



Original article

Genotypes x Environment Interaction and Stability of Bread Wheat (*Triticum Aestivum L.*) Cultivar Under Rainfed Conditions

İrfan Öztürk *

Department of Field Crops, Trakya Agriculture Research Institute, Edirne, Turkey

Abstract

The significant genotype (G) and environment (E) interaction and genetic diversity in the breeding programs are essential issues for the breeder to develop new cultivars. The experiment was conducted in the experimental area of Trakia Agriculture Research Institute Edirne, Turkey at eight environments from 2006-2007 to 2013-2014 growing cycles. In the study, nine released cultivars were used in randomized complete block design with four replications. Grain yield data were subjected to analysis of variance (ANOVA), the additive main effect, and multiplicative interaction (AMMI) and genotype and genotype-by-environment (GGE) biplot analyses. Stable genotypes were identified with GGE biplot and AMMI models. ANOVA and AMMI analysis revealed highly significant ($p < 0.01$) differences among test environments (E), genotypes (G), and their interaction ($G \times E$). The graphical result from PCI showed that the first principal component PC1 explained 49.43% of the interaction while the second principal component, PC2 explained 29.08% of some of the square interaction. The result of PCA revealed that the 2 principal components (PC1, PC2) contributed 78.51% of the total variability. The environmental effect was responsible for the greatest part of the variation, followed by genotype and genotype by location interaction effects. Genotypes, when tested across eight environmental conditions, showed significant variation in grain yield. The highest grain yield was performed by cultivar Bereket (G8) and followed by Selimiye (G7) and Gelibolu (G4). Environment E4 and E1 was found near the ideal test environment of the average environment coordination. It was determined that cultivars G7 (Selimiye) and G8 (Bereket) were well adaptable to all environmental conditions. Cultivar G4 (Gelibolu) was well adaptable to well fertile environmental conditions.

Keywords: Bread wheat, Environment, GGE Biplot, GE interaction, Yield stability.

Received: 20 September 2021 * **Accepted:** 28 September 2021 * **DOI:** <https://doi.org/10.29329/ijjaar.2021.378.1>

* Corresponding author:

İrfan Öztürk, Department of Field Crops, Trakya Agriculture Research Institute, Edirne, Turkey.
Email: irfanozturk6622@gmail.com

INTRODUCTION

Bread wheat is a widely produced crop throughout the Trakia region of Turkey. Because of the various environmental conditions yield and quality varies in wheat and GGE biplot analysis provides an easy and comprehensive solution to genotype by environment interaction (Öztürk and Korkut 2018). Genotype \times trait biplot analysis is highlighted among the multivariate methodologies because it assesses genotypes based on multiple traits and identifies those that are superior to the desired variables; these can be used as parents in breeding programs or even as possible commercial cultivars. A quick and practical visualization of the genetic correlation between traits is also provided by this analysis (Yan and Tinker, 2006). Performance trials have to be conducted in multiple environments because of the presence of GE. Variety trials provide essential information for selecting and recommending crop cultivars. However, a variety of trial data are rarely utilized to their full capacity. Although data may be collected for many traits, an analysis may be limited to a single trait usually yield and information on other traits is often left unexplored. Furthermore, analysis of genotype by environment data is often limited to genotype evaluation based on genotype main effect (G) while genotype-by-environment interactions (G \times E) are treated or a confounding factor (Yan and Tinker, 2006). The long-term value of a genotype depends not only on its absolute productivity or the possession of some other desirable traits but also on its ability to maintain sufficient levels of these traits under different environmental conditions. Experiments that include testing cultivars for several years under a range of locations (or treatments) require analysis of genotype-environment interaction (GE) in addition to the analysis of means. Genotype environment interaction occurs in both long-term (several years at several locations) and short-term (3-4 years testing at a location) crop performance trials, but researchers usually ignore this, especially in short-term trials (Kang 1993). Numerous methods have been developed to reveal patterns of G \times E interaction, additive main effects and multiplicative interaction (AMMI) (Gauch, 1992). The AMMI and GGE biplot has frequently been used to explain GE interaction and determine high yielding and wide adaptability cultivars. These two statistical analyses (AMMI and GGE) have broader relevance for agricultural researchers because they pertain to any two-way data matrices, and such data emerge from many kinds of experiments (Naroui et al., 2013). It is important to identify and understand the pattern of GE to be able to use it constructively in genetic manipulations (Zobel 1990). Additive main effects and multiplicative interaction (AMMI) is ordinarily the model of choice when main effects and interaction are both important (Gauch 2006), which is the most common case with yield trials (Zobel et al. 1988). The AMMI model is more parsimonious than the conventional analysis of variance model in describing GE and provides greater scope for modelling and interpreting GE than simple regression on the site means, because GE can be modelled in more than one dimension (Vargas et al. 1999). Therefore, the objective of this study was to assess the yield performance of the released bread wheat cultivars, the magnitude of GE and to identify high-yielding cultivars, and to investigate their yield stability and genotype-by-environment interactions across various environmental conditions.

MATERIALS and METHODS

This experiment was conducted to determine the GE interaction for yield performance in bread wheat cultivars. The experiment was carried out at eight environments in the Trakya region, Turkey, from 2006-2007 to 2013-2014 growing seasons. Each year was considered a single environment. Nine bread wheat cultivars were examined with randomized complete block design (RCBD) with four replications. Each plot was 6 meters long and had 6 rows, spaced 0.17 meters apart. A seed rate of 500 seeds m² was used. The AMMI method combines the traditional ANOVA and PCA into a single analysis with both additive and multiplicative parameters (Gauch, 1992). The first part of AMMI uses the normal ANOVA procedures to estimate the genotype and environment main effects. The second part involves the PCA of the interaction residuals (residuals after the main effects are removed). Data were analysed statistically for analysis of variance the method described by Gomez and Gomez (1984). The significance of differences among means was compared by using Least Significant Difference (L.S.D. at a %5) test. Several methods have been developed to analyze genotype x environment interaction (Lin et al., 1986; Piepho, 1998). Finlay and Wilkinson's joint regression model (1963) and Eberhart and Russel's method (1966) were applied and the regression coefficient (b), determination coefficients of the regression equations (R²) were calculated (Finlay and Wilkinson, 1963; Eberhart and Russell, 1966 and 1969; Tai, 1971).

RESULTS and DISCUSSION

The results of variance analysis of the research are presented in Tables 1 and 2. The combined ANOVA revealed significant differences among year, cultivar and its interaction (P<0.01) (Table 1 and 3). The results of variance analyses showed that there were significant differences (P<0.01) among year, cultivars and their interaction. Cultivars, when tested across eight environmental conditions, showed significant variation in grain yield. Mean grain yield across eight environments varied from the smallest 5616 kg ha⁻¹ in environment E7 to the highest 8877 kg ha⁻¹ in environment E2. The highest grain yield was performed by cultivar Bereket (G8) and followed by Selimiye (G7) and Gelibolu (G4) (Table 2 and 3).

Table 1. Analysis of variance for yield in 9 bread wheat cultivar grown across eight environments

Source of variation	DF	Sum of Squares	Mean of Squares	F Ratio
Environments (E)	7	745984.85	106569.3	39.213**
Genotypes (G)	8	231407.93	28925.99	10.644**
E×G	56	523176.87	9342.44	3.438**
Error	192	521797.9	2717.7	
C. Total	287	3634595.1		

Table 2. Mean yield of the genotypes across eight environments

No	Cultivar	E1	E2	E3	E4	E5	E6	E7	E8	Mean
G1	Prostor	7529	8806	7273	7453	7344	7723	5014	7451	7324 ^{bc}
G2	Kate A-1	6897	9155	7092	7067	7033	7750	3867	7449	7039 ^d
G3	Pehlivan	7040	9068	6845	7491	6761	7620	5403	7714	7243 ^{cd}
G4	Gelibolu	7102	9180	7489	7703	7015	8411	5205	8172	7534 ^{ab}
G5	Tekirdağ	7100	8579	6545	7618	6514	8052	6600	7149	7270 ^{cd}
G6	Aldane	5787	8323	6183	6587	6428	6269	6572	7362	6689 ^e
G7	Selimiye	7290	8760	6791	7460	7465	7655	6128	8815	7545 ^{ab}
G8	Bereket	7416	9498	7150	8000	6816	7913	6274	7881	7618 ^a
G9	Flamura85	6493	8528	6293	7003	7449	7687	5480	7214	7018 ^d
	Mean	6962	8877	6851	7376	6980	7676	5616	7689	7253
	CV (%)	5.0	4.8	7.6	6.3	9.4	6.8	12.0	6.2	7.2
	LSD (0.05)	51.1	61.7	76.3	67.8	95.2	75.9	98.4	69.1	25.7

Significance at **: P<0.01 and *: P<0.05, E: Environment, G: Genotype

The data of 9 bread wheat cultivars in multi-location and year trials were analyzed to determine whether the effect of the Genotype x Environment (GE) interaction was significant; means were separated using the least significant differences (LSD) test with significance set at P<0.01. Data were also graphically analyzed by the genotype × trait biplot method as recommended by Yan and Thinker (2006). The result of the AMMI model for grain yield is presented in (Table 3). The classical analysis of variance showed that the GEI was significant. So the multiplicative variance of the treatment sum of squares due to GEI was further partitioned by principal component analysis. The ordination technique revealed significant differences for IPC1 and IPC2. The partitioning of SS indicated that environment effect (E) was a predominant source of variation followed by GE and genotype effect. The environmental effect was higher than GEI, which suggests the possible existence of different environmental groups.

Table 3. The variance of AMMI analysis on grain yield of bread wheat cultivar

Source of variation	DF	SS	MS	F	SS%
Treatments	71	2923187	41172	15.15**	
Genotypes (G)	8	231408	28926	10.64**	6.36
Environments (E)	7	2168602	309800	39.21**	59.66
Block	24	189610	7900	2.91**	
Interactions (G×E)	56	523177	9342	3.44**	14.39
IPCA1	14	328838	23488	8.64**	9.04
IPCA2	12	85628	7136	2.63**	2.35
Residuals	30	108710	3624	1.33**	
Error	192	521798	2718		
Total	287	3634595	12664		

* and ** indicate significances, at P<0.05 and P<0.01, respectively. ns: non-significant.

Table 4. AMMI selections the first four genotypes for per environment and PCA scores

Environment	Mean yield (kg ha ⁻¹)	Score	1	2	3	4	IPCA[1]	IPCA[2]
E1	6962	3.045	G4	G8	G1	G5	3.045	2.705
E2	8877	2.361	G4	G8	G7	G1	2.361	0.488
E3	6851	4.107	G4	G8	G1	G2	4.107	0.078
E4	7376	0.222	G8	G4	G5	G1	0.222	3.853
E5	6980	1.855	G7	G4	G1	G8	1.855	-6.171
E6	7676	4.310	G4	G8	G1	G5	4.310	4.990
E7	5616	-15.248	G5	G6	G8	G7	-15.248	1.678
E8	7690	-0.652	G7	G4	G8	G1	-0.652	-7.623

Genotypes when tested across different environmental conditions often show significant variation in grain yield. This fluctuation is generally known as GE interaction. However, GE interaction is likely to be more severe in stress conditions which complicate the process of selecting high yielding stable genotypes (Cooper and Byth, 1996). AMMI selections of the first four cultivars per environment and PCA scores were given in Table 4. Cultivar G4 (Gelibolu) had higher yield potential in four environments and G7 (Selimiye) had across two environmental conditions.

A combined analysis of variance was conducted to test the significance of the environment, genotype, and GE interaction. Genotype and genotype x environment (GGE) biplot analyses were conducted using GGE biplot software (Yan and Kang, 2002) to determine performance and stability for grain yield. The biplot analysis was used to identify genotypes superior for individuals as well as for multiple traits. GGE biplot analysis has been widely used to determine performance stability in multi-location trials when identifying superior genotypes (Yan et al., 2007; Sharma et al., 2010). Many researchers witnessed that the best accurate AMMI model prediction can be made using the first two IPCA (Yan et al., 2000). Yan et al., (2000) indicated that in the graphic analysis the first principal component (IPCA1) represents genotype productivity and the second principal component (IPCA2) genotype stability. The graphical result from PCI showed that the first principal component PC1 explained 49.43% of the interaction sum of the square while the second principal component, PC2 explained 29.08% of some of the square interaction. The result of PCA revealed that the 2 principal components (PC1, PC2) contributed 78.51% of the total variability.

Table 5. The stability parameters and IPCA parameters of AMMI model of the genotypes across eight environments

No	Genotype	X	R ²	S ² d	b	a	IPCAg[1]	IPCAg[2]
1	G1	7324	0.87	1253.76	1.06	-36.34	4.72	0.43
2	G2	7039	0.91	1729.82	1.52	-396.08	9.98	-1.55
3	G3	7243	0.99	88.74	1.12	-85.22	1.14	0.88
4	G4	7534	0.94	752.94	1.24	-142.64	4.54	0.64
5	G5	7270	0.69	1572.74	0.68	234.43	-5.37	7.97
6	G6	6689	0.45	3053.21	0.58	249.00	-10.21	-4.13
7	G7	7545	0.80	1403.43	0.88	118.39	-2.52	-6.59
8	G8	7618	0.91	697.01	1.00	38.65	-1.82	3.96
9	G9	7018	0.87	991.16	0.94	19.81	-0.46	-1.61

X: mean yield, R²: coefficient of determinations, S²d: Deviation from regression, a: intercept value, b: regression coefficient

A genotype having a high yield across the environment is very important for wheat breeding to develop new varieties. GE interaction is the main issue in improving high-yielding and stable genotypes across variable environments. The stability parameters of the genotypes are presented in Table 5. Genotypes G8 and G7 and G4 had higher yield potential across 8 environments. Genotypes G3 was very stable due to the highest determinations coefficient (R²). It was shown that the regression coefficients (b) values ranged between 0.58 and 1.52 among genotypes. The variation in b value reflected a wide range of stability among genotypes. The large variation in b values indicated that 9 genotypes showed different performances across various environments. Cultivar Bereket (G8) had an exact b value and followed by the G1 optimum b value. It was determined the highest positive intercept values (a) in genotypes G6 (Aldane), G5 (Tekirdağ), and G7 (Selimiye). This result showed that genotypes G4, G8 and G7 were higher yield potential both under well and less fertile environment conditions (Table 5).

In the GGE biplot (Figure 1a), the vectors from the biplot center divided the graph into five distinct sectors. The highest and lowest yielding genotypes were identified for each sector. The genotypes located on vertices of polygon performed either best or poorest in one or more environments. The G4 (Gelibolu) was the highest yielding and best performer genotype in environment E2. Genotype G2 (Kate A-1) and G6 (Aldane) was the poorest performer genotypes across all genotypes (Figure 1a). Genotype G4 is the “winner” in environments E2, E3, E1, and E6. The discrimination and representativeness of genotypes based on traits are displayed in Figure 1a.

Genotype ranking relative to an ideal genotype is also shown in Figure 1b. This figure shows that a representative “ideal center” over the property mean values and allows evaluating genotypes according to their nearness or distance to center (Yan et al., 2000; Yan and Tinker, 2005). An ideal genotype should have high mean performance and be absolutely stable across environments. The arrow direction of the single-arrowed line indicates the ideal genotype. The most ideal genotypes are located in the center, whereas genotypes located on the mean vertical axis, but far from the center, are ideal; genotypes located

below the vertical axis are undesirable. Cultivars G8 (Bereket) was closest to the ideal genotype while cultivars G6 (Aldane), G9 (Flamura85) and G2 (KateA-1) were below-average in the yield.

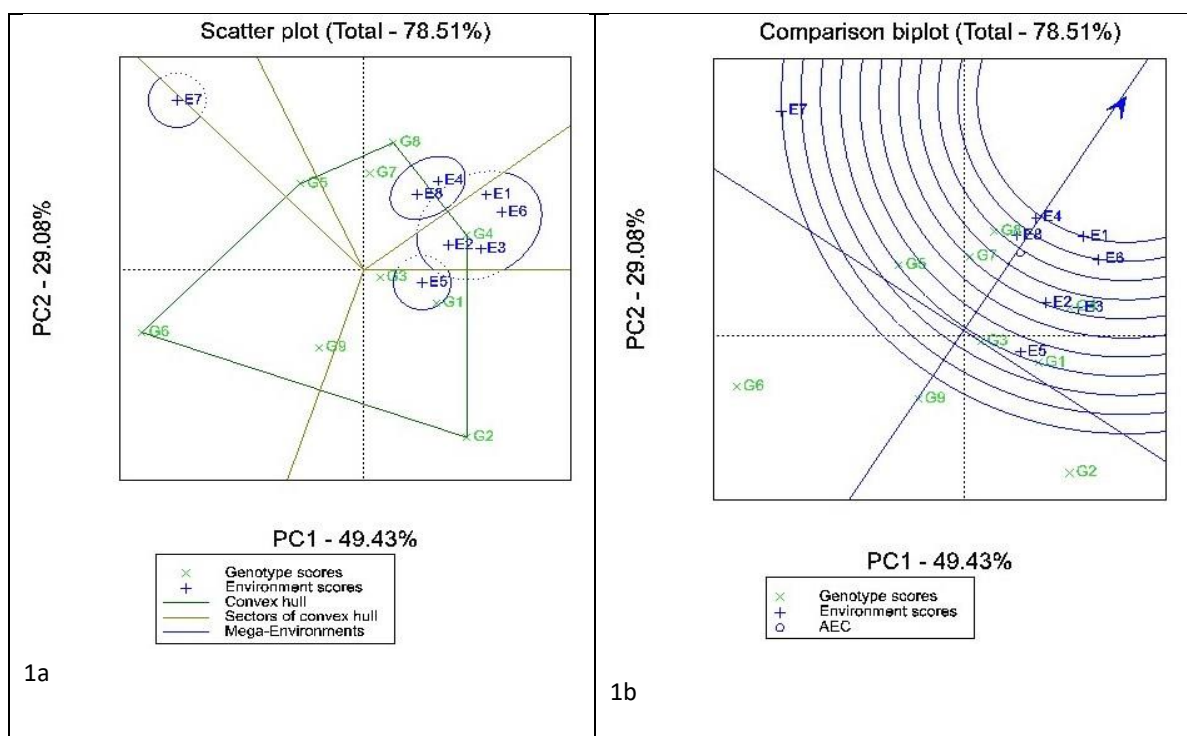


Figure 1. Polygon views of the GGE biplot graph showed that the mega-environments and the which-won-where view of the genotype for grain yield (1a) and, GGE-biplot based on genotype-focused scaling for comparison of the genotypes with the ideal genotype (Figure 1b).

Similarly to the ideal genotype, the ideal environment is located in the first concentric circle in the environment-focused biplot, and desirable environments are close to the ideal environment. The ideal environment is representative and has the highest discriminating power (Yan and Tinker 2006). The GGE biplot in Figure 1b shows the relative ranking of the environments relative to the ideal. The ideal environment represented by the small circle with an arrow pointing to it (Figure 1b) is the most discriminating of genotypes and yet representative of the other test environments. The environment closest to the centre of the concentric circles is the most representative of the environments. The environment closest to the centre of the concentric circles E4 and E2 are the representatives' environments (Fig 1b).

GGE Biplot graph in Figure 2a showed that the mean performance according to environments and stability of genotypes in grain yield. The yield stability of genotypes was evaluated by an average environment coordination (AEC) method (Yan and Hunt, 2001; Rad et al., 2013). A line drawn through the biplot origin is called the average environment axis and serves as abscissa of the AEC. Genotypes are separated by AEC ordinate and genotype which has a shorter absolute length of projection in either of the two directions of AEC ordinate represents a smaller tendency of GEI, which means it is the most

stable genotype across different environments (Yan and Kang, 2003). This ideal genotype is graphically defined by the longest vector in PC1 and without projections in PC2. The concentric circles in Figure 2a help visualize the distance between each genotype and the ideal genotype. It is more desirable for a genotype to be located closer to the ideal genotype; hence, genotypes G8, G4 and G7 were ideal in terms of higher-yielding ability and stability.

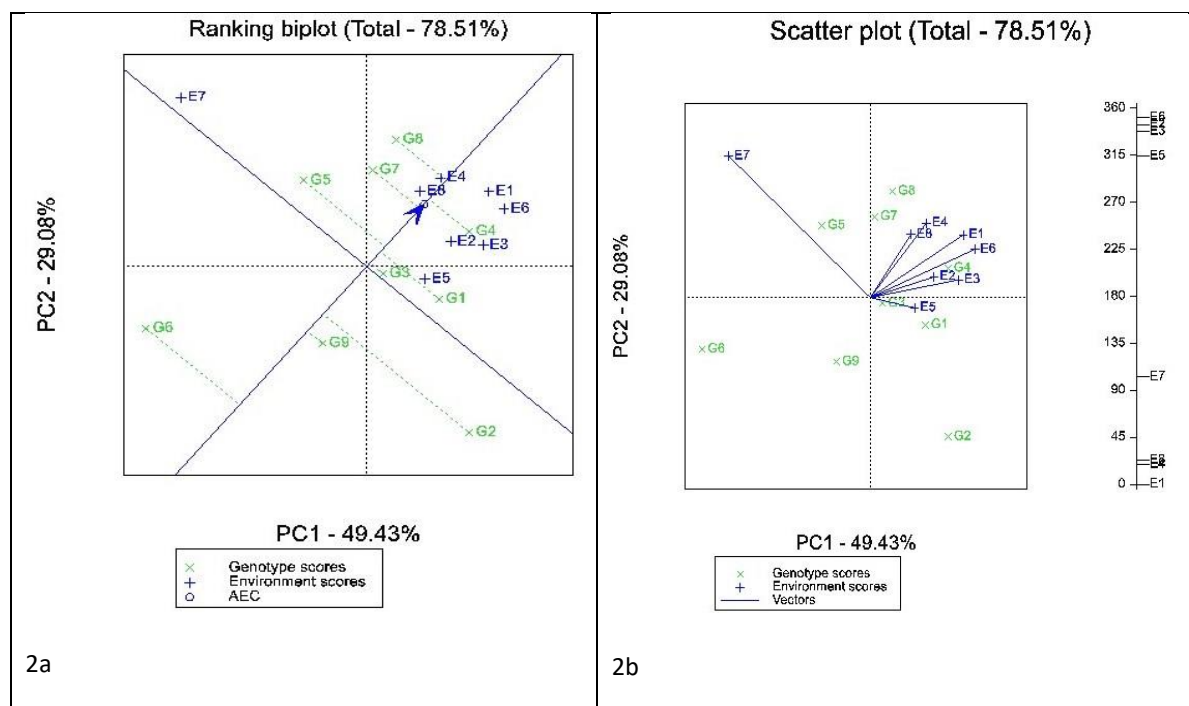


Figure 2. GGE Biplot graph showing ranking of 9 genotypes for stability in grain yield (2a), and GGE biplot showing relationships between test environments (Figure 2b)

The interrelationship among the environments is presented in the vector view of the GGE-biplot (Figure 2b). Environment-vector view of the GGE-biplot indicated that a long environmental vector reflects a high capacity to discriminate the genotypes. Furthermore, the cosine of an angle between vectors of two environments approximates the correlation between them: a wide obtuse angle indicates a strong negative correlation, an acute angle indicates a positive correlation while a close to 90° angle indicates a lack of correlation (Yan and Tinker 2006; Yan and Rajcan, 2002). The angle between the environment vectors provides further information on the correlation between environments, where an acute angle indicates a positive correlation, an obtuse angle indicates a negative correlation and a right angle indicates no correlation (Figure 2b). Accordingly, all environments were positively correlated except E7 as all of the angles among them were smaller than 90° suggesting that indirect selection for yield can be suitable across these test environments. There is also a strong positive correlation between environment E4 and E8, E2 and E3 (Figure 2b). With the longest vectors from the origin, environments E7 was the most discriminating, E1 and E6 was moderately discriminating, and E5 was least discriminating (Figure 2b). In order to visually display relations of observed traits and genotypes

multivariate biplot analysis (genotype by trait biplot), described by Yan and Rajcan, (2002), Yan and Tinker (2006), and Yan and Kang (2003) was used.

Regression coefficient for grain yield was determined and given in Figure 3b. For grain yield it was determined that cultivars G7 and G8 were well adaptable to all environmental conditions. Genotypes G1, G3 and G9 were medium adaptable to all environment conditions. Genotypes G4 was well adaptable to well fertile environment conditions (Figure 3b). The adaptability of a variety of diverse environments is usually tested by the degree of its interaction with different environments under which it is grown. A variety or genotype is considered to be more adaptive or stable if it has a high mean yield but a low degree of fluctuation in yielding ability when grown over diverse environments (Patel et al, 2014).

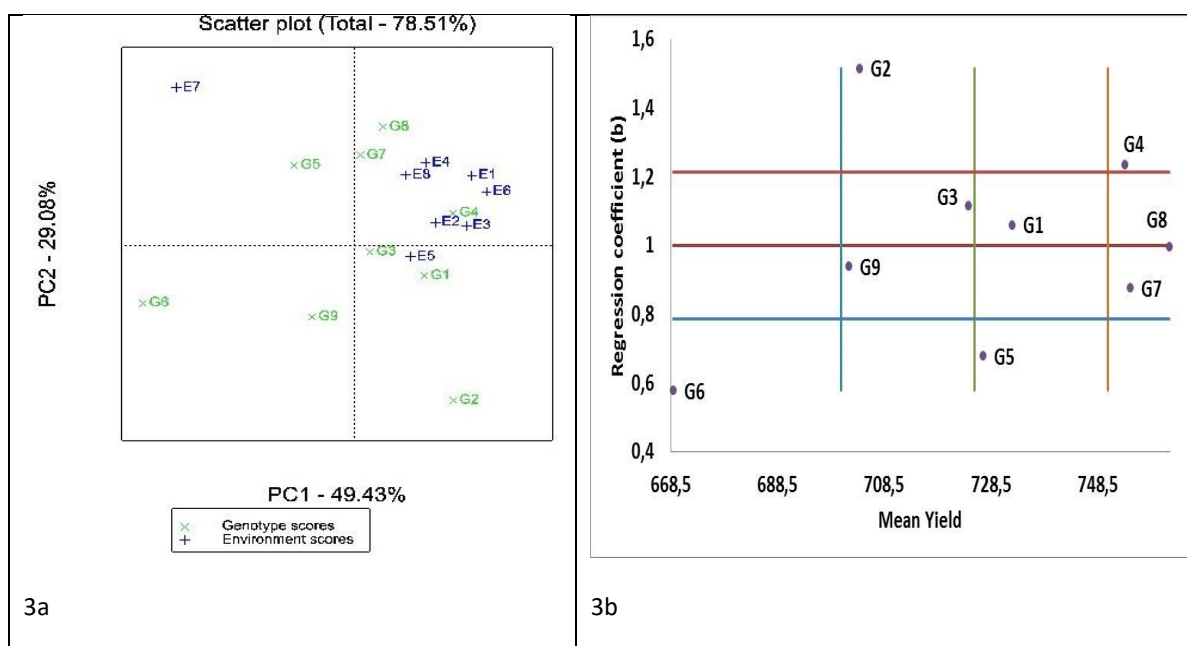


Figure 3. A biplot of grain yield environmental means vs IPCA1 for 9 cultivars in the 8 environments (3a), and scatter plot of regression coefficient of mean yield of nine bread wheat cultivars (3b).

According to Eberhart and Russell (1966), a stable variety should have around unit regression coefficient over environments ($b_i \approx 1$) and minimum deviation from the regression ($S^2d=0$) in addition to higher grain yield than the population mean. The cultivar Bereket (G8) had over average grain yield, showed lower deviation from linear regression (S^2d), positive intercept value (a), and its optimum regression coefficient (b) was one. Thereby it was identified as a stable genotype across the environments. Among these, genotype G7 (Selimiye) was well adapted to the poor environment condition and it has above average stability; while genotypes G8 had equal unit regression coefficient, and was well adapted to all the environments (Figure 3a).

CONCLUSION

The results of ANOVA and AMMI analysis revealed highly significant differences among test environments (E), genotypes (G), and their interaction (G×E). Mean grain yield across eight environments varied from the smallest in environment E7 to the highest in environment E2. The highest grain yield was performed by cultivar Bereket (G8) and followed by Selimiye (G7) and Gelibolu (G4). The partitioning of SS indicated that environment effect (E) was a predominant source of variation followed by GE and genotype effect. The environmental effect was higher than GEI, which suggests the possible existence of different environmental groups. AMMI selections of the first four cultivars per environment and PCA scores showed that cultivar G4 (Gelibolu) had higher yield potential in four environments and G7 (Selimiye) had across two environmental conditions. Results of the AMMI analysed showed that cultivars G8 (Bereket) and G7 (Selimiye) were closest to the ideal Genotypes. G4 (Gelibolu) was also the highest yielding and best performer genotype in environment E2. The environment closest to the centre of the concentric circles is the most representative so E4 and E2 are the representatives' environments. Environment E4 and E1 was found near the ideal test environment of the average environment coordination. It was determined that cultivars G7 (Selimiye) and G8 (Bereket) were well adaptable to all environmental conditions and also were ideal in terms of higher-yielding ability and stability.

Acknowledgement

This research was supported by Ministry of Agriculture and Forestry, General Directorate of Agricultural Research and Policies. Project name is “Bread Wheat Breeding Research in Trakia-Marmara Region”

REFERENCES

- Cooper, M., and Byth, D.E. (1996). Understanding plant adaptation to achieve systematic applied crop improvement: A fundamental challenge. In: Cooper, M and Hammer, GL (eds.) Plant adaptation and crop Wallingford: CABI Publishing.
- Eberhart, S.A., & Russell, W.A. (1966). Stability parameters for comparing varieties. *Crop. Sci.*6:36-40.
- Eberhart, S.A., & Russell, W.A. (1969). Yield stability for a 10-line diallel of single-cross and double-cross maize hybrids. *Crop Sci.* 9, 357-361.
- Finlay, K.W., & Wilkinson, G.N. (1963). The Analysis of Adaptation in a Plant Breeding Programme. *Aust. J. Agric. Res.*, 14: 742-754.
- Gauch, H.G. (1992). Statistical analysis of regional yield trials: AMMI analysis of factorial designs. Elsevier, Amsterdam, Netherlands.
- Gauch, H.G. (2006). Statistical analysis of yield trials by AMMI and GGE. *Crop Science* 46, 1488-1500. doi: 10.2135/cropsci2005.07-0193

- Gomez, K.A., & Gomez, A.A. (1984). Statistical Procedures for Agricultural Research. 2nd Ed. John Willey and Sons, Inc. New York. 641.
- Kang, M.S. (1993). Simultaneous selection for yield and stability in crop performance trials: consequences for growers. *Agronomy Journal* 85, 754-757.
- Lin, C.S., Binns, M.R., and Lefkovich, L.P. (1986). Stability analysis: where do we stand? *Crop Sci.* 26: 894-900.
- Naroui, M.R.R., Kadir, M.A., Rafii, M.Y., Hawa Jaafar, Z.E., Naghavi, M.R., and Ahmadi, F. (2013). Genotype \times environment interaction by AMMI and GGE biplot analysis in three consecutive generations of wheat (*Triticum aestivum*) under normal and drought stress conditions. *AJS* 7 (7):956-961.
- Öztürk, İ., and Korkut, Z.K. (2018). Evaluation of Drought Tolerance Indices and Relationship with Yield in Bread Wheat Genotypes under Different Drought Stress Conditions. *Journal of International Scientific Publications. Agriculture & Food.* Volume 6, p: 359-367.
- Patel, B.C., Y.M. Rojasara., V.R. Akbari., and J.A. Patel. (2014). Stability analysis for grain yield in bread wheat (*Triticum aestivum* L.) for irrigated ecosystems. *Journal of Wheat Research* 6(2):160-162
- Piepho, H.P. (1998). Methods for comparing the yield stability of cropping systems' a review. *J. of Agron. and Crop Sci.* 180: 193-213.
- Rad, M.R., Naroui-Abdul, M., Rafii, M.Y., Jaafar, H., Naghavis, M.R., Ahmadi, F. (2013). Genotype \times environment interaction by AMMI and GGE biplot analysis in three consecutive generations of wheat (*Triticum aestivum* L.) under normal and drought stress conditions. - *Aust. J. Crop Science* 7: 956-96.
- Sharma, R.C., Morgounov, A.I., Braun, H.J., Akin, B., Keser, M., Bedoshvili, D., Bagci, A., Martius. C., van Ginkel, M. (2010). Identifying high yielding stable winter wheat genotypes for irrigated environments in Central and West Asia. *Euphytica* 171: 53-64.
- Tai, G.C.C. (1971). Genotypic stability analysis and its application to potato regional trials. *Crop Sci.* 11: 184-190.
- Vargas, M., Crossa, J., van Eeuwijk, F.A., Ramirez, M.E., Sayre, K. (1999). Using partial least squares regression, factorial regression, and AMMI models for interpreting genotype environment interaction. *Crop Science* 39, 955-967.
- Yan, W., Hunt, L.A., Sheng, Q., and Szlavnic, Z. (2000). Cultivar evaluation and mega-environment investigation based on the GGE biplot. *Crop Science* 40(3):597-605.
- Yan, W., and Rajcan, I.R. (2002). Biplot analysis of test sites and trait relations of soybean in Ontario. *Canadian Journal of Plant Science* 42:11-20.
- Yan, W., and Kang, M.S. (2002). *GGE Biplot Analysis: A Graphical Tool for Breeders, Geneticists, and Agronomists.* New York, NY, USA: CRC Press.
- Yan, W., and Kang, M.S. (2003). *GGE biplot analysis: a graphical tool for breeders, geneticists, and agronomists* (CRC Press: Boca Raton, FL).
- Yan, W., Kang, M.S., Ma, B., Woods, S., Cornelius, P.L. (2007). GGE biplot vs. AMMI analysis of genotype-by-environment data. *Crop Sci.* 47: 643-653.
- Yan, W., and Hunt, L.A. (2001). Interpretation of genotype \times environment interaction for winter wheat yield in Ontario. *Crop Science* 41: 19-25.

- 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.
- Yan, W., and Tinker, N.A. (2006). Biplot analysis of multi-environment trial data: Principles and applications. *Can. J. Plant Sci.* 86: 623-645.
- Zobel, R.W. (1990). A powerful statistical model for understanding genotype by environment interaction. In 'Genotype by environment interaction and plant breeding'. (Ed.MSKang) pp. 126-140. (Louisiana State University: Baton Rouge, FL).
- Zobel, R.W., Wright, M.J., and Gauch, H.G. (1988). Statistical analysis of a yield trial. *Agronomy Journal* 80, 388-393.