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RESEARCH PAPER

Optimizing Chickpea Yield: GGE Biplot Analysis of Sowing Seasons

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Abstract

H. Güngör. 2024. Optimizing Chickpea Yield: GGE Biplot Analysis of Sowing Seasons. Int. J. Agric. Nat. Resour. 127-139. Maximizing chickpea production in varying environmental conditions is crucial for ensuring food security and agricultural sustainability. This study addresses this challenge by evaluating sixty-six chickpea genotypes across winter and spring sowing seasons over two years (2016-17 and 2017-18). Utilizing an Augmented Trial Design with three replications and six check varieties, the study reveals significant effects of genotype, sowing season, and their interaction on all examined traits ($p \leq 0.01$). Notably, winter sowing season led to a substantial increase in yield, demonstrating up to a 57.1% improvement compared to spring sowing season. The first two components of principal component analysis accounted for 67% of the total variation of chickpea genotypes. In the examined traits, the lowest variation was observed in 100 seed weight, followed by seed yield. Biplot analysis, Pearson's correlation, and heatmap analysis indicated a positive association of seed yield with pod number of plant and seed number per plant, yet a negative association for plant height, first pod height and 100 seed weight. SMN56, SMN57, and SMN51 genotypes consistently performed well across both sowing and growing seasons for desired traits. Furthermore, genotypes SMN13, SMN20, SMN37, SMN38, and SMN54 excelled during spring sowing season, while Gülümser, İnci, Aydın 92, SMN14, SMN20, and SMN39 were superior in winter. This study not only underscores the advantage of winter sowing for improved yield and other traits but also demonstrates the effectiveness of GGE biplot analysis in genotype selection, offering valuable implications for future chickpea breeding efforts.

Keywords: Chickpea yield, environment interaction, GGE biplot analysis, sowing seasons.

Introduction

Chickpea (*Cicer arietinum* L.), the only cultivated species in the genus *Cicer*, is a highly self-pollinated annual diploid crop with a genome size of ~931 Mbps and a cross-pollinating rate of less than 1% (Koul et al., 2022). The chickpea is a valuable source of carbohydrates and protein, and its protein quality is considered better than that of other pulses (Jukanti et al., 2012). Additionally, the nitrogen-fixing ability of chickpeas enhances soil fertility, reducing the need for nitrogen fertilization, promoting sustainable production, and benefiting subsequent cereal crops (Richards et al., 2022).

In 2022, chickpea cultivation covered approximately 14.8 million ha across 50 countries, yielding

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a global production of 18 million tons, with an average yield of 1221 kg ha^{-1}. Türkiye significantly contributed with 457.000 ha and 580.000 tons of production, with an average yield of 1270 kg ha^{-1}. India retained its position as the largest producer with 13.5 million tons, comprising 75% of global production. Türkiye's production came third, behind India and Australia (FAO, 2024; TUIK, 2024).

As an indeterminate plant, the chickpea presents both advantages and disadvantages for spring and winter sowing strategies. In spring sowings, low seedbed soil moisture levels may result in poor stand establishment, insufficient germination, and high seedling mortality. Plants undergo flowering and pod-setting stages under water deficit conditions. Conversely, winter sowings offer more favorable environmental conditions including sufficient water availability and lower temperatures, resulting in taller plants with more flowers and pods, and ultimately granting higher yield potential (Duarte, 2022).

Grain yield in any crop is a complex trait, resulting from the interaction of multiple contributing factors. Understanding these factors, and how they relate with each other and with yield, is crucial for developing breeding programs focused on yield improvement. The primary goal of such studies is to assess the contribution of different yield components to overall yield, and to establish selection criteria for individual plant selection from segregating populations. These studies also aim to identify parental lines with desirable traits for hybridization, enabling the integration of various traits into a single genotype (Bakhsh et al., 2006; Srivastava et al., 2017; Karimizadeh et al., 2023).

Plant breeders strive to develop superior varieties that can adapt to diverse environmental conditions and possess desired traits. Identifying genotypes that consistently perform well across various traits is challenging but essential. The GGE analysis, known as GGE Biplot, merges genotype and G×E (genotype × environment interaction) effects into a single graph, providing breeders with a visual tool for comprehensive data evaluation. This innovative method, applied in research across different genotypes, environments or years, enables simultaneous visual assessment of multiple traits and enhances success in selection, making it a valuable tool in plant breeding (Yau, 1995; Yan et al., 2007). The following aims are investigated herein:

i. Examine the impact of sowing seasons on chickpea genotypes' yield and agronomic traits

ii. Explore the correlation among chickpea genotypes' traits

iii. Identify high-yielding and ideal chickpea genotypes across sowing and growing seasons using PCA and GGE biplot methods.

Materials and Methods

Plant Materials and Growth Conditions

The research was conducted in farm fields west of Istanbul in Kırklareli-Luleburgaz (41° 22′ 19″ N, 27° 24′ 19″ E) during the 2016-2017 and 2017-2018 cropping years. In the study, 42 advanced lines and 24 chickpea cultivars were used as plant materials. Table 1 provides climate data for the experiments’ growing seasons. During the 2016-17 growing season, the average temperature was 9.3°C, with a total precipitation of 366.3 mm, while in 2017-18, the average temperature increased to 12.0 °C, and total precipitation was 696.3 mm (Table 1).

The study was arranged in an Augmented Trial Design with three replications of six check cultivars (Aksu, Azkan, Cevdetbey 98, Gülümser, Sarı 98, and Taek-Sağel). Experiment plots consisted of two 5 m rows, with 40 cm of separation and 5 cm intra-rows. At planting, 30 kg of pure N and 60 kg of pure P_2O_5 fertilizer per ha were applied.

Table 1. Climate data (temperature and rainfall) for the experimental years (2016-2018).

Months	Temperature (°C)		Precipitation (mm)	
	2016-2017	2017-2018	2016-2017	2017-2018
October	14.1	13.4	53.3	65.7
November	1.2	9.4	7.0	78.1
December	1.2	7.6	7.0	117.8
January	-0.4	4.6	48.0	83.9
February	5.5	6.1	60.3	48.0
March	9.5	8.5	43.6	172.6
April	12.1	16.1	75.5	2.4
May	17.6	19.5	43.8	34.0
June	23.1	22.5	27.8	93.8
Mean	**9.3**	**12.0**		
Total			**366.3**	**696.3**

Weed control in the test plots was done manually (three times) with no pesticides applied. In the research, plant height (PH), first pod height (FPH), pod number per plant (PPP), seed number per plant (SPP), 100 seed weight (100SW), and seed yield (SY) traits were evaluated.

Statistical Analyses

Variance analysis (ANOVA) was applied to the two years of data, and the least significant difference (LSD) test was carried out using Duncan grouping test to compare means. Principal component analysis (PCA) was conducted and evaluated using the biplot approach on the average data (SAS Institute Inc. JMP 15.1., 2020). GGE Biplot analyses were performed using Genstat 14th (VSN International Ltd., 2014) on mean data over two sowing seasons and years (Yan, 2001).

Results

Effect of sowing and growing seasons on yield and examined traits

Table 2 presents variance analysis for genotypes (G), years (Y), and sowing seasons (SS) on the examined traits, along with trait averages.

Plant height showed no insignificant difference between years, but significant differences were observed among sowing season and growing season. The interactions between Y×G, Y×SS, and Y×G×SS were not significant, while the G×SS interaction was statistically significant. Plant height ranged from 40.4 to 60.0 cm among advanced chickpea lines, and from 45.4 to 55.9 cm among cultivars. Among advanced chickpea lines, SMN20 was the shortest, while among cultivars Aksu had the shortest plant height. Conversely, line SMN82 was the tallest among advanced chickpea lines, and Diyar 95 was the tallest among cultivars. In the first year (48.2 cm), the PH values were higher compared to the second year (48.1 cm), with taller plants observed in the winter sowing season (50.8 cm) than in the spring sowing season (45.6 cm) (Table 2).

Significant differences in FPH were observed among Y, SS, and G. Y×G, G×SS, and Y×G×SS interactions were not statistically significant, while the Y×SS interaction proved to be significant. Among advanced chickpea lines, line SMN20 had the lowest FPH (19.7 cm), and line SMN10 had the highest (30.7 cm). Among cultivars, Canıtez 87 had the lowest FPH (23.4 cm), while Menemen 92 had the highest (33.1 cm). FPH varied based on genotype, sowing season, and years. It was higher in the winter sowing season (26.7 cm) compared to spring season (24.9 cm), and higher in the first

Table 2. Mean data for years, sowing seasons, genotypes and averages of the examined traits.

Traits			PH (cm)	FPH (cm)	PPP (no)	SPP (no)	100SW (g)	SY (kg ha^{-1})
			ns	*	ns	ns	**	**
Years		2017	48.2	26.1 a	23.7	23.7	38.5 a	2101 a
		2018	48.1	25.4 b	23.0	23.3	37.4 b	1946 b
Mean			48.1	25.7	23.3	23.5	37.9	202.3
			**	**	**	**	**	**
Sowing Season		Winter	50.8 a	26.7 a	27.3 a	27.3a	39.2 a	2473 a
		Spring	45.6 b	24.9 b	19.4 b	19.8b	36.7 b	1574 b
Mean			48.2	25.8	23.3	23.5	37.9	2023
LSD (p≤0.05)			0.63**	0.68**	0.75**	0.82**	0.22**	5.05**
Genotypes	1	Akça	52.5	27.7	14.7	14.4	45.6	1409
	2	Akcin 91	46.0	27.9	17.2	16.8	41.5	1689
	3	Aksu^{+}	45.4	27.7	15.1	14.9	41.8	1983
	4	Aydın 92	53.0	30.3	26.0	24.4	34.8	2288
	5	Aziziye 94	52.5	24.3	17.6	16.3	36.3	1981
	6	Azkan^{+}	50.8	26.5	25.4	26.1	43.5	2324
	7	Çağatay	46.5	24.8	24.4	23.1	46.0	1849
	8	Canıtez 87	52.5	23.4	15.4	15.1	44.0	1924
	9	Cevdetbey 98^{+}	50.6	27.6	22.0	21.6	51.9	2153
	10	Damla 89	47.4	25.8	21.1	20.9	33.6	1878
	11	Dikbaş	48.6	25.6	13.4	13.0	47.9	1625
	12	Diyar 95	55.9	31.7	18.2	18.0	39.4	1977
	13	Er 99	50.2	29.0	17.9	16.7	47.6	1669
	14	Eser 87	48.1	27.5	18.5	18.6	29.9	2213
	15	Gökçe	47.3	25.8	12.9	14.1	42.9	1610
	16	Gülümser^{+}	52.7	28.8	29.2	28.6	39.0	2323
	17	Hisar	50.3	28.4	12.0	11.7	42.5	1555
	18	İnci	48.0	29.0	23.0	23.2	36.6	1826
	19	İzmir 92	48.1	26.3	20.5	20.9	39.7	2221
	20	Menemen 92	52.9	33.1	18.7	18.9	40.1	2002
	21	Sarı 98^{+}	49.2	25.8	18.1	18.4	57.4	1948
	22	SMN 101	51.3	23.9	22.7	25.2	44.3	2245
	23	SMN01	49.1	21.8	26.1	25.9	43.8	1599
	24	SMN02	45.7	20.5	33.7	32.7	37.7	1811
	25	SMN03	50.3	23.9	30.5	32.8	27.6	1892
	26	SMN04	44.5	23.0	33.8	35.6	43.6	2240
	27	SMN05	47.5	27.2	29.0	27.8	34.6	1969
	28	SMN07	43.5	27.4	20.8	20.3	45.2	1659
	29	SMN08	49.4	20.0	36.5	35.4	34.9	2329
	30	SMN10	47.6	30.7	34.1	31.7	37.3	1983
	31	SMN11	47.8	22.1	40.8	36.3	35.7	1706
	32	SMN13	45.9	26.4	38.9	38.8	35.2	2162
	33	SMN14	47.4	28.1	30.6	31.4	34.2	2268
	34	SMN15	52.2	30.3	29.3	31.2	31.9	2259
	35	SMN16	50.4	27.9	22.4	24.2	30.6	2049
	36	SMN17	45.9	23.8	23.3	25.7	36.4	2365
	37	SMN19	44.1	21.3	21.9	21.7	41.8	2263
	38	SMN20	40.4	19.7	21.1	20.2	42.5	2457
	39	SMN21	44.2	22.6	19.2	18.9	37.9	2035
	40	SMN37	44.8	20.6	25.8	24.6	32.1	2161
	41	SMN38	45.2	22.4	23.2	23.4	32.4	2190
	42	SMN39	46.1	23.3	24.5	25.1	32.3	2301
	43	SMN40	42.4	20.8	22.5	23.7	14.7	1786
	44	SMN41	42.1	20.5	20.0	24.1	14.1	1731
	45	SMN42	44.5	25.0	24.6	22.7	38.6	2062
	46	SMN43	44.1	23.0	18.4	20.2	42.2	1965
	47	SMN44	47.6	29.1	22.7	23.0	27.7	2086
	48	SMN45	47.9	26.7	19.4	18.8	38.0	2041
	49	SMN46	46.7	27.7	18.7	22.6	26.8	1913
	50	SMN48	47.2	27.3	19.7	18.8	44.9	2153
	51	SMN49	47.4	26.6	25.3	24.0	38.4	2229
	52	SMN50	43.9	22.9	23.0	21.2	37.8	1952
	53	SMN51	49.1	24.3	26.6	27.5	32.3	2533
	54	SMN52	47.3	27.6	24.6	25.3	40.2	1911
	55	SMN54	50.8	22.8	28.8	28.0	36.2	2179
	56	SMN55	49.1	30.3	24.2	26.1	40.6	2689
	57	SMN56	47.4	22.6	29.6	31.4	40.1	2857
	58	SMN57	48.6	24.1	22.7	23.7	39.1	1805
	59	SMN58	48.8	24.1	24.0	25.4	34.6	2367
	60	SMN60	49.2	23.1	27.9	30.3	29.5	1811
	61	SMN61	53.4	28.0	24.4	26.3	43.0	1987
	62	SMN62	45.9	21.8	27.8	29.5	41.2	1949
	63	SMN82	60.0	30.0	27.2	26.3	31.7	1962
	64	Taek-Sağel^{+}	49.9	30.1	17.1	17.5	37.5	1641
	65	Uzunlu 99	48.1	31.3	10.8	10.9	38.9	1584
	66	Yaşa 05	47.6	27.3	21.3	18.8	40.2	1954
Mean			48.2	25.7	23.3	23.5	37.9	2023
LSD (p≤0.05)			3.16	3.41	3.80	4.12	1.12	25.42
		YxG	ns	ns	ns	ns	**	*
		YxSS	ns	**	ns	ns	**	*
		GxSS	**	ns	**	**	**	**
		YxGxSS	ns	ns	*	ns	**	*

$^{+}$Standard varieties. ns, *, and **: Not-significant, significant at p≤0.05, and p≤0.01, respectively. PH: Plant height, FPH: First pod height, PPP: Pod number per plant, SPP: Seed number per plant, 100SW: 100 Seed weight, SY: Seed Yield.

year (26.1 cm) of the trial compared to the second year (25.4 cm) (Table 2).

In the research, an insignificant variation in PPP was observed among Y, while significant variation was observed among SS and G. Y×G and Y×SS interactions were insignificant, while G×SS and Y×G×SS interactions were significant. Among the cultivars, Gülümser exhibited the highest PPP (29.2 pods plant^{-1}), while Uzunlu 99 had the lowest (10.8 pods plant^{-1}). Among advanced chickpea lines, SMN11 recorded the highest PPP (40.8 pods plant^{-1}), while SMN43 had the lowest count (18.4 pods plant^{-1}). The PPP showed variability influenced by genotype and sowing season factors, with years also playing a role in PPP. The PPP across different years and sowing seasons indicated higher counts during the winter sowing season (27.3 pods plant^{-1}) and in the first year of the trial (23.7 pods plant^{-1}) (Table 2).

In the examination, there was a statistically insignificant difference observed among Y regarding SPP, while significant differences were found among SS and G. The interaction of Y×G, Y×SS, and Y×G×SS was insignificant, while the G×SS interaction was statistically significant. SPP variation ranged from 18.8 to 38.8 (seed plant^{-1}) among advanced chickpea lines and from 10.9 to 28.6 (seed plant^{-1}) among cultivars. The lowest SPP was observed in SMN45 and SMN48 among advanced chickpea lines, while Uzunlu 99 had the lowest number among cultivars. Conversely, the highest SPP was obtained from SMN13 among advanced chickpea lines and from Gülümser among cultivars. SPP varied depending on the genetic structure and sowing season. Higher SPP was observed in the first year of the study (23.7 seed plant^{-1}), while SPP obtained during the winter sowing season (27.3 seed plant^{-1}) were found to be higher compared to the spring sowing season (19.8 seed plant^{-1}) (Table 2).

The research presented significant differences at the 1% threshold among Y, SS, G, and their interactions, including Y×G, Y×S, G×SS, and Y×G×SS interactions, regarding the 100SW trait. For advanced chickpea lines, SMN07 had the highest 100SW at 45.2 g, while line SMN41 had the lowest at 14.1 g. In the cultivars, Eser 87 exhibited the lowest 100SW at 29.9 g, while Sarı 98 had the highest at 57.4 g.The 100SW exhibited variations across years, sowing seasons, and genetic structures. The 100SW values determined during the winter sowing season (39.2 g) were higher than those observed during the spring season (36.7 g), and the values in the first year (38.5 g) of the experiment were higher than those in the second year (37.4 g) (Table 2).

In the experiment, significant differences were observed at the 1% level among Y, SS, G, and G×SS interaction, while significant differences were detected at the 5% level among Y×G interaction, Y×SS interaction, and Y×G×SS interaction regarding seed yield. The highest seed yield among the advanced chickpea lines was achieved by SMN56 (2857 kg ha^{-1}), while the lowest was recorded in SMN01 (1599 kg ha^{-1}). Amongst the cultivars, Azkan showed the highest seed yield (2324 kg ha^{-1}) and Akça exhibited the lowest (1409 kg ha^{-1}). Seed yield varied depending on genotype and sowing season factors, with years also affecting seed yield. It was observed that seed yield was higher in the first year (2101 kg ha^{-1}) compared to the second year (1946 kg ha^{-1}) and also higher in the winter sowing season (2473 kg ha^{-1}) than in the spring sowing season (1574 kg ha^{-1}) (Table 2).

Principal Component (PCA) and GGE-Biplot Analysis

Principal component analysis was used to visualize genotype distribution based on numerous traits. The PCA biplot graph of correlations between genotype and traits appears in Figure 1.

The two-dimensional PCA score plot for the 66 genotypes mean data derived from investigated traits and explained 67% (43.2% and 23.8% by

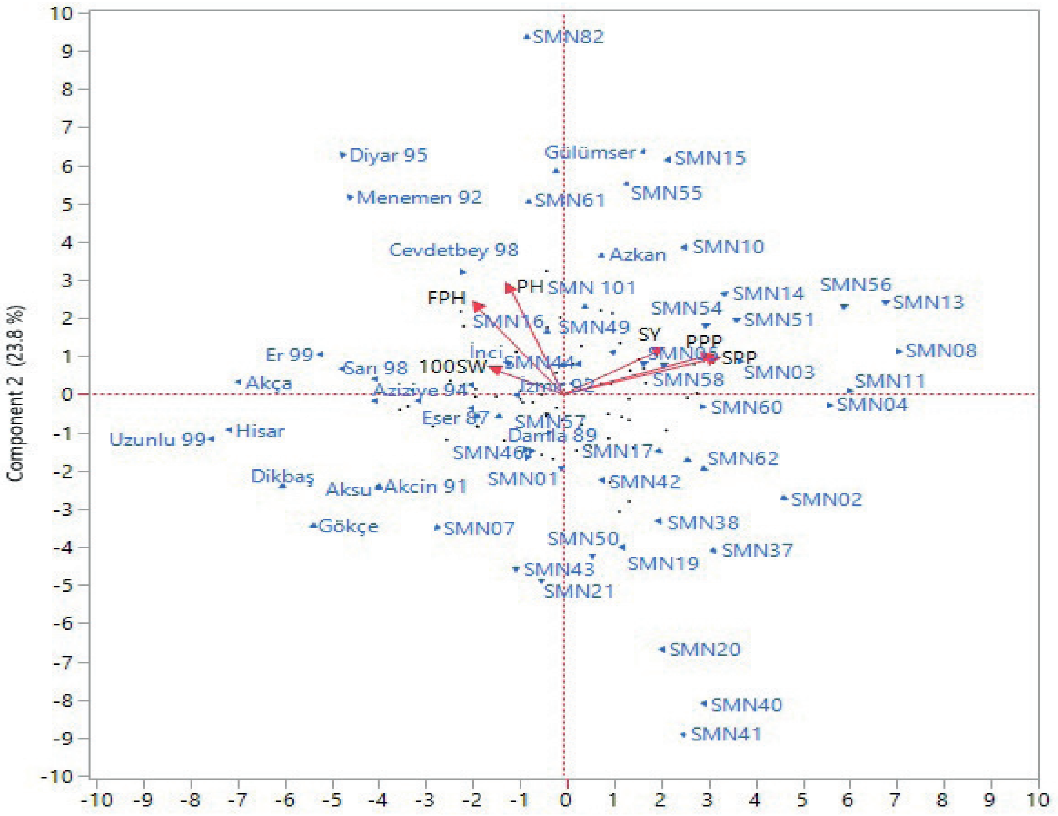

Figure 1. Relationship of traits and genotypes based on PCA Biplot analysis.

PC1 and PC2, respectively) of the total variation (Figure 1). SY showed positive correlations with both PPP and SPP; on the other hand, 100SW, FPH, and PH have also shown positive correlations. Among these traits, the lowest variation was observed in 100SW, followed by SY. PH, FPH, SPP, and PPP showed higher variation compared to 100SW and SY. Notably, the genotypes SMN56 excelled in yield, SMN13 in number of seeds per plant, Diyar 95 in plant height, Menemen 92 in first pod height, and Sarı 98 in terms of 100SW. The genotypes İzmir 92 and SMN38, positioned closer to the axis center, exhibited values closely resembling the experimental mean. In terms of the examined traits, among the chickpea cultivars used in the study, the Azkan and Gülümser cultivars exceeded the average values, while the other cultivars had values below the averages. Advanced chickpea lines exhibited higher values compared to the chickpea cultivars (Figure 1).

The GGE biplot model (Figure 2a, 2b) illustrates genotype-sowing season relationships in the study as 85.09%, 14.91%, and 100% for PC1, PC2, and PC1+PC2, respectively. Figure 2a highlights the distinct relationship between two different sowing (winter and spring) seasons and the relationship between genotype and sowing seasons. Figure 2a visually illustrates that the two sowing seasons are distinct and not closely related, implying that chickpea genotypes can be considered as separate environments for selection purposes. Upon averaging all traits across both sowing seasons, genotypes SMN56, SMN55 and SMN51 consistently displayed high performance across both sowing seasons. Conversely, genotypes like SMN13, SMN37, SMN38, and SMN54 performed better during the spring sowing season, while genotypes such as cultivar Aydın 92, SMN08, SMN14, SMN39, and SMN58, exhibited superior results for the winter season. These findings suggest that these genotypes could be valuable selections for sowing seasons with similar ecological conditions. However, the Akça, Gökçe, Hisar, and Uzunlu 99 cultivars, and the SMN01 genotype did not exhibit favorable outcomes across any sowing seasons, suggesting their unsuitability for recommendation in such environments. The ideal genotype comparison based on sowing seasons appears in Figure 2b. In the study, SMN56, SMN55, and SMN51 were centrally located in the concentric circle, indicating their favorable performance. Conversely, cultivars Akça, Dikbaş, Hisar, Uzunlu 99, and the SMN01 genotype were positioned farther from the center, suggesting their less favorable genotypes. SMN56 is thus considered the most ideal genotype, making it a recommended choice for release, along with SMN55 and SMN51, due to their consistent performance across both sowing seasons.

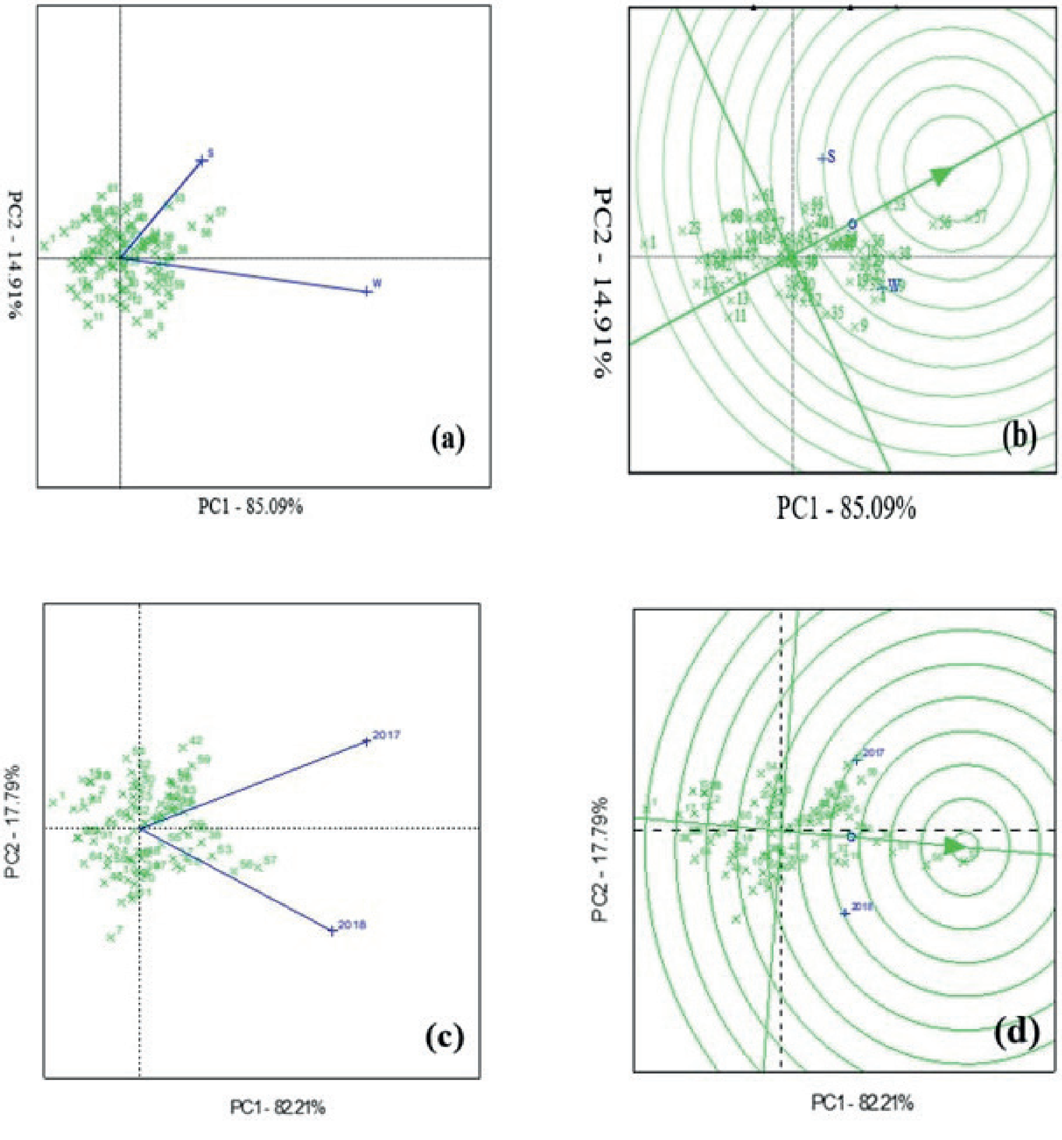

Figure 2. Relationship genotypes and sowing seasons (a), ideal genotype comparison based on sowing seasons (b), relationship genotypes and growing seasons (c), and ideal genotype comparison based on growing seasons (d).

The GGE biplot model in Figure 2 (c, d) demonstrates genotype-growing season relationships in the research, with a proportion of 100% (PC1:17.79%, and PC2:82.21%). This figure provides insight into the correlation between different growing seasons and the relationship between genotype and growing seasons. It suggests that there is no close association between the growing seasons, implying that chickpea genotypes can be evaluated as distinct environments concerning years. Genotypes SMN56, SMN55, and SMN51 consistently showed superior performance across both growing seasons. In the year 2018, genotypes such as the Aydın 92 and Gülümser cultivars, and SMN17 and SMN19 exhibited noteworthy performance, while in 2017, genotypes like SMN58, SMN39, SMN14, and the Azkan cultivar displayed superior results. Conversely, the genotype SMN01 and cultivars Hisar, Uzunlu 99, and Taek-Sağel performed poorly in both years (Figure 2c).

The comparison of ideal genotypes based on growing seasons appears in Figure 2d. In this study, SMN56, SMN55, and SMN51 emerged as the ideal genotypes, while SMN20 also showed favorable characteristics. Conversely, the cultivars Akça, Hisar, Uzunlu 99, Dikbaş and SMN01 were identified as unfavorable genotypes. As a result, SMN56 is considered the most optimal genotype, with SMN55 and SMN51 also suggested for release due to their reliable performance across both growing seasons (Figure 2d).

Relationships among traits (Pearson's correlation and heatmap analysis)

Figure 3 shows the Pearson's correlation coefficient analysis and heatmap analysis. There was a positive and significant relationship between SY and PPP and SPP, while a negative and insignificant relationship was observed with 100SW, PH, and FPH. PPP showed a positive and significant relationship with the SSP, and a negative and insignificant relationship with 100SW, PH, and FPH. SPP exhibited a negative and significant relationship with both 100SW and FPH, while it showed a negative and insignificant relationship with PH. A positive and insignificant relationship was also observed between 100SW and PH, as well as FPH. A positive and significant relationship was determined between PH and FPH (Figure 3a). The heatmap analysis revealed strong correlations, particularly between the PPP and SPP. A significant correlation was observed between PH and FPH as well. A strong correlation was also identified between SY and both PPP and SPP (Figure 3b).

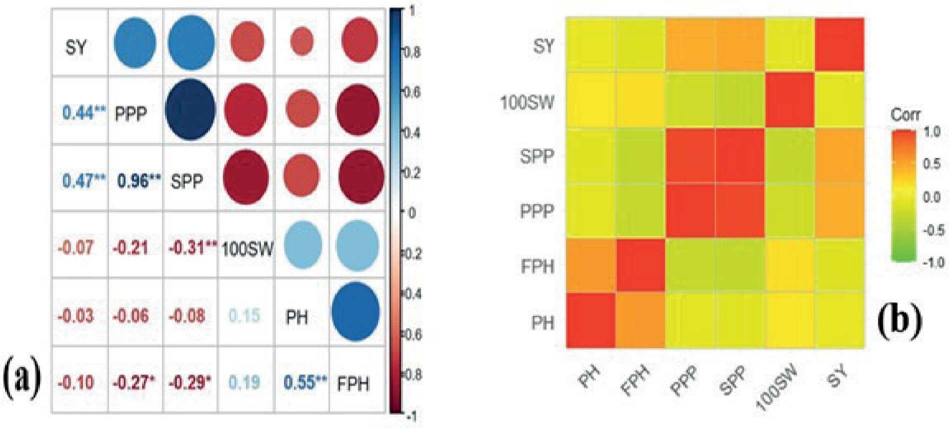

Figure 3. Pearson's correlation (a) and heatmap analysis (b) for the chickpea genotypes' relationship.

Discussion

The sowing season significantly influences crop productivity due to variations in environmental conditions affecting phenological crop stages (Fotiadis et al., 2019). This study investigated the performance of chickpea genotypes across winter and spring sowing seasons, uncovering significant differences in PH, FPH, PPP, SPP, 100SW, and SY characteristics. Variances were noted among years, particularly in FPH, 100SW, and SY traits, with winter sowing presenting overall higher trait values than spring sowing. It has been determined that there are differences at the 1% level in terms of genotype x sowing season interaction for all traits examined.

The observed variations among chickpea genotypes based on sowing season underscore the critical role of sowing season in chickpea cultivation. Seed yield in the winter sowing season was 57.1% higher than in the spring sowing season. The significant increase in seed yield during the winter sowing season is due to more favorable climatic conditions, particularly lower temperatures and adequate precipitation during critical growth phases. Winter sowing, with its cooler temperatures and sufficient precipitation, provides a more conducive environment for chickpea growth, leading to higher yields. In the 2016-2017 growing season, the average temperature was 9.3 °C with 366.3 mm of total precipitation, creating a cooler and more stable environment for chickpea growth, especially during early vegetative and flowering stages. For instance, January 2017 had a temperature of -0.4 °C and 48.0 mm of precipitation, which helped maintain soil moisture and reduce evaporation rates. This combination is crucial for chickpeas, preventing water stress and supporting steady growth and development.

Lopez-Bellido et al. (2008) reported that chickpea seed yield from late autumn and early to mid-winter planting dates was 50 to 80% higher compared to the late winter sowing season. Tayyar et al. (2008) found significant differences in the examined traits between genotypes and sowing seasons. They also noted a statistically significant genotype × sowing season interaction in terms of seed yield. Winter sowing resulted in a yield of 2050 kg ha^{-1}, while spring sowing yielded 1588 kg ha^{-1}. Hama-Ali (2018) reported a PH of 73.8 cm, a PPP of 49.5 pods plant^{-1}, a 100SW of 29.8 g, and a SY/P of 15.0 g during the winter sowing season. In contrast, the spring sowing season had a PH of 53.8 cm, a PPP of 22.7 pods plant^{-1}, a 100SW of 29.0 g, and an SY/P of 6.81 g. The obtained results are consistent with these conclusions.

Winter sown chickpea plants benefit from more favorable environmental conditions, including better water availability and lower temperatures, resulting in taller plants with more flowers and pods that ultimately increase yield potential (Duarte, 2022). On the other hand, it is proved that production, yield, and yield stability of crops are higher in autumn cultivation due to the better establishment, proper use of precipitation, and avoiding common heat and drought stresses in late spring and early summer (Nezami et al., 2022).

Numerous factors and their interactions affect grain yield, an important measure of crop production. For breeding efforts to increase yield potential, an understanding of these characteristics is crucial. The selection of parent plants for hybridization is guided by character correlations, which make it easier to include desired characteristics and optimize trait combinations. For complex qualities like seed production impacted by both genetic and environmental factors, this understanding is crucial for developing efficient selection criteria. Efforts to increase grain yield have largely relied on selective breeding and hybridization (Bakhsh et al., 2006; Srivastava et al., 2017). In the investigation, GGE Biplot, Pearson correlation, and heatmap analysis were used to assess the associations between the features that were analyzed. According to GGE Biplot (Figure 1), SY is positively correlated with both PPP and SPP; on the other hand, 100SW, FPH, and PH have also shown positive correlations. In the examined traits, the lowest variation was observed in 100SW, followed by SY. A strong and positive correlation between SY and PPP, as well as with SPP, was discovered based on Pearson correlation analysis. SY, however, had a weak and unfavorable correlation with PH, FPH, and 100SW. A noteworthy and affirmative correlation was also discovered between PPP and SPP (Figure 3a). The heatmap analysis highlighted a strong correlation between PPP and SPP, indicating their close relationship. SY showed a significant correlation with both PPP and SPP as well (Figure 3b). The findings from the heatmap analysis were in line with the results obtained from Pearson's correlation and biplot analysis. Our results mesh with the findings of Hama-Ali (2018), and Richards et al. (2022), both of whom observed a positive and significant association between SY and PPP, as well as SPP. The findings imply that enhancing yield potential in chickpea cultivation may involve prioritizing traits like pods per plant and seeds per plant during the selection approach.

Environmental factors can have a major impact on genotype performance, either positively or negatively, depending on the region, growing seasons, years, nitrogen levels, rainfall, day lengths, temperature (Falconer, 1965; Tilahun et al., 2015). The key reasons contributing to the decline and volatility of chickpea production are the unpredictability of climatic changes and exposure to varied environments (Considine et al., 2017). Genotype by environment interactions (G×E) are crucial in plant breeding, meriting close examination. Repeatable G×E interactions can alter genotype rankings across various environments, providing significant guidance for targeted breeding strategies (Sabaghnia et al., 2008; Kaloki et al., 2019). GGE biplot is a method for analyzing genotype by environment interactions (GEI), evaluating both genotype main effects and interactions. It assesses genotypes based on yield across environments, considering stability, yield, environment distinctiveness, and representativeness (Yan & Kang, 2003). The correlations between the genotypes and examined chickpea attributes appear in Figure 1 using the principal component analysis. The results shown in Figure 1 indicate that Uzunlu 99 and Hisar varieties performed the lowest, while SMN13 and SMN08 showed the best performance. The genotypes SMN 56, SMN 54, SMN14, and SMN51 stood out in terms of seed yield. In contrast, the most unfavorable genotypes were found to be the Uzunlu 99, Akça and Hisar cultivars.

GGE biplot graphs were used to illustrate the relationships between genotypes and sowing seasons (Figure 2a), and genotypes and growing seasons (Figure 2c). Figure 2b and Figure 2d show the genotype ranking by optimal genotype according to sowing and growth seasons. Superior attribute means and high stability are characteristics of an ideal genotype. The genotypes SMN56, SMN55, and SMN51 consistently performed well when the attributes were averaged throughout the period of the two sowing seasons. On the other hand, genotypes such as SMN13, SMN37, SMN38, and SMN54 demonstrated remarkable performance in the spring sowing season, but cultivars Aydın 92, SMN08, SMN14, SMN39, and SMN58 exhibited better performance in the winter (Figure 2a). Genotypes SMN56, SMN55, and SMN51 consistently performed well across both growing seasons. In 2018, the Aydın 92 and Gülümser cultivars and SMN17 and SMN19 genotypes exhibited better performance, while in 2017, genotypes like SMN58, SMN39, and SMN14, and the Azkan cultivar displayed outstanding results (Figure 2c). SMN56, SMN55, and SMN51 stand out as ideal genotypes, while SMN20 also exhibits favorable characteristics across sowing seasons and growing seasons. Conversely, cultivars Akça, Hisar, Uzunlu 99, Dikbaş, and SMN01 are identified as unfavorable genotypes. Notably, SMN56 emerges as the most ideal genotype, with SMN55 and SMN51 also recommended for release due to their consistent performance across both sowing seasons and growing seasons (Figure 2b and Figure 2d).

Consequently, SMN56 is deemed the most ideal genotype, with SMN55 and SMN51 also recommended for release due to their consistent performance across both sowing and growing seasons. In order to identify the most stable and favorable genotypes in chickpea plants, the study made considerable use of mega-environment analysis using GGE biplot (Maqbool et al., 2015; Hajivand et al., 2020; Cheema et al., 2024).

Türkiye is the third-largest producer of chickpeas worldwide, providing a crucial source of protein to ensure food security. Considerable economic benefits resulted from 57.1% greater yield values during the winter sowing season contrasted to the spring sowing season. Producers can gain advantages by evaluating the performance of genotypes highlighted during the winter sowing season against biotic/abiotic stress factors and utilizing stress-resistant genotypes in production planning and breeding programs.

Conclusion

This study aimed to evaluate chickpea genotypes across different sowing and growing seasons, examining the relationships between key traits. Significant performance variations were observed among the genotypes across both sowing seasons and years. Chickpea genotype adaptation to various environmental conditions (sowing seasons and years) was demonstrated using GGE biplot analysis. The application of GGE biplot analysis revealed that genotypes SMN56, SMN57 and SMN53 were consistently high-performing across diverse conditions. This analysis underscores the importance of selecting genotypes based on traits like pod number per plant and seed number per plant to enhance seed yield. The findings suggest that incorporating these promising genotypes into breeding programs, particularly for winter and spring sowing, will substantially benefit chickpea cultivation. This research highlights the potential of GGE biplot analysis in optimizing genotype selection and provides actionable recommendations for improving chickpea productivity in varying environmental conditions.

Resumen

H. Güngör. 2024. Optimización del Rendimiento de Garbanzo: Análisis GGE Biplot de las Épocas de Siembra. Int. J. Agric. Nat. Resour. 127-139. Maximizar la producción de garbanzos en diversas condiciones ambientales es fundamental para asegurar la seguridad alimentaria y la sostenibilidad agrícola. El presente estudio aborda este desafío mediante la evaluación de sesenta y seis genotipos de garbanzo en estaciones de siembra de invierno y primavera durante dos años (2016-17 y 2017-18). Se utilizó un Diseño de Prueba Aumentado con tres repeticiones y seis variedades testigo. Los resultados muestran efectos significativos del genotipo, la temporada de siembra y su interacción en todos los parámetros examinados ($p \leq 0{,}01$). En particular, la temporada de siembra de invierno condujo a un incremento sustancial en el rendimiento, con una mejora de hasta el 57.1% en comparación con la siembra de primavera. Los dos primeros componentes del análisis de componentes principales explicaron el 67% de la variación total entre los genotipos de garbanzo. Entre los rasgos examinados, la menor variación se observó en el peso de 100 semillas, seguido por el rendimiento de semillas. El análisis de biplot, la correlación de Pearson y el análisis de mapas de calor revelaron una asociación positiva del rendimiento de semillas con el número de vainas por planta y el número de semillas por planta, mientras que mostraron una asociación negativa con la altura de planta, la altura de la primera vaina y el peso de 100 semillas. Los genotipos SMN56, SMN57 y

SMN51 destacaron por su rendimiento consistentemente alto en ambas temporadas de siembra y crecimiento para los rasgos deseados. Además, los genotipos SMN13, SMN20, SMN37, SMN38 y SMN54 destacaron durante la temporada de siembra de primavera, mientras que Gülümser, İnci, Aydın 92, SMN14, SMN20 y SMN39 demostraron ser superiores en invierno. Este estudio no solo subraya la ventaja de la siembra invernal para mejorar el rendimiento y otros rasgos, sino que también demuestra la efectividad del análisis de biplot GGE en la selección de genotipos, ofreciendo valiosas implicaciones para los futuros esfuerzos de mejoramiento del garbanzo.

Palabras clave: Análisis GGE biplot, épocas de siembra, interacción ambiente, rendimiento de garbanzos.

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