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Grain Yield Stability of Durum Wheat Genotypes: A Graphical Approach

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ABSTRACT

The study was conducted in the Thrace Region in 2019 and 2020. Fifteen elite lines and 10 varieties of durum wheat were used as material. The aim of this study was to determine the stability of elite lines and varieties by using the graphical AMMI and GGE biplot analyses. Elite lines 3, 4, 5, 7, 8, 9, 10, 12, 15 and varieties Cabato and NKU Ziraat had values above the general mean. The grain yield results of the elite lines indicate that the selected breeding materials possess high yield potential, demonstrating the effectiveness of the selection process. Stability analysis of the genotypes indicated that three out of eight environments contributed positively to grain yield, whereas the remaining five had a negative impact. These data reveal the importance of identifying suitable environments for high grain yield in durum wheat. Among the durum wheat genotypes examined, elite lines 7 and 4 had better stability and grain yield for all environments. When genotype performance was assessed across individual environments, elite lines 3, 9 and 10 showed the most superior characteristics for environments 1 and 4, while elite lines 12 and 15 were most suitable for environments 7 and 8.

1. INTRODUCTION

Durum wheat (*Triticum durum* Desf.), which is grown on a limited basis in certain countries around the world, is a grain product with high prices and plays an important role in world trade. Durum wheat is well adapted to the Mediterranean climate since it is heat and drought tolerant and performs well in poor soils (Mastrangelo et al., 2005). Thus, durum wheat is cultivated as the main crop in four countries in southern Europe (Spain, France, Italy, and Greece), three countries in northern Africa (Morocco, Algeria, and Tunisia) and two countries in southwest Asia (Türkiye and Syria) (Martínez-Moreno et al., 2022).

Türkiye was the largest producer of durum wheat (*Triticum durum* Desf.) after Russia, with a cultivation area of 1.6-2 million hectares in the 19th and early 20th centuries. Durum wheat accounted for 80% of the wheat area in Southeast Anatolia, 60% in Thrace, and 40% in the coastal areas (Ozberk et al., 2005). As in many other countries, the introduction of high-yield bread wheats into the region, as a reflection of the "Green Revolution" caused an increase in bread wheat production and a rapid decrease in durum wheat production.

As a result of the high adaptation to new bread wheat varieties in the Thrace Region within the scope of the National Wheat Project, the proportion of durum wheat varieties in wheat production was approximately 60% in the 1960s but decreased to 2.5% after the 1980s (Sehirali & Genctan, 1985; Ada, 1993). Today, durum wheat production is at the level of 1%. The main reason for this situation is the lack of new genotypes with high yield and quality. Finding and developing cultivars with improved grain yields has been the main agenda of many durum wheat breeding programs worldwide (Khayatnezhad & Gholamin, 2020), which are expected to play a crucial role in climate change adaptation (De Vita & Taranto, 2019). Therefore, it is important to select genotypes that have the desired agronomic characteristics and are well adapted to the environment (Bilgin et al., 2008).

The different responses of genotypes to various environmental conditions, that is, genotype × environment interactions, make it difficult to select stable and well-adapted genotypes. Genotype selection depends on understanding genotype, environment, and genotype × environment interactions (Jat et al., 2017). Yan et al. (2000) developed a “genotype main effect and genotype by environment interaction (GGE) biplot” methodology for graphical analysis of multi-environment trials (MET) data. The GGE biplot is constructed by plotting the first two principal components (PC1 and PC2) derived from singular value decomposition of the environment-centered data. Increasingly, plant breeders/agronomists have found GGE useful in mega-environment analysis (Yan & Tinker, 2005; Kang et al., 2006; Fan et al., 2007), test-environment evaluation (Dimitrios et al., 2008), trait association and trait profile analyses (Yan & Rajcan, 2002).

The Additive Main Effects and Multiplicative Interaction (AMMI) model, a widely adopted approach in stability analysis, incorporates both additive main effects and genotype-by-environment (G×E) interaction effects in its assessment. In contrast, the GGE biplot method graphically represents multi-environment trial data, facilitating the identification of superior genotypes across test environments. Through GGE biplot analysis, genotypes can be evaluated for mean performance, stability, and general or specific adaptations in individual environments or between environments. A stable genotype is a genotype that has high yield with minimum fluctuation in performance when grown in diverse environments (Zerihun et al., 2016). Additive main effects and multiplicative interactions analysis indicated that the yield performances of bread wheat cultivars were highly affected by the major environmental factors. The first two principal component axes (PCA 1 and PCA 2) were significant and they explained 60.9% of the total genotype x environment interaction (Ilker et al., 2012).

These graphical tools play a special role in the simultaneous evaluation of yield and stability, as well as the selection of multi-environments (ME) and specific adaptability (Ajay et al., 2020). Among those models, the AMMI model and the GGE biplot are statistical methods most extensively used for modeling genotype × environment interactions (GEI) and increasing the efficiency of selection in yield trials and group environments in multi-environment trials of cereal crops, including wheat. GGE-Biplot analysis showed that although the durum wheat yield trials were conducted in many environments, outcomes alike can be obtained from one or two representatives of each ME (Kaya, 2022). According to GGE-Biplot analysis, it was determined that two mega-environments instead of four environments would be sufficient for the stability of Lucilla and Glosa genotypes (Gungor et al., 2022).

This study, which was carried out for 2 years in 4 different locations with 15 elite durum wheat lines and 10 durum wheat varieties, aimed to determine appropriate elite lines to be bred for different environments and varieties to be produced in the region by using AMMI and GGE biplot graphics.

2. MATERIALS AND METHODS

Field trials and materials

The trials were conducted for two years (2019 and 2020) under natural rainfall conditions in the Thrace region in Suleymanpasa (Tekirdag), Hayrabolu (Tekirdag), Luleburgaz (Kırklareli) and Edirne locations to represent different ecologies. Geographical descriptions of the locations are given in Table 1.

Table 1. Geographical characteristics of test locations

Locations	Longitude Latitude	Altitude, m	Soil Texture	Temperature (°C) Min.	Max.	Rainfall, mm	Temperature (°C) Min.	Max.	Rainfall, mm
				2019			2020		
Suleymanpasa	40° 59′ 37" N 27° 34′ 53" E	20	Silt Loam	3.1	28.2	404.4	2.8	25.1	394.1
Hayrabolu	41° 12′ 49" N 27° 6′ 22" E	81	Clay Loam	0.8	31.7	381.8	- 0.7	30.2	411.2
Luleburgaz	41° 24′10" N 27° 21′ 56" E	45	Clay Loam	- 0.2	32.0	350.4	- 2.4	28.5	394.4
Edirne	41° 40′ 38" N 26° 33′ 21" E	252	Clay Loam	1.1	32.0	478.3	- 0.9	30.1	393.2

Soil classification system (Ulgen and Yurtsever, 1995).

Fifteen elite lines of durum wheat developed by combination breeding in the Department of Field Crops of the Faculty of Agriculture and 10 commonly cultivated durum wheat varieties were used as material in the study (Table 2). The experiments were conducted according to a randomized complete block design with 4 replications. Sowing was made with a parcel sowing machine on 7.5 m long and 1.02 m wide plots with 500 plants per square meter. In the trials, 250 kg of 20.20.0 compound fertilizer was given per hectare with sowing, 180 kg of urea (46%) was given in the tillering period, and 200 kg of ammonium nitrate fertilizer (26%) was given during stem elongation. Herbicide was applied to the weeds during the tillering period.

Table 2. Pedigrees of the durum wheat elite lines and varieties used in the experiment

Geno. no	Elite lines	Pedigree	Geno. no	Elite lines	Pedigree
1	NZFM 8	*IDSN261/Svevo*	14	NZFM 45	*Tunca79/Svevo*
2	NZFM 22	*Ged75//Ged75/Yav79*	15	NZFM 49	*Epidur/Zenit*
3	NZFM 32	*IDSN165/Kızıltan91*		**Varieties**	
4	NZFM 33	*Fuatbey2000/Zenit*	16	Caboto	*Saragolla/Line D97.15*
5	NZFM 35	*Zenit/YP43*	17	NKU Ziraat	*Gediz75/Yavaros79*
6	NZFM 37	*Zenit/Tunca79*	18	Mirzabey 2000	*GD-2/D-1184528*
7	NZFM 38	*Svevo/Hacımestan*	19	Zenit	*Valriccardo/Vic.*
8	NZFM 39	*Zenit/Hacımestan*	20	Saragolla	*Iride/Linea-PSB-0114*
9	NZFM 40	*Zenit/7113M5*	21	Pitegora	*V702/Levante*
10	NZFM 41	*Ç 1252/Svevo*	22	Kızıltan 91	*UVY 162/61-130//BY2E/TC*
11	NZFM 42	*Fuatbey2000/Svevo*	23	Svevo	*Cimmyt-Selection/Zenit*
12	NZFM 43	*Ionia/Zenit*	24	Ç 1252	*61-130//Kunduru414-44/377-2*
13	NZFM 44	*Ged75/Yav79//Zenit*	25	Maestrale	*Iride/Svevo*

Statistical analysis

The grain yield values obtained in the research conducted with 25 durum wheat genotypes were analyzed via variance analysis using the JMP 16.0 statistical program. Significant differences between genotypes were determined using the least significant difference $TUKEY_{HSD}$ test. The obtained data were analyzed using the BAFR statistical package program (Kahrıman, 2020) according to the AMMI and GGE biplot methods, which allow two-way evaluation by combining the effects of genotype and genotype × environment (G × E) interaction on the same graph. The performance of durum wheat genotypes was assessed using stability models (1) AMMI (Gauch & Zobel, 1997) and (2) GGE biplot (Yan & Kang, 2002). The AMMI analysis is based on two previously discovered simple models. AMMI first analyzes the main effects of genotypes and environments (additive) using analysis of variance (ANOVA) and then analyses the residual from this model (namely the interaction) using principal components analysis (PCA). The model for AMMI analysis is given.

$$Y_{ij} = \mu + \delta_i + \beta_j + \Sigma_{\lambda k}\delta_{ik}\beta_{jk} + \varepsilon_{ij} \quad (1)$$

where Y_{ij} is the average yield of the i^{th} variety in the j^{th} environment, μ is the general mean, δ_i is the genotypic effect of the i^{th} cultivar, β_j is the j^{th} environment effect, λ_k is the eigenvalue of the principal component axis k, δ_{ik} is the genotype eigenvector value for PC axis n, β_{jk} is the environment eigen vector value for PC axis k, and ε_{ij} is the residual error. The following linear-bilinear GE biplot model was used to explore G plus GE variability in durum wheat's grain yield.

$$Y_{ij} = \mathrm{m} + \mathrm{b}_j + \sum_{n=1}^{k} \lambda_n \xi_{in} \eta_{in} + \varepsilon_{ij} \quad (2)$$

where Y_{ij} is the mean of genotype i in environment j; μ is the grand mean; β_j is the main effect of environment j; n is the singular value; λ_{in} and ζ_{in} are the singular vectors for genotypes and environments for lambda = 1, 2, ... k, respectively; and ε_{ij} is the residual effect. The dataset was then subjected to graphical analysis using the GGE biplot in the BAFR statistical package program (Kahrıman, 2020). The GGE biplots were drawn using the first two symmetrically scaled principal components for generating average tester coordinate and polygon view graphs (Yan & Kang, 2002). The vector view biplot was obtained to visualize relationships between locations.

3. RESULTS AND DISCUSSION

In this study, the mean grain yields of 15 elite durum wheat lines and 10 durum wheat varieties at 4 different locations over 2 years ranged from 705.44 to 551.94 kg ha^{-1} (Table 3). While 9 durum wheat elite lines and 2 durum wheat varieties had grain yields above the general mean, 6 elite lines and 8 durum wheat varieties had grain yields below the general mean. The mean yield of the elite lines was 654.74 kg ha^{-1} and the mean yield of the varieties was 626.88 kg ha^{-1}. The environmental impact on grain yield was positive in the Suleymanpasa, Hayrabolu and Luleburgaz locations in 2019, while the environmental impacts were negative in the Edirne location in 2019 and in the Suleymanpasa, Luleburgaz, Hayrabolu and Edirne locations in 2020. The genotypic effects of elite lines 3, 4, 5, 7, 8, 9, 10, 12, 15 with Caboto and NKU Ziraat durum wheat varieties on grain yield were positive, while the genotypic effects of the other elite lines and durum wheat varieties were negative.

Table 3. Mean grain yield, genotypic and environmental effect values

Genotype no	Genotypes	2019				2020				Mean	Genotypic effect
		Tekirdag	***Hayrabolu***	***Luleburgaz***	***Edirne***	***Tekirdag***	***Hayrabolu***	***Luleburgaz***	***Edirne***		
1	NZFM 8	845,75	754,00	808,00	615,75	533,50	576,00	560,50	451,75	643,16 c-h	-0,44
2	NZFM 22	869,00	679,50	830,00	546,50	516,00	520,50	546,25	443,25	618,88 ghı	-24,72
3	NZFM 32	871,00	825,25	923,50	663,25	500,25	650,25	624,75	535,50	699,22 a	55,63
4	NZFM 33	935,00	766,75	897,00	524,00	593,00	610,50	557,00	454,25	667,19 a-e	23,59
5	NZFM 35	828,00	701,75	908,75	503,75	583,50	525,00	607,25	551,50	651,19 b-g	7,59
6	NZFM 37	702,25	638,75	711,50	381,50	545,25	535,75	562,50	497,00	571,81 k	-71,78
7	NZFM 38	882,50	774,00	1013,50	576,00	654,25	623,75	534,00	466,50	690,56 ab	46,97
8	NZFM 39	795,25	817,75	866,00	510,50	612,00	668,50	622,25	508,25	675,06 a-d	31,47
9	NZFM 40	891,25	721,75	966,50	657,25	584,25	559,25	639,00	487,00	688,28 ab	44,69
10	NZFM 41	921,75	834,25	972,25	622,75	600,75	541,25	539,50	507,00	692,44 ab	48,84
11	NZFM 42	838,75	660,25	811,00	496,00	609,25	562,75	521,00	450,75	618,72 ghı	-24,88
12	NZFM 43	819,75	721,75	929,25	579,00	676,75	599,50	617,25	525,50	683,59 abc	40,00
13	NZFM 44	777,00	622,00	775,75	426,75	618,75	703,50	633,25	531,25	636,03 d-h	-7,56
14	NZFM 45	917,00	683,00	837,75	571,00	546,75	486,75	489,00	431,00	620,28 f-ı	-23,31
15	NZFM 49	819,75	711,25	893,75	569,50	666,25	589,50	547,75	519,25	664,63 a-f	21,03
16	CABOTO	849,25	799,50	898,00	594,00	740,50	586,50	629,25	546,50	705,44 a	61,84
17	NKU ZIRAAT	861,75	753,25	973,25	562,00	734,50	614,00	601,00	504,50	700,53 a	56,94
18	MIRZABEY	840,75	612,50	720,25	529,00	480,50	427,75	568,25	461,75	580,09 ıjk	-63,50
19	ZENIT	840,25	615,75	802,00	532,50	457,00	579,75	526,75	448,00	600,25 hıj	-43,34
20	SARAGOLLA	841,25	717,00	764,00	565,00	497,25	512,50	568,25	517,00	622,78 e-ı	-20,81
21	PITEGORA	786,25	710,00	809,00	634,75	501,25	479,25	589,00	488,25	624,72 e-ı	-18,88
22	KIZILTAN 91	799,75	604,75	673,25	510,75	494,00	346,25	569,00	417,75	551,94 jk	-91,66
23	SVEVO	778,50	763,50	863,25	539,50	511,00	560,00	511,00	471,50	624,78 e-ı	-18,81
24	Ç 1252	848,75	720,50	772,25	537,75	620,25	464,25	591,00	434,75	623,69 e-ı	-19,91
25	MAESTRALE	828,25	744,00	819,00	542,50	564,00	541,00	544,75	493,25	634,59 d-h	-9,00
Mean of lines		847,60	727,47	876,30	549,57	589,37	583,52	573,42	490,65	654,74	
Mean of varieties		827,48	704,08	809,43	554,78	560,03	511,13	569,83	478,33	626,88	
Environments mean		839,55	718,11	849,55	551,65	577,63	554,56	571,98	485,72	643,59	
Environmental effect		195,96	74,52	205,96	-91,94	-65,96	-89,03	-71,61	-157,87		

E1, Tekirdag-Suleymanpasa location in 2019; E2, Tekirdag-Hayrabolu location in 2019; E3, Kırklareli-Luleburgaz location in 2019; E4, Edirne location in 2019; E5, Tekirdag-Suleymanpasa location in 2020; E6, Tekirdag-Hayrabolu location in 2020; E7, Kırklareli-Luleburgaz location in 2020 ve E8, Edirne location in 2020.

The AMMI variance analysis and principal component analyses performed on the grain yield data obtained from 8 environments are given in Table 4. When the main effects and variance AMMI regarding grain yield values obtained in eight environments were examined, environment, genotype, and genotype × environment interactions were found to be statistically significant at the 0.01 level (Table 4).

Table 4. AMMI variance analysis and principal component analysis for grain yield values

Sources of Variation	Degrees of Freedom	Sum of Squares	Mean Squares	F Value	Impact Rate
Environments	7	137000	196000	398.00 **	80.07
Replication (E)	24	1180	492	1.73*	0.69
Genotypes	24	13900	5770	20.3**	8.12
Genotype × Environment Int	168	19000	1130	3.99**	11.11
PC1	30	6620	2210	7.77**	34.8
PC2	28	4870	1740	6.12**	25.6
PC3	26	3190	1230	4.32**	16.8
PC4	24	1850	773	2.72**	9.70
PC5	22	1300	589	2.07**	6.80
PC6	20	736	368	1.30	3.90
PC7	18	461	256	0.90	2.40
Residuals	576	16400	284		
Total	967	207000	2140		

The result of the analysis of variance of the AMMI model revealed that grain yield was significantly ($p < 0.01$) affected by environment, genotype, and genotype-environment interaction, which explained 80.07%, 8.12% and 11.11% of the variation, respectively. Moreover, three PCs (PC1, PC2 and PC3) explained 77.2%, a significant part of the genotype-environment interaction, as shown in Table 4. AMMI analysis showed that much of the variation in grain yield was due to environmental differences, indicating that the environments varied significantly. This finding is consistent with findings of studies by Mohammadi et al. (2017), Ngailo et al. (2019) and Bhardwaj et al. (2020). The highest proportion of variation from the environment, followed by GEI is in agreement with results for barley (Pour-Aboughadareh et al., 2022) and durum wheat grain yield (Mohammadi et al., 2015).

According to the results obtained by the AMMI graphic method, PC1 explained 34.8% of the variation in grain yield, PC2 explained 25.6% and PC3 explained 16.8%. The fact that PC1, PC2 and PC3 explain 77.2% of the grain yield shows that these three main components are sufficient to visually represent the grain yield of durum wheat varieties. The grain yield explanation rate was determined as 9.7% for PC4, 6.8% for PC5, 3.9% for PC6 and 2.4% for PC7. Temesgen Bacha et al. (2015) stated that two-way principal component analysis explained 66.56% of the genotype and environment interaction.

In the AMMI1 analysis, the abscissa and ordinate of the biplot show the 1st principal component (PC1) term and the significant effect of the trait, respectively. The AMMI model describes the position of genotypes relative to each other and to the studied environments (Elakhdar et al., 2017). In the AMMI1 biplot, genotypes or environments that appear on a perpendicular line on a graph had similar mean yields, and those that fall almost on a horizontal line had similar interactions (Crossa et al., 1990). Genotypes or environments on the right side of the midpoint of the perpendicular line have higher mean values than those on the left side. AMMI2 is a principal component (PC1 and PC2) scores-based graphical representation of summarized information, which has advantages over joint regression-based analysis. AMMI2 allows inferences to be made about complicated GEI that involves significant multi-environments and detection of genotypes with either broad or narrow spectrum adaptability. The AMMI results for the mean grain yield of the 25 durum wheat genotypes are shown in Figure 1 and Figure 2.

When 25 durum wheat genotypes are examined according to the AMMI1 biplot analysis results, 8 environments were grouped into 5 mega-environments. According to the AMMI1 biplot environments, environments 1 and 2 were the 1st mega-environment, environment 3 was the 2nd mega-environment, environments 6 and 5 were the 3rd mega-environment, environments 8 and 7 were the 4th mega-environment and environment 4 was the 5th mega-environment. These results reveal that the study can be carried out in 5 mega-environments instead of 8 environments. Mohamed et al. (2022) reported in their studies that AMMI and GGE biplot results constituted four mega-environments and durum wheat genotypes were also in two mega-environments in terms of grain yield.

In the mega-environment formed by environments 1 and 2, there are genotypes with mean grain yields above the general mean and regression coefficients below one. Elite lines 3, 9 and 10 in this mega-environment are genotypes that do not respond strongly enough to improvements in environmental conditions. The mega-environment created by environment number 3 was located on elite line 4, above the general mean. Although this elite line has high stability, it did not a have a high response to improving environmental conditions. Elite line 7, Caboto and NKU Ziraat durum wheat varieties were genotypes with yield above the general mean and a regression coefficient above 1. These genotypes were the most suitable genotypes in terms of stability and had strong responses to changing environmental conditions. The mega-environment containing environments 6 and 5 contained genotypes that show good results in specific environments.

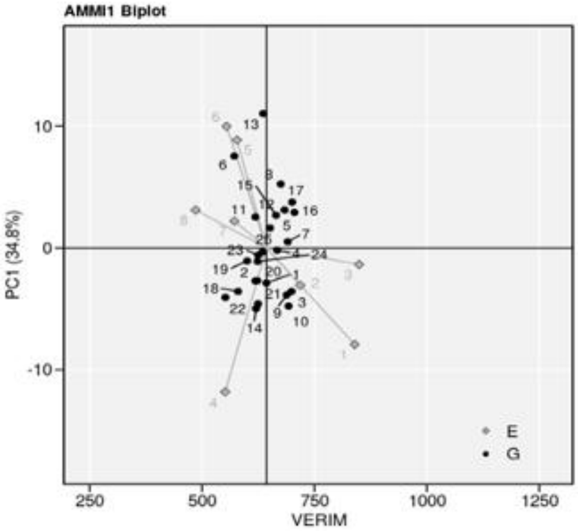

Figure 1. AMMI1 biplot graph for grain yield

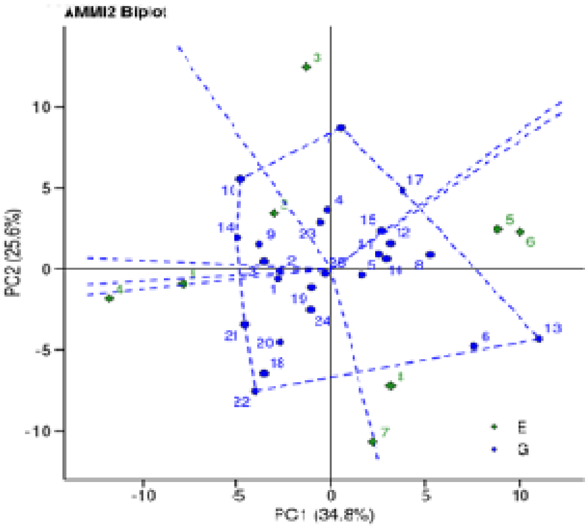

Figure 2. AMMI2 biplot graph for grain yield

Elite lines 6 and 13, which had values below the general average, showed specific adaptation to the mega environment created by environments 6 and 5, and reached high grain yields, while elite line 11, which had a yield below the general average, was the genotype with higher stability in this mega environment. Elite line 14, Mirzabey, Zenit, Pitegora and Kızıltan 91 varieties, which had values below the general mean and adapted to adverse environmental conditions, were located in the 5th mega-environment where the 4th environment is located. Lines that were superior in terms of grain yield, as determined by GGE biplot analysis, could be included in regional yield trials to be evaluated at the registration stage (Tekdal et al., 2017).

The AMMI2 biplot polygon relates genotypes to each other and to environments in terms of grain yield values obtained under multiple environmental conditions and shows which genotype is most compatible with which environment. It also provides more detailed information by dividing the environment into different sectors. If the genotype and environment are located in the same sector, the interaction of these two factors is positive; if they are located in different sectors, the interaction of the two factors is negative; and if they are both located in the same sector, the interaction of the two factors is a mixed interaction (Islam et al., 2015). If the genotypes appear very close to each other, all environments are similar to each other, and if the genotypes are located at opposite points, then the genotypes have different results from each other (Akter et al., 2014).

In the analysis graph (Figure 2), 8 environments were divided into 7 sectors. In the first sector (environments 1, 5 and 6), there were elite lines 5, 6, 8, 11, 12 and 13; in the third sector (environment 3), there were elite lines 4 and 7, and durum wheat varieties NKU Ziraat and Svevo; in sector number 4 (environment 2), there were elite lines 2, 3, 9, 10 and 14; in sector number 6 (environment 8), there was elite line 2; and in sector number 7 (environment 4), there were elite line 1 and durum wheat varieties Zenit, Saragolla, Pitegora, Kızıltan 91 and Ç 1252. The fact that the genotypes used in the study are located in different sectors reveals a genetic difference in grain yield. Genotypes that are close to each other in the same sector are genetically closer to each other. There were no environments in the second and fifth sectors. The fact that the environments in the study from the same year were located in different sectors shows the differences between the environments. In this study, the fact that elite lines 5, 6, 8, 11, 12 and 13 are in the same sector indicates that these genotypes are well adapted to environments 1, 5 and 6. Genotypes 2, 5, 19 and 25, which are closer to the center of the polygon, are better adapted to all environments than the other genotypes, while elite line 5 is above the general mean. Khan et al. (2020), Mekonnen et al. (2020) and Verma and Singh (2021) examined the stability of wheat genotypes and reported that the AMMI method, which has high fitting power is more suitable than other methods for determining the adaptability of genotypes at different locations.

The GGE biplot showing the mean and stability values (Figure 3), and the which-won-where (Figure 4) in terms of grain yield for the 25 genotypes included in the experiment at 8 different environments are given in graphs.

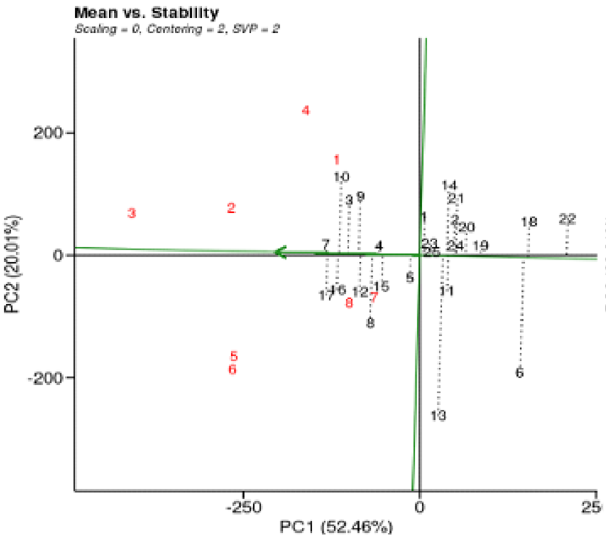

Figure 3. Mean and stability graph for grain yield

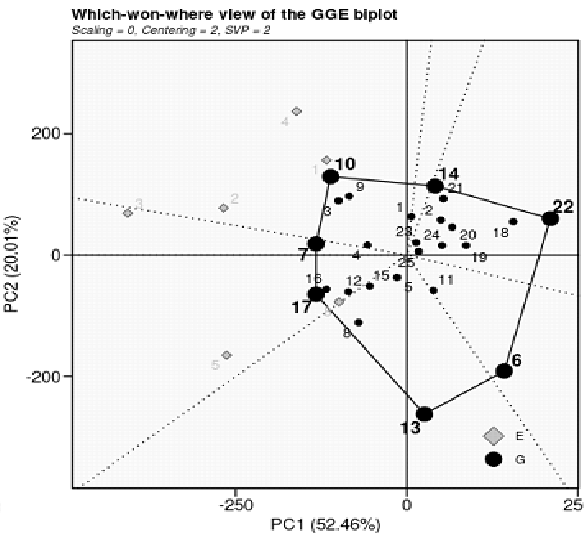

Figure 4. Which-won-where graph for grain yield

The length of the abscissa gives the grain yields of genotypes with above-mean and below-mean grain yields to the right and left of the origin, respectively. The length of the ordinate approaches the GEI associated with the genotype, where more length corresponds to higher variability and lower stability. GGE is the distribution created by a model when the genotype is suitable for the environment, which is one of the most important approaches for biplot analysis. The genotypes at the corners of the polygon drawn in the GGE biplot chart are the most preferred genotypes for the environments in that sector (Yan & Thinker, 2006). According to the GGE biplot analysis, the shorter the projection of a genotype with a vertical line passing through the starting point, the greater the stability of the genotype. The genotypes and environments the closest to the vector ends on the abscissa are those with closest to ideal performance (White & Broadley, 2009).

In this study, environment (E) contributed to 80% of the total variation in the data, while the contribution rates of genotype (G) and genotype × environment interaction (GEI) were lower, at 8.12% and 11.11% of the total variation in the data, respectively.

The GGE biplot has been used in some studies to analyze the MET data for wheat in Turkey (Tekdal et al., 2017; Kendal, 2019). Putto et al. (2008) revealed that 50-80% of the total variation was attributed to environment, while the main effect of genotype contributed to 15-46% of the total variation.

A GGE biplot is constructed by plotting the first principal component (PC1) scores of the genotypes and the environments against their respective scores for the second principal component (PC2) that results from SVD of environment-centered or environment-standardized GED (Yan et al. 2007). According to the GGE biplot analysis result, the total variation for grain yield was 72.47%, of which 52.46% was represented by component 1 (PC1) and 20.01% by component 2 (PC2) (Figures 3 and 4). The total variability explained by the two principal components, PC1 and PC2, in the available GE data is greater than 60%, and the variability explained by GE is greater than 10% in determining the stability and effectiveness of genotypes (Yang & Holland, 2010). Jedzura et al. (2022) reported that the main effects of the environment explained 89.0% of the sum of squared deviations for yield means. The high value of this parameter indicates that the means for yield differ greatly according to the environments. The study's results are largely similar to those of other studies.

The GGE biplot combines traits with yield and can help visually identify the best cultivars (Kendal, 2019). In this study, while elite lines 4 and 7, which had above-general mean values and the shortest projection lines, were the most stable, elite lines 5, 12 and 15, varieties Caboto and NKU Ziraat, which had above-general mean values, follow these elite lines (Figure 3). In contrast, the Zenit, Ç 1252 and Maestrale varieties showed high stability, but their grain yields were not high. Megerssa et al. (2024) indicated that genotypes with the highest stability did not have the highest yield in their study. The genotypes with the lowest stability are those with the longest projection line and values below the general mean. According to the obtained data, the longest projection lines were found for elite lines 6 and 13, followed by elite lines 8, 10, 14, which had low stability and yielded above the general mean. Elite lines 6, 13 and 14 had yields below the general mean.

The which-won-where biplot is established by combining the furthest (i.e., vertex) genotypes that form a polygon (Yan, 2001). Genotypes at the polygon's vertices are either the best or the lowest in one or more environments. The genotype at the vertex of the polygon performs best in the environment entering the sectors. The which-won-where biplot for grain yield is presented in Figure 4. The biplot demonstrates the presence of the cross-over GEI and mega-environments (MEs) for grain yield.

The equality line in the polygon was divided into 6 sectors in the which-won-where graph for grain yield. While there was no environment in sectors 2, 3 and 4, the environments were distributed in sectors 1, 5 and 6. Environment 7 was located in the 1st sector, environments 1, 2 and 4 were in the 5th sector, and environments 3, 5, 6 and 8 were in the 6th sector. When the genotypes at the corner of the polygon were evaluated according to the environments, although elite lines 13 and 6 had values below the general mean, elite line 13 showed more stability than elite line 6 for environment 7. Elite line 10, which had a value above the general mean, showed more stability in environments 1, 2 and 4 than elite line 14, which had a value below the general mean. The stability of the genotypes for environments 1, 2 and 4 was 10>14>22, while for environments 3, 5, 6 and 8, the stability of the genotypes was 17>7>10. According to the obtained data, elite lines 3, 9 and 10 had grain yields above the general mean in environments 1, 2 and 4, while elite lines 7 and 12, varieties NKU Ziraat and Caboto had grain yields above the general mean in environments 5, 6 and 8. Elite line 8 had grain yield above the general mean, while elite line 13 had grain yield below the general mean in environment 7.

High-yielding newly bred durum wheat varieties may have higher yield potential due to better adaptation and stability in different environments compared to previous ones (Ayed et al., 2021; Frankin et al., 2021). These findings confirm the results of this study.

The study reveals that all test environments, except environment 3 are closely related, and most (especially 1, 4, 7 and 8) have values close to the mean. Environments 1, 4, 7 and 8 were the most representative and suitable test environments to select widely adapted genotypes. Environment 3, which was the most distant from the origin, was more discriminative than environments 1, 4, 7 and 8. Discriminative environment 3 helped identify genotypes adapted to specific environments. Plavsin et al. (2021) also stated that graphical representation can easily identify genotypes or genotypes specifically adapted to a particular environment.

4. CONCLUSION

The results obtained from a study conducted with 25 durum wheat genotypes in 8 environments show that most of the elite lines had higher grain yield and stability than the varieties. Nine elite lines had performance above the mean and high stability. Although 3 environments had positive effects on grain yield, the negative effects of 5 environments indicate that it is important to determine the appropriate environment for high grain yield in durum wheat. The fact that the majority of elite lines had a positive effect on grain yield shows that the selection of elite lines with good yield potential among breeding lines was successful. Regarding stability, elite lines 7 and 4 were determined to have the highest performance in all environments. Elite lines 3, 9 and 10 were most suitable for environments 1 and 4, elite line 8 and variety NKU Ziraat were most suitable for environments 5 and 6, and elite lines 12 and 15 was most suitable for environments 7 and 8. Environments 1, 4, 7 and 8 were the most representative and suitable test environments to select widely adapted genotypes. Environment 3, which was the most distant from the origin, was more discriminative than environments 1, 4, 7 and 8. Discriminative environment 3 helped identify genotypes adapted to specific environments. The AMMI and GGE biplot analysis results provided very effective and accurate information for the selection of superior elite lines for plant breeding studies selecting regionally adapted varieties.

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DISCLOSURE STATEMENT

The author declares no conflict of interest.

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