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Original Article

Determination of Genotype × Environment Interaction for Seed Yield in Oilseed Flax (*Linum usitatissimum* L.) Genotypes

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ABSTRACT

This research investigated the performance of oilseed flax (*Linum usitatissimum* L.) genotypes cultivated under varying conditions in Edirne province during 2023 and 2024, focusing on grain yield and Genotype x Environment (GE) interactions by various analytical approaches. Fifteen genotypes were used in the study. The trials were conducted using a randomized complete block design with three replications. To assess the stability of genotypes regarding grain yield, the following parameters were employed: $S^{(1)}$, $S^{(2)}$, $S^{(3)}$, $S^{(6)}$, $NP^{(1)}$, $NP^{(2)}$, $NP^{(3)}$, $NP^{(4)}$, W_i^2, σ^2_i, s^2d_i, b_i, CVi, $\theta_{(i)}$, θ_i, KR parameters, and GGE biplot analysis. The analysis of variance indicated that genotypes, environments, and genotype-environment interaction exerted highly statistically significant impacts ($p<0.01$) on grain yield. The stability assessments revealed that the G5 genotype distinguished itself through superior yield and stability, while the G10 and G6 genotypes had high grain yield and broad adaptability. The GGE biplot analysis indicated that these genotypes exhibited extensive adaptability and effectiveness of some environments in distinguishing between them.

Key words: Flax varieties, stability, genotypes, seed yield, GGE-biplot

Yağlık Keten (*Linum usitatissimum* L.) Genotiplerinde Tane Verimi Yönünden Genotip x Çevre İnteraksiyonunun Belirlenmesi

ÖZ

Bu araştırmada 2023 ve 2024 yılında Edirne ilinde farklı koşullarda yetiştirilen yağlık Keten *(Linum usitatissimum* L.*)* genotiplerinin tane verimi yönünden performansları ve Genotip x Çevre (GÇ) interaksiyonları çeşitli analiz yöntemleriyle değerlendirilmiştir. Araştırmada 15 adet genotip kullanılmıştır. Denemeler tesadüf blokları deneme desenine göre üç tekerrürlü olarak kurulmuştur. Genotiplerin tane verimi yönünden stabilitelerini belirlemek amacıyla $S^{(1)}$, $S^{(2)}$, $S^{(3)}$, $S^{(6)}$, $NP^{(1)}$, $NP^{(2)}$, $NP^{(3)}$, $NP^{(4)}$, W_i^2, σ^2_i, s^2d_i, b_i, CVi, $\theta_{(i)}$, θ_i, *K*R parametreleri ile GGE biplot analizi kullanılmıştır. Varyans analizi sonuçları, genotipler, çevreler ve GÇ interaksiyonunun tane verimi üzerinde istatistiksel olarak yüksek düzeyde anlamlı ($p<0.01$) etkiler oluşturduğunu ortaya koymuştur. Stabilite analizleri sonucunda G5 genotipi hem yüksek verimi hem de stabil performansıyla öne çıkarken, G10 ve G6 genotipleri de yüksek tane verimi ve geniş adaptasyon yetenekleriyle dikkat çekmiştir. GGE biplot analizi, bu genotiplerin geniş adaptasyon yeteneklerini ve bazı çevrelerin genotip ayrımı açısından daha ayırt edici olduğunu ortaya koymuştur.

Anahtar kelimeler: Keten çeşitleri, stabilite, genotipler, tohum verimi, GGE-biplot

INTRODUCTION

Flax (*Linum usitatissimum* L.) is a significant cultivated species, valued for its fiber and oil, with an extensive historical background. Today, due to its economic and nutritional significance, it is utilized extensively in textiles, food, cosmetics, animal feed, and pharmaceuticals. Flaxseed comprises 35-40 % oil, referred to as linseed oil. Linseed oil is used as a raw material especially in the dye industry due to its quick drying properties

(İncekara, 1979). Recent climatic changes have directly impacted agriculture, necessitating the development of new varieties and a reassessment of the adaptation of existing ones to the environment. Consequently, identifying genotypes capable of producing high and consistent yields across varying environmental circumstances is crucial for sustainable agriculture. Global vegetable oil production is mostly derived from palm, soybean, canola, sunflower, peanut, cottonseed, olive, corn, and coconut oils, with the flax plant having been incorporated into this list in recent years (Kurt, 2002).

In breeding studies, various statistical methods have been developed for the analysis and interpretation of data. These methods are typically classified into two primary categories: parametric and nonparametric studies, based on their approach to assessing GE interactions and the statistical assumptions underlying them (Gauch, 2006).Parametric analyses include regression coefficient (bi) (Finlay and Wilkinson, 1963), variance of deviation from regression (Sdi^2) (Eberhart and Russell, 1966). Wricke's ecovalence stability index (W_i^2) (Wricke, 1962). Shukla's stability variance (σi^2) (Shukla, 1972), coefficient of environmental variation (CV_i) (Francis and Kannenberg, 1978), mean variance (θ_i) (Plaisted and Peterson, 1959). GE variance component $\theta_{(i)}$ (Plaisted, 1960) and yield stability index (YS_i) (Kang, 1988). Parametric statistics are widely used in the evaluation of quantitative traits of economic importance (Akçura et al., 2006; Sözen et al., 2018; Akçura and Turan, 2020). Nonparametric stability analysis methods include $S^{(1)}$ and $S^{(2)}$ statistics developed by Huehn (1990), $S^{(3)}$ and $S^{(6)}$ statistics proposed later by Huehn. The parameters $NP^{(1)}$, $NP^{(2)}$, $NP^{(3)}$ and $NP^{(4)}$ proposed by Thennarasu (1995). KR (Kang's rank-sum) developed by Kang (1988) and "top rank" methods defined by Fox et al. (1990) and the "top rank" methods described by Fox et al. Since these rank-based analyses involve fewer assumptions than parametric methods, they are widely used in trials conducted under different environmental conditions (Sabaghnia et al., 2006).

In nowadays, parametric and non-parametric stability analyses are utilized together to evaluate genotype x environment interactions. These approaches determine the performance of genotypes under various environmental conditions more reliably and increase the accuracy of genotype selection. (Koc, 2021; Goksoy et.al., 2019)

The GGE biplot method is a graphical and easily interpretable technique that assesses genotype and GE interactions in the analysis of data from multi-environmental trials. This method enables a visual comparison of genotype performance and stability. while simultaneously assessing the discrimination and representativeness of settings (Yan and Kang. 2003). GGE biplot analysis is effective in determining which varieties excel in specific conditions. hence identifying high-yielding and stable cultivars (Yan 2001; Bayhan et al., 2022). The GGE biplot method assesses genotype-environment interactions more efficiently than alternative analytical approaches. Unlike other parametric approaches that typically assess genotype stability. GGE biplot method facilitates the identification of genotype adaptation to specific contexts and elucidates the performance variations of genotypes across all experimental settings (Yan and Tinker, 2006).

This study evaluated oilseed flax (*Linum usitatissimum* L.) genotypes cultivated under diverse conditions for grain production and identified genotypes with high and steady yield potential by assessing GE interactions with different statistical approaches. The study aims to discover how environmental factors affect genotype performance and identify genotypes resistant to production year and environment fluctuation.

This study aimed to evaluate the grain yield performance and stability of 15 oilseed flax genotypes under six different environmental conditions in Edirne, Türkiye

MATERIALS AND METHODS

This study assessed the interaction of genotype and environment with grain production in oilseed flax (*Linum usitatissimum* L.) genotypes using classical analysis of variance alongside other parametric and nonparametric approaches. Furthermore, GGE Biplot analysis was utilized for a more thorough and visual explanation of GE interactions. This analysis determined the discriminative capacity of environments concerning genotypes and the stability of genotypes under varying environmental conditions, thereby establishing a scientific foundation for selecting genotypes that can adapt to the ecological conditions of Edirne.

The study utilized 15 genotypes, comprising 9 varieties of domestic and foreign origin, 5 advanced-candidate lines, and 1 population from Turkiye (Table 1). The experiments were sown in 6 environments according to the randomized complete block design with 3 replications. The plots were planned as 1.02 m wide and 6.2 m long, containing 6 plant rows with 17 cm space in between. At harvest, the middle 4 rows with a length of 5 m were harvested. In sowing, 1250 seeds were used per $1m^2$. Nitrogen was applied at the rate of 300 kg urea per hectare in each environment during sowing. Bentazone (2000 g/ha) for broadleaves and Quaizilophop-p-ethyl (1000 g/ha) for narrowleaves were applied in each environment for weed control. Grain yield was expressed in kilograms per hectare, adjusted to 7 % seed moisture content.

Table 1. Flax genotypes used in the study and their origins

No	Genotype	Flower Color	Seed Color	Hybrid / Pedigree	Year of registration	Country of origin
G1	Karakız	Blue	Brown	Registered variety	2020	Türkiye
G2	Beyaz Gelin	White	Brown	Registered variety	2020	Türkiye
G3	Sarı Dane	Pinkish White	Yellow	Registered variety	2021	Türkiye
G4	KVD-2019/5	Blue	Brown	Victory x Dunes TRE-K10-02-411210T	Candidate Line	Türkiye
G5	KVD-2019/12	White	Brown	Diadem x Tsian TRE-K09-01-912110T	Candidate Line	Türkiye
G6	KVD-2019/15	White	Brown	Diadem x Dunes TRE-K09-02-811110T	Candidate Line	Türkiye
G7	Start	Blue	Brown	Registered variety	-	Russia
G8	F7K2019-7	Blue	Brown	Sarı-85 x T.397 TRE-K11-04-211110T	Advanced Line	Türkiye
G9	F7K2019-8	Blue	Brown	Sarı-85 x T.397 TRE-K11-04-211210T	Advanced Line	Türkiye
G10	Milas	Blue	Light Brown	Population	-	Türkiye-Milas
G11	Sarı-85	White	Yellow	Registered variety	-	Türkiye
G12	Glenelg	White	Brown	Registered variety	-	Australia
G13	Culbert 79	Blue	Brown	Registered variety	-	U.S.A.
G14	Adin	Blue	Brown	Registered variety	-	Romania
G15	Windermere	Light Blue	Yellow	Registered variety	-	Canada

Field experiments were conducted in three locations in Edirne Province, Turkey: two in the Karaagaç district and one at the Trakya Agricultural Research Institute (TARI) during the 2023 and 2024 growing seasons. The same locations were used in both years, resulting in six environment combinations (three locations × two years). This research was performed in three distinct locations with varying treatments in Edirne province during 2023 and 2024 growing seasons. Two trials were conducted in the Karaağaç district and one at the headquarters of the Trakya Agricultural Research Institute (TARI). One of the trials at Karaağaç location was conducted under rainfed + supplemental irrigation and the other under rainfed conditions. In the irrigated environment (sandy-loamy soil), irrigation was applied twice, at the beginning of flowering and capsule filling periods, and 12 liters of water per m² (60 liters per plot) was applied in each irrigation. The non-irrigated trial in the same area was left to natural rainfall only. The third experiment was conducted in the TARI experimental field with clay-loamy soil structure without irrigation (Table 2). The soil structure across environments ranged from sandy-loam to clay-loam, with organic matter content being very low in all environments (0.55–1.08%). Soil pH values were neutral (7.09–7.46), ensuring suitability for flax cultivation.

Table 2. Irrigation status and soil properties of the experimental environments

Code	Environment	Irrigation Status	Irrigation period	Total amount of water supplied (liters/plot)	Soil structure	Organic Matter	Soil Ph
E1	Karaagac 2023	Irrigated 2 times	Flowering Start and Capsule Filling period	120	Sandy loam	0.65 (very low)	7.45 (neutral)
E2	Karaagac 2023	rainfed	-	-	Sandy loam	0.63 (very low)	7.46 (neutral)
E3	Institute Land 2023	rainfed	-	-	Clay loam	0.66 (very low)	7.29 (neutral)
E4	Karaagac 2024	irrigated 2 times	Flowering Start and Capsule Filling period	120	Sandy loam	1.08 (low)	7.20 (neutral)
E5	Karaagac 2024	rainfed	-	-	Sandy loam	0.91 (very low)	7.25 (neutral)
E6	Institute Land 2024	rainfed	-	-	Clay loam	0.55 (very low)	7.09 (neutral)

Between 2023 and 2024, notable disparities were noticed regarding temperature, humidity, and precipitation. In 2023, significant precipitation occurred, particularly in April, resulting in higher humidity compared to 2024, with a total of 222.2 mm of rainfall. The season in 2024 commenced favorably in March, then experienced minimal precipitation (12.6 mm) in June. The year 2023 exhibited elevated humidity levels, comparing with 2024., In the year 2024, temperatures were elevated, particularly between April and July (Table 3). The 2024 growing season was characterized by lower precipitation and humidity, especially in June and July, which may have influenced genotype performance and revealed differential stability responses under drought stress.

Table 3. Edirne Province climate data for 2023 and 2024 growing seasons

Months	Precipitation (mm)		Moisture (%)		Temperature °C					
					Min		Max.		Average	
	2023	2024	2023	2024	2023	2024	2023	2024	2023	2024
March	39.8	56.8	81.3	88.7	-4.1	-0.9	22.1	27.2	9.4	10.3
April	84.6	58.8	86.5	73.2	1.4	3.8	22.1	30.6	12.2	16.3
May	39.4	34.0	77.7	75.5	3.3	6.1	30.1	30.6	16.9	17.1
June	35	12.6	68.9	53.7	9.9	14.3	35.5	38.4	22	26.3
July	23.4	13.8	59.5	49.6	18.5	16.1	35.4	41.4	26.7	28.1
Total/Average	222.2	176	74.78	68.14						

In each environment and year, physiological observations and field practices (sowing, maintenance, harvesting) were carried out according to standard techniques. Sowing was carried out in March-April and harvesting was carried out in July according to the physiological maturity of the genotypes. The grain yield was determined by converting the total seed quantity harvested from each plot into kilograms per hectare. The acquired data were subjected to analysis of variance, and the statistical significant levels of genotype, environment, and GE interactions were ascertained. R-based STABILITYSOFT software developed by Pour-Aboughadareh et al. (2019) was-utilized for stability analysis of genotypes in terms of grain yield. This software allows the calculation of different stability parameters in an online environment and provides significant convenience in the analysis process (https://manzik.com/stabilitysoft/). In this context; Stability statistics developed by Nassar and Huehn (1987) and Huehn (1990), Thennarasu's (1995) analysis, Wricke's (1962) ecovariance index, Shukla's (1972) stability variance, Eberhart and Russell's (1966) mean squared deviations from regression. Finlay and Wilkinson's (1963) regression coefficient. Francis and Kannenberg's (1978) environmental coefficient of variation. Plaisted's (1960) GE variance component, Plaisted and Peterson's (1959) variance component and Kang's (1988) rank sum method were utilized.

To achieve a robust assessment of genotype stability, both parametric (e.g., Shukla's variance, Eberhart–Russell model) and nonparametric (e.g., Nassar and Huehn's statistics, Kang's rank-sum) methods were employed. This combination allows for evaluating stability under diverse assumptions of data distribution and interaction structure.

In order to visually examine the genotype stability, GGE biplot analysis was performed based on mean data across six environments using the Genstat 14th Edition software (Copyright 2011. VSN International Ltd.).

RESULTS AND DISCUSSION

The GE interaction on the grain production of flax genotypes cultivated under varying environmental conditions was assessed, and the genotypes responses to environmental variability were studied. The variance analysis results of the study conducted with 15 spring-planted flax genotypes across 6 environments over 2 years-2 in the Karaagac region (irrigated and dry) and 1 at the Institute headquarters under 3 distinct environmental conditions during the 2023 and 2024 growing seasons—are presented in Table 4.The interaction of environment, genotype, and GE of grain yield were statistically significant at the $p<0.01$ probability level (Table 4). "F" value for the environment indicates a high variation ($F = 14.63$) This suggests that genotype performance is strongly influenced by environment. Grain yield differences between genotypes were also significant ($F=30.66$). This reveals that the studied genotypes had significant yield variability due to their genetic structure. Kroonenberg (1995) and Yan & Kang (2003) noted that GM interaction affects agronomic yield characteristics, making multiple environment trials essential for genotype evaluations. The extremely significant GE interaction shows that genotypes respond differentially to environments and that environmental variability impacts genotype yield. It is vital for genotypes to have high yield potential and be able to retain it under diverse environmental circumstances.

Table 4. Analysis of variance results of genotype x environment interaction for grain yield (kg/ha) ~~genotypes~~

Source of Variation	Degrees of freedom	Sum of Squares	Mean Squares	F Value
Environment (E)	5	66825.5	13365.1	14.6346**
Replications (Environment)	12	10959.1	913.255	14.1428**
Genotype (G)	14	27718.6	1979.9	30.6611**
Environment*Genotype (ExG)	70	19892	284.171	4.4007**
Error2	168	10848.39	64.57	
Total	269	136243.53		

Table 4 presents grain yield values (kg/ha) together with overall averages. The analysis of average grain yield across the genotypes revealed that genotype G5 had the highest average yield at 754.1 kg/ha. The G10 genotype (743.1 kg/ha) and G6 genotype (741.2 kg/ha) followed this value, respectively. The genotypes with the lowest average grain production were G15 (451.3 kg/ha), G3 (471.6 kg/ha), and G8 (476.5 kg/ha).

The analysis of average grain yield across environments revealed the highest value under E4 conditions, with 955 kg/ha. The minimum yield was recorded under E2 conditions (472.3 kg/ha). This indicates that environmental variables, particularly irrigation, significantly influence grain yield. Table 5 reveals that the genotypes exhibit varying reactions to the environments in the GE interaction analysis. For instance, G5 demonstrated elevated yield across all three conditions, exhibiting both stability and high productivity. G8 produced a minimal yield of 179.1 kg/ha under E2 conditions, whereas it yielded 894.1 kg/ha at E4 conditions. This case demonstrated that genotype G8 produced multivariate outcomes across several contexts and exhibited great sensitivity to environmental factors, indicating instability. While G13 (Culbert 79) demonstrated a good yield in the E6 environment, it garnered attention due to its poor yield of 461.2 kg/ha in the E3 environment. Genotypes G5, G6, and G10 exhibited superior yield and a more consistent performance across settings.

In plant breeding, it is crucial that genotypes possess not just high yield potential but also demonstrate consistent performance across varying environmental circumstances. Consequently, stability analyses are crucial for assessing the response of genotypes to environmental variability. This study's extensive stability assessments facilitated a thorough assessment of the genotypes regarding yield and stability (Table 6). According to Wricke (1962), genotype G1 showed the most stable performance against environmental changes; however, this genotype had low grain yield. On the other hand, genotype G5 was noteworthy for both high yield and stable performance. When the stability variance (σ^2_i) as defined by Shukla (1972) is analyzed. G1 genotype again stands out as the most stable genotype, while G5 is considered as a preferable genotype with both high yield and low variance value. According to Eberhart and Russell (1966) model, G5 was determined as the most suitable genotype with its high yield and stability. According to the analysis of Finlay and Wilkinson (1963) based on regression coefficient, genotype G5 showed superior performance especially in favorable environments, while genotype G10 was found more successful in terms of general adaptability. According to the CV % based evaluation proposed by Francis and Kannenberg (1978), G10, G7 and G6 genotypes were among the prominent genotypes in terms of both high yield and stable performance (Table 6).

The GE variance component θ(i) is a modified measure of the stability parameter. Genotypes with larger values are considered more stable (Plaisted, 1960). In this study, the most stable genotypes according to θ(i) parameter were determined as G1, G5 and G3. However, in the trials conducted under different environmental conditions, not only the stability of the genotypes but also the stability and grain yield averages together give better results. In this context, although genotype G1 has high stability, its grain yield is low; on the other hand, genotype G5 stands out as the most suitable genotype due to both high yield and high stability (Table 6). The mean variance component (θi) statistic developed by Plaisted and Peterson (1959) includes the mean variances estimated for all combinations of common genotypes. In the analysis based on this parameter, G1, G5 and G3 genotypes were determined as the most stable genotypes. Here again, although G1 genotype was the most stable. it was limited with low yield level, while G5 showed a superior performance due to both high yield and low θi value. According to Nassar and Huehn (1987) and Huehn (1990) parameters, G5 was the most stable and reliable genotype. It is also a productive and environmentally compatible genotype because of its high yield**.** According to Thennarasu (1995), G5 was the most stable genotype with both high yield and stability. G1, G4 and

G6 are also notable stable genotypes. According to Kang's rank sum (KR) parameter (Kang. 1988). G5. G6 and G7 are the most suitable genotypes because they are both high yielding and stable.

Table 5. Average grain yield values (kg/ha) of different flax genotypes for genotype. environment and genotype x environment interaction

Genotype Number	Genotypes	2023			2024			Genotype Mean
		E1	E2	E3	E4	E5	E6	
G1	Karakiz	489.0	446.5	502.1	883.8	527.0	483.5	555.3e
G2	Beyaz Gelin	563.5	501.2	483.5	854.9	546.6	581.9	588.6e
G3	Sari Dane	383.5	342.6	357.4	808.8	573.5	363.7	471.6f
G4	KVD-2019/5	625.3	554.1	675.0	952.9	751.5	438.0	666.1cd
G5	KVD-2019/12	651.8	595.6	764.7	1144.1	777.0	591.1	754.1a
G6	KVD-2019/15	769.1	617.6	754.1	1104.9	703.0	498.4	741.2ab
G7	Start	651.5	491.5	711.5	955.4	767.2	699.8	712.8abc
G8	F7K2019-7	397.4	179.1	462.9	894.1	527.8	397.5	476.5f
G9	F7K2019-8	532.4	231.5	719.7	972.1	517.2	578.3	591.8e
G10	Milas	732.2	479.4	694.4	1024.5	908.3	628.6	743.1ab
G11	Sari-85	612.4	393.5	560.6	693.6	531.9	494.3	547.7e
G12	Glenelg	807.6	522.6	501.5	1024.5	552.4	530.9	656.6d
G13	Culbert 79	767.1	636.8	461.2	1215.2	588.7	507.1	696.0bcd
G14	Adin	622.9	535.0	550.3	1171.6	747.6	566.1	698.9bcd
G15	Windermere	432.6	557.9	340.6	624.5	424.0	328.4	451.3f
Averages		602.0bc	472.3e	569.3c	955.0a	629.6b	512.5d	

Parametric and nonparametric analysis indicate that while the most stable genotype was G3, its yield fell below the average. Genotype G5 is the best appropriate for high yield and stability criterion among the genotypes. Genotypes G6 and G10 need assessment regarding their specific and broad adaptability potential. The previously mentioned parametric and non-parametric stability metrics allow for the assessment of genotypes based on their stability across various experimental contexts; nonetheless, they exhibit shortcomings in the specific evaluation of individual environments. Therefore, GGE biplot analysis was used to visually evaluate the specific adaptation of genotypes to the experimental environments in terms of grain yield.

The polygon biplot generated by the GGE biplot analysis approach for the comparative assessment of genotype performance across various settings for grain production is illustrated in Figure 1. This method not only elucidates the degree of genotypic adaptation to certain settings but also facilitates the analysis of the distinctiveness of these environments regarding their capacity to differentiate genotypes. In the study conducted by Kumar and Kumar (2021), the yield responses of flax genotypes to different environments were evaluated by GGE biplot analysis and it was emphasized that GE interaction played an important role in genotype selection and it was reported that LC 2063 and LCP 87 genotypes stood out in terms of both high yield and stability. The results indicate that this analysis method is an effective tool in identifying genotypes that are sensitive to environmental variability. In the biplot plot, the first two principal components (PC1 and PC2) explained most of the total variation (77.47%). Genotypes G5, G10 and G6 showed high performance in terms of yields in the majority of the experimental environments and were located at the corner points of the polygon close to the experimental environments. Genotypes G15, G3 and G8 were located at the other corners of the polygon but far away from the trial environments due to their low performance. This structure indicates that genotype G5 possesses extensive adaptability and demonstrates overall success that is not confined to certain situations. Genotypes G5, G10, and G13 exhibit stability regarding both elevated yield and closeness to PC2. On the other hand, genotypes such as G15 and G9 exhibited low stability due to both low yield and high variation. The GGE biplot analysis applied in this study showed once again that it is an effective tool to evaluate the performance and stability of genotypes under different environmental conditions. The G5, G10, and G6 genotypes exhibited elevated yields across various settings and were positioned near the vertices of the polygon in the biplot graphs, indicating their broad adaptability.

Table 6. Stability parameters of grain yield of different flax genotypes

Genotype	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12	G13	G14	G15
Y	55.53	58.86	47.16	66.61	75.41	74.12	71.28	47.65	59.19	74.31	54.77	65.66	69.6	69.89	45.13
W_i^2	65.25	241.07	177.49	278.93	171.86	280.77	291.27	368.29	967.11	405.42	501.87	539.7	1038.15	342.65	959.57
σ^2_i	7.77	48.35	33.67	57.08	32.37	57.51	59.93	77.7	215.89	86.27	108.53	117.26	232.29	71.79	214.15
s^2d_i	8.15	18.83	25.24	38.83	18.73	37.6	32.09	31.89	130.94	57.9	20.31	75.67	108.81	16.92	63.73
b_i	0.93	0.73	1.02	0.93	1.17	1.11	0.79	1.31	1.18	1.01	0.51	1.08	1.43	1.39	0.41
CVi	29.36	23.05	39.46	26.51	27.49	27.58	21.25	49.5	41.39	26.36	18.71	32.44	39.63	34.94	26.18
$\theta_{(i)}$	100.91	98.02	99.06	97.39	99.16	97.36	97.19	95.92	86.05	95.31	93.72	93.09	84.88	96.34	86.17
θ_i	57.99	76.82	70.01	80.88	69.41	81.08	82.2	90.45	154.61	94.43	104.77	108.82	162.23	87.71	153.81
$S^{(1)}$	1.53	3.27	2.6	3.53	1.53	3.27	3.8	2.13	5.73	3.87	3	3.6	5.67	2.6	4.07
$S^{(2)}$	1.77	8.17	6.17	8.57	1.77	8.17	9.37	3.07	22	10.27	5.9	9.87	22.3	4.97	19.37
$S^{(3)}$	1.83	5.98	9.74	4.85	0.67	3.45	4.32	4.6	15.71	4.53	5.36	5.29	10.62	2.44	30.58
$S^{(6)}$	1.1	1.85	3.05	1.51	0.41	1.13	1.38	2.4	3.43	1.24	2	1.36	2.19	0.92	5.58
$NP^{(1)}$	2	3.83	3	3.17	3.67	3.5	3.83	3.33	4.67	2.83	3.67	3.83	6.33	2.83	3.17
$NP^{(2)}$	0.43	0.39	2.13	0.23	0.44	0.24	0.29	1.76	0.57	0.35	0.82	0.3	0.36	0.52	5.5
$NP^{(3)}$	0.53	0.63	1.22	0.42	0.31	0.37	0.38	1.22	0.73	0.34	0.78	0.49	0.61	0.38	1.32
$NP^{(4)}$	0.32	0.48	0.82	0.4	0.12	0.28	0.35	0.64	0.82	0.34	0.55	0.39	0.54	0.26	1.28
***K*R**	12	14	17	12	3	9	11	22	23	12	23	20	21	13	28

Y: Mean grain yield of genotypes (kg/da). $W_{(i)}^{(2)}$: Ecovariance (Wricke, 1962), σ^2_i: Stability variance (Shukla, 1972), s^2d_i: Mean squared deviations from regression (Ebehart and Russel, 1966), b_i: Coefficient of regression (Finlay and Wilkinson, 1963), CVi: Coefficient of variation (Francis and Kennenberg, 1978), θ(i): Variance component (Plaisted, 1960), (θi): Mean variance component (Plaisted and Peterson, 1959), $S^{(1)}$, $S^{(2)}$, $S^{(3)}$ and $S^{(6)}$: Huhn's and Nassar's nonparametric statistics, (Nassar and Huehn, 1987) and (Huehn.1990). $NP^{(1)}$, $NP^{(2)}$, $NP^{(3)}$, $NP^{(4)}$: Thennarasu's nonparametric statistics (Thennarasu, 1995), KR: Kang's rank sum (Kang, 1988).

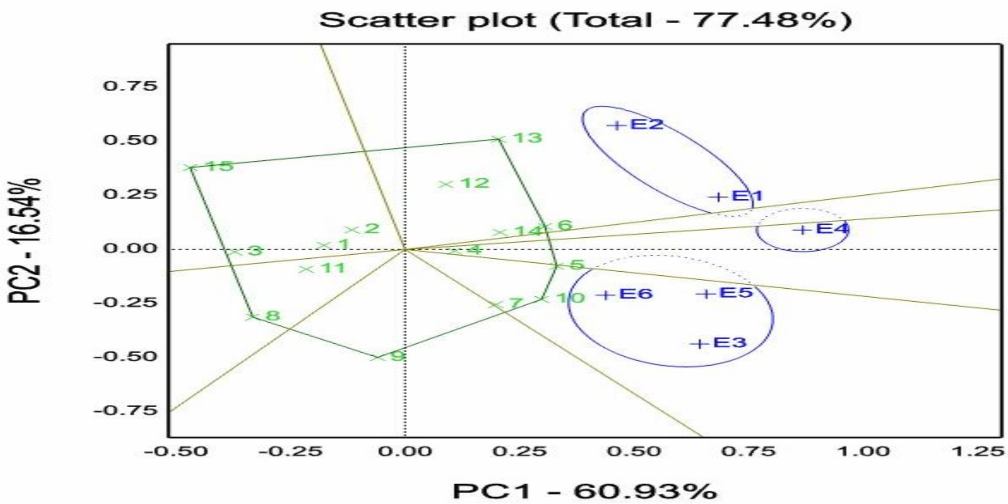

Figure 1. GGE biplot analysis image showing which genotypes are better in which environments in terms of grain yield (kg/da) (1:Karakız, 2:Beyaz Gelin, 3:Sarı Dane, 4:KVD-2019/5, 5: KVD-2019/12, 6:KVD-2019/15, 7:Start, 8:F7K2019-7, 9:F7K2019-8, 10:Milas, 11:Sarı 85, 12: Glenelg, 13:Culbert 79, 14:Adin, 15:Windermere, E1:Karaagac Wet 2023, E2:Karaagac Dry 2023, E3:Institute Center Land 2023, E4: Karaagac Irrigation 2024, E5: Karaagac Rainfall 2024, E6: Institute Center Land 2024)

The results of this study are in agreement with the results of Yan et al. (2000) who showed that GGE biplot analysis is an effective method for evaluating genotypes in terms of both yield and stability. In the aforementioned study, they emphasized that GGE biplot analysis is a powerful tool for evaluating the performance and stability of genotypes in different environments by visualizing GE interaction. Similarly, in the study conducted by Rad et al. (2013) on flax genotypes, it was reported that some genotypes stood out in terms of both high yield and stability using GGE Biplot and AMMI analyses. This result coincides with the fact that genotypes such as G5 and G10 stood out with similar traits in the present study. Furthermore, in a study conducted by Chobe and Ararsa (2018) in the central and southeastern highlands of Ethiopia, it was determined that some flax genotypes showed superior performance in terms of both high yield and stability using GGE Biplot and AMMI analyses. The study revealed that genotypes responded differently to environmental changes and environments differed in their power to discriminate genotypes. In addition, it was found that the effect of GE interaction was approximately two times larger than the effect of genotype. This result indicates that the genotype's response to environmental conditions is more determinant of yield than its genetic potential.

The present study makes a unique contribution to the literature in that it was carried out in Edirne ecological conditions with the data obtained from multi-circle trials in which different environments irrigations and rainfall conditions) were taken into consideration. It provides important contributions to regional adaptation studies, especially in terms of providing original results based on field data for the determination of genotypes suitable for spring flax cultivation in the Thrace Region of Türkiye. The assessment of parametric and non-parametric stability analyses, along with GGE Biplot outputs, facilitated a multidimensional examination of genotype responses to environmental variability, hence enhancing the reliability and comprehensiveness of genotype selection judgments. In this respect, the study has the potential to affect decisions on genotype selection both in terms of agronomic research and breeding programs.

The findings from this study reaffirm the efficacy of GGE Biplot analysis in assessing the interaction between genotype and environment. It was determined that the irrigated conditions of 2024 provided the most significant setting for genetic discrimination. This underscores the important importance of environmental selection in elucidating genetic differences. Purchase et al. (2000) underscored the influence of environmental factors on genotype selection and asserted that environmental sensitivity must be factored into genotype assessments. In conclusion, the results of the present study are in agreement with other studies in the literature and this analysis method plays an important role in genotype selection, especially in breeding programs where environmental interactions are significant.

CONCLUSION

Grain yield of the genotypes showed significant variability among years and environments. Genotypes G5, G10, G6, G13, and G7 exhibited remarkable grain yield and reliable performance across several conditions. Conversely, genotypes G15, G3, and G8 exhibited low yields across numerous settings.

Genotypes G5, G10, and G6 are distinguished as high-yielding and stable choices for grain production in oil flax farming within the Edirne ecological context. In 2024, irrigated conditions were identified as the most significant environmental factors in differentiating the genotypes. As a result, the E4 environment, where irrigation was applied in 2024, produced the highest seed yield across all genotypes. This clearly demonstrates the decisive effect of irrigation on yield performance. In addition, the mild temperature conditions and adequate humidity observed during the flax growth period—from April to July—may have further supported plant development and contributed positively to yield. These findings indicate that genotype × environment interactions should be evaluated not only in relation to rainfall, but also by considering irrigation practices and prevailing climatic conditions throughout the growing season.

Given the significant degree of genotype-environment interaction, it is crucial to evaluate genotypes across various contexts in breeding operations. The application of multidimensional analyses like GGE Biplot facilitates the simultaneous assessment of yield and stability in genotype selection, hence enhancing decision-making efficacy.

Genotype G5 having high yield and stability may be suggested to farmers due to its reliability against changeable climatic conditions in terms of production.

Genotypes G6 and G10 which have wide adaptability are advantageous for other areas to broaden agricultural extension.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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