and E7 are located in the above average sector for traits; therefore, these environments can be used to study traits, whereas, E1, E4, and E8 are below average in terms of traits and are not useful for studying durum wheat. Consequently, the biplot indicates that E6 is a favorable environment that can be recommended for the study of durum wheat.

The relationship between genotypes and traits

An understanding of the relationship between genotypes and traits can aid in better understanding of breeding objectives and in identifying traits that are positively or negatively correlated with genotypes as well as traits that can be used to indirectly select for another trait (Yan and Thinker 2006). The biplot showed three groups that were highly correlated in terms of traits (Fig. 6). Thus, for five traits, positive correlations were found among genotypes in Group 1 (ES, SS, VIT, SDS, SC, and PC), as indicated by the acute angles between their respective vectors (vector angles <90°); among those in Group 2 (LS, MT, NSS, TGW, and HD); and among those in Group 3 (YS, NGS, ES, PH, GY, and HW). Also, relationships among environments with regard to traits were observed. The biplot showed relationships between G4 and G10 for six traits (ES, SS, VIT, SDS, PC, and SC), between G5 and G8 for five traits (LS, MT, NSS, TGW, and HD), among G2, G3 and G6 for five traits (YS, NGS, ES, PH, GY, and HW). By contrast, the biplot model showed no significant relationship between G7 and G9 for any traits because these two genotypes were not positioned relative to these particular traits. Thus, the biplot showed excellent discriminating ability in selecting specific genotypes with particular traits and in recommending genotypes for particular traits. The

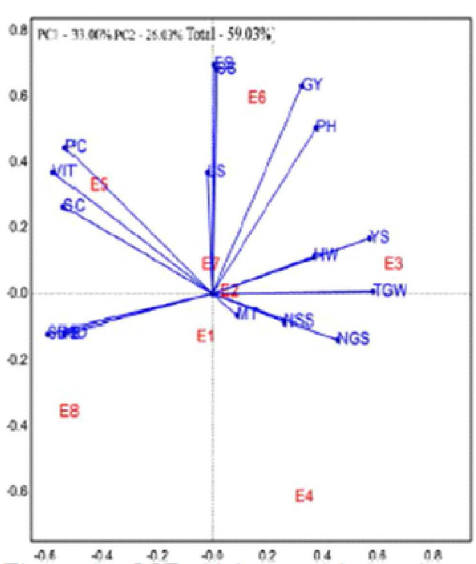

Fig. 4. GGE biplot model based on relationships components among test environments

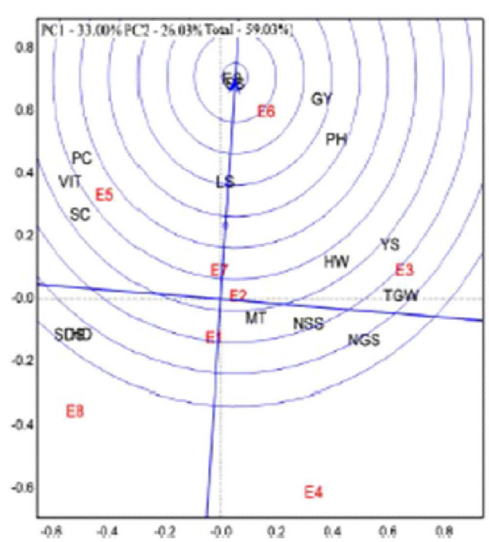

Fig. 5. GGE biplot based on components - focussed scaling for comparison the environments with the ideal environment

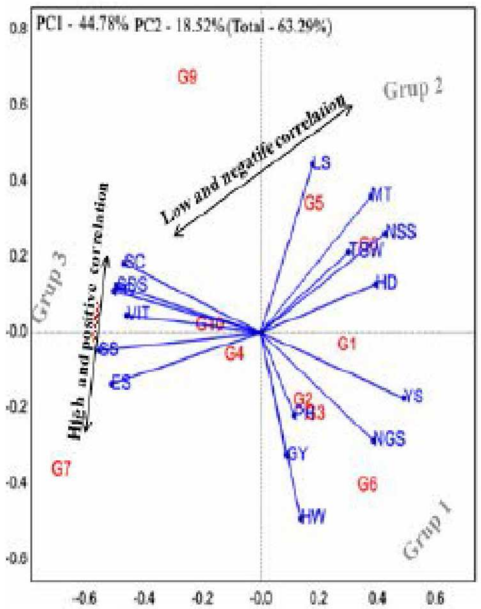

Fig. 6. GGE biplot model based on relationships components among genotypes

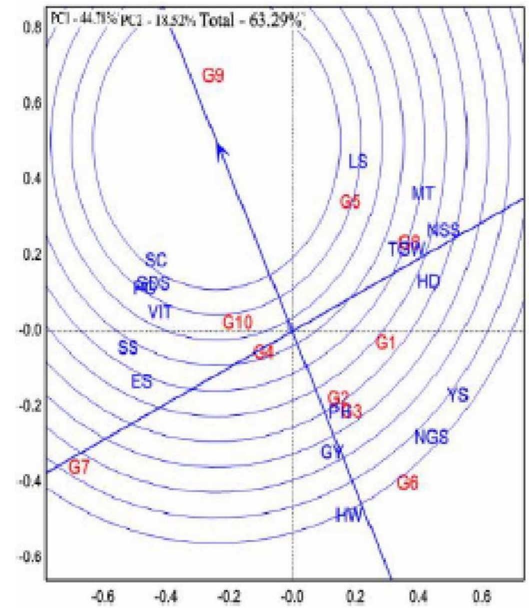

Fig. 7. GGE biplot focused scaling for comparison the genotypes with the ideal genotype

relationships among genotypes according to traits indicated that Zühre (G10) is suitable for use in improving quality and Saricanak 98 for use in improving grain yield in durum wheat. Previous findings indicate that analysis of multi-location trail data using GGE and AMMI model is important for determining visual comparisons and adaptability/stability, as well as for focusing on overall performance to identify superior genotypes (Hagos and Abay 2013). The GT (genotype-trait) biplot provides an excellent tool for visualizing genotype × trait data (Adjabi et al. 2014).

Comparison of genotypes by traits based on mean and stability

The biplot model showed that G9 (Zenit) was located in the center of AEA, identifying it as absolutely stable. Therefore, it is an ideal genotype to study all traits of durum wheat. Furthermore, G5 (Harran 95), G8 (Sahinbey) and G10 (Zühre) were above average in terms of traits, rendering them favorable for the study of traits. By contrast, Artuklu, Aydin, Eyyubi, Guneyyildzi, Saricanak 98 and Svevo were below average in terms of traits and therefore, not suitable for use in the study of durum wheat. Thus, the biplot indicated that Zenit was the most favorable genotype and was recommended for utilization in improvement of traits in durum wheat. Earlier researchers reported that ideal cultivars could be used as commercial cultivars. Moreover, ideal cultivars can be used as parental cultivars for the development of new wheat lines in breeding programs (Sabaghnia and Janmohammadi 2014). An important advantage of the GT(genotype-trait) biplot is that it can be used to identify redundant traits, thus reducing the cost of measuring traits in field experiments without sacrificing precision (Mohammadi and Amri 2011; Sayar and Han 2015).

The results of this study indicated that the relationships among yield components could be divided into three groups. Positive correlations were found between each quality parameters, also yield components, whereas negative correlations were observed between quality parameters, yield and yield components. The GGE biplot indicated that E5 was the ideal environment to improve quality parameters, and E6 was an ideal environment to study and improve all traits of durum wheat. Additionally, Zenit was the best cultivar in terms of all traits, whereas Zühre and Saricanak 98 were the best cultivars for quality and grain yield, respectively.

Acknowledgements

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