ISPEC Tarım Bilimleri Dergisi, 8(3): 572-582, 2024
ISPEC Journal of Agricultural Sciences, 8(3): 572-582, 2024
DOI: https://doi.org/10.5281/zenodo.12579041

Evaluation of Heterosis and Heterobeltiosis for Spike-Related Traits in F_1 and F_2 Populations of Hexaploid Bread Wheat

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Abstract
The study aimed to evaluate the heterosis and heterobeltiosis of F_1 and F_2 bread wheat populations, comprising twenty crosses for spike characters during the 2019-20 and 2020-21 cropping seasons in a randomized complete block design with three replications. In the research spike length, number of spikelets per spike, number of grains per spike, grain weight per spike, and grain yield were investigated. Results revealed that genotypes (parents, F_1 and F_2 populations) were differed significantly ($P \leq 0.01$) for all studied traits. Genotypes in both F_1 and F_2 populations demonstrated higher averages compared to the parents across the investigated traits. In the F_1 population, the maximum heterosis and heterobelthiosis were recorded at Köprü/Glosa and Ginra/Lucilla (30.88 and 29.92 %) for spike length, Krasunia odeska/Rumeli (25.96 and 19.60 %) for number of spikelets per spike, Köprü/Glosa and Krasunia odeska/Glosa (66.76 and 62.83 %) for grain number per spike, Krasunia odeska/Glosa and Krasunia odeska/Rumeli (85.97 and 52.57 %) for grain weight per spike and Rumeli/Lucilla and Krasunia odeska/Glosa (108.54 and 100.96 %) for grain yield respectively. The highest heterosis and heterobeltiosis values were recorded in the F_2 population; Ginra/Lucilla (15.15 and 14.20 %) for spike length, Krasunia odeska/Aslı (30.99 and 26.55 %) for spikelet numbers per spike, Glosa/Aslı (47.76 and 45.29 %) for grain number per spike, Glosa/Aslı and Krasunia odeska/Rumeli (35.16 % and 28.28 %) for grain weight per spike and Krasunia odeska/Rumeli and Rumeli/Lucilla (87.43 and 80.58 %) for grain yield respectively. These crosses could be further utilized in breeding programs to obtain superior individuals in advanced generations, enriching spike-related traits.

Research Article

Article History
Received :10.04.2024
Accepted :20.05.2024

Keywords
Heterosis
heterobeltiosis
bread wheat
spike features
grain yield

1. Introduction

Global wheat demand is expected to increase by an estimated 70 % over the next few decades (2020–2050) as human population pressure and rising income levels dramatically increase household consumption (Rosegrant, 2011). Common wheat (*Triticum aestivum*) is a staple food for more than 35 % of the world's population, providing 21 % of calories and 20 % of dietary proteins (Li et al., 2022; Ozkan, 2022).

Wheat stands as a pivotal source of plant-based food worldwide. Its importance is increasing by growing human population. Yet, shifting climates and environmental challenges such as salinity, drought, pests and diseases grave threaten wheat production. These challenges emphasize the critical need for improving wheat breeding programs to enhance yield per unit area (Bilgin et al., 2011; Erdem and Sakin, 2023).

Heterosis breeding has been proven to be the potential method of increasing yield in most of the cross-pollinated crops, but the commercial exploitation of heterosis in self-pollinated crops like wheat is not applicable due to technical difficulties involved in sufficient hybrid seed production. For enhancing the genetic yield potential of the varieties and hybrids, the choice of suitable parents for improving better varieties/hybrids is a matter of great concern to the plant breeders. The nature and magnitude of heterosis help in identifying superior cross combinations that may produce desirable individuals in the advanced generations. The crosses exhibiting high heterosis could be exploited for obtaining transgressive segregants for improvement of yield and yield components (Bilgin et al., 2022; Dudhat et al., 2022).

The main objective of this study was to examine the heterosis and heterobeltiosis for spike-related traits, including spike length, number of spikelets per spike, number of grains per spike, grain weight per spike, and grain yield of F_1 and F_2 generations of bread wheat populations.

2. Materials and Methods

In this study, thirteen bread wheat cultivars with different agro-morphological and quality traits (Aslı, Midas, Köprü, Lucilla, Pehlivan, Masaccio, Flamura-85, Ginra, Krasunia odeska, Rumeli, Selimiye, Esperia, and Glosa) were used as parents in crossings. As a result of the crossing between the selected cultivars, twenty different F_1 hybrid combinations were obtained (Table 1).

Table 1. The cross hybrids employed in the experiment

No	Crosses	No	Crosses
1	Aslı/Midas	11	Ginra/Midas
2	Aslı/Köprü	12	Lucilla/Pehlivan
3	Aslı/Lucilla	13	Ginra/Lucilla
4	Glosa/Aslı	14	Glosa/Midas
5	Rumeli/Aslı	15	Pehlivan/Köprü
6	Krasunia odeska/Aslı	16	Flamura-85/Esperia
7	Krasunia odeska/Rumeli	17	Flamura-85/Lucilla
8	Krasunia odeska/Glosa	18	Rumeli/Lucilla
9	Krasunia odeska/Lucilla	19	Selimiye/Glosa
10	Köprü/Glosa	20	Masaccio/Lucilla

The research was carried out in a randomized complete block design with three replications under Duzce ecological conditions. Sowings of parents and F_1 population were made in 1meter length rows with a row spacing of 30 cm and a plant spacing of 10 cm within rows, whereas sowing of parents and F_2 population were carried out in 1meter length rows with a row spacing of 30 cm and with 500 seeds per m^2. The planting of trials for each year occurred in the first week of November. Herbicide was used for weed control in the plots, while no application was made for diseases and pests. At the sowing, 50 kg ha^{-1} of nitrogen and 50 kg ha^{-1} of phosphorus were applied. The top-dressing fertilizer was divided into two parts, 90 kg ha^{-1} of nitrogen during tillering stage and 60 kg ha^{-1} of nitrogen applied during jointing stage. The harvest was conducted in the first week of July for each growing seasons. In the research, characteristics such as spike length, spikelet numbers per spike, grain numbers per spike, grain weight per spike and grain yield were examined. Grain yield was determined as yield per plant in the F_1 population and as yield obtained per 1 meter row in the F_2 population. The other traits were calculated based on randomly selected 10 main plants. In the study, statistical analyses of the data obtained from the F_1 and F_2 populations were conducted using the JMP program (JMP, 15.1 Sas Institute Inc., 2020), and Duncan's test was applied for comparing the means. Heterosis and heterobeltiosis are the percentage increases of F_1 and F_2 hybrid combinations over the parental average and the superior parent. The ratios of heterosis and heterobeltiosis for the hybrids were determined as percentages relative to the mean of the two parents and the superior parent. Heterosis (Ht) and heterobeltiosis (Hb) were determined using the formula provided below:

$$\boldsymbol{Ht}\,(\%) = \frac{F_1\text{-MP}}{MP} \times 100 \quad (Chang\ and\ Smith, 1967)$$

$$\boldsymbol{Hb}\,(\%) = \frac{F_1\text{-BP}}{BP} \times 100 \quad (Fonseca\ and\ Patterson, 1968)$$

where: Ht: Heterosis, Hb: Heterobeltiosis, MP: Mean mid-parent value, BP: Mean better parent value, F_1: Mean performance of the cross.

3. Results and Discussion

Through crosses of 13 bread wheat genotypes that featuring different traits, 20 cross combinations were obtained. In the study parents, F_1, and F_2 populations were found to be statistically significant at the 1 % level for all examined traits. Spike length, spikelet numbers per spike, and grain numbers per spike averages are presented in Table 2, while heterosis and heterobeltiosis values are provided in Table 3. Grain weight per spike and grain yield averages are shown in Table 4, and heterosis and heterobeltiosis values are presented in Table 5.

3.1. Spike length

Spike length significantly influences yield, as longer spikes lead to increased grain yield per unit area by accommodating more spikelets per spike (Shahwani et al., 2014; Mahpara et al., 2015; Ullah et al., 2021). In terms of spike length, while the cultivar Flamura-85 (12.06 cm) showed the longest spike length among the parental genotypes in the F_1 population, the cultivar Masaccio (7.80 cm) had the shortest spike length. In the F_2 population, the cultivar Krasunia odeska (11.87 cm) displayed the highest spike length, with the cultivar Midas (9.43 cm) exhibiting the shortest spike length. The cross Ginra/Lucilla recorded the highest spike length (14.0 cm), whereas the cross Aslı/Midas (9.96 cm) exhibited the shortest in the F_1 population. Meanwhile, the cross Krasunia odeska/Aslı displayed the highest spike length (12.67 cm), while the cross Ginra/Midas (9.20 cm) had the shortest in the F_2 population. Crosses' average spike length in both F_1 and F_2 populations exceeded that of parental genotypes (Table 2). Kalhora et al. (2015) reported spike lengths ranging from 11.87 to 15.87 cm among parents and from 11.60 to 16.93 cm among hybrids, while Shah et al. (2022) indicated spike lengths ranging from 10.60 to 12.40 cm within parents and from 10.90 to 13.75 cm within cross combinations.

For spike length, heterosis values in the F_1 population ranged from -3.24 to 30.88 %, while heterobeltiosis values ranged from -9.23 to 29.92 %. The highest heterosis in the F_1 population was observed in the cross Köprü/Glosa, while the lowest heterosis value was found in the combination Aslı/Midas. The highest heterobeltiosis was achieved in the combination Ginra/Lucilla, while the lowest heterobeltiosis value was obtained in the cross Flamura-85/Esperia. In the F_2 population, heterosis values ranged from -7.6 to 15.15 %, and heterobeltiosis values ranged from -13.33 to 14.20 %. The lowest heterosis and heterobeltiosis values were observed in the cross Flamura-85/Lucilla combination, while the highest heterosis and heterobeltiosis values were found in the cross Ginra/Lucilla (Table 3). In previous studies, heterosis and heterobeltiosis values for spike length were reported as follows: 3.93 % and 7.16 % (Kalharo et al., 2015), 28.76 % and 22.73 % (Gungor et al., 2018), 16.8 % and 9.93 % (Choudhary et al., 2022), 5.45 % and 1.09 % (Shah et al., 2022), and -0.24 % and -7.41 % (Bayhan et al., 2023).

3.2. Spikelet numbers spike^{-1}

The number of spikelets per spike plays a crucial role in enhancing the grain yield of wheat crops. Mahpara et al. (2015) and Ullah et al. (2021) confirmed that an increased number of spikelets per spike leads to higher grain yields. In the F_1 population, the cultivar Aslı (23.30) displayed the highest number of spikelets per spike, while the cultivar Masaccio had the lowest (17.30). The cultivar Esperia (21.00) exhibited the highest spikelets number per spike, while the cultivar Ginra had the lowest (16.70) in the F_2 population. The cross Köprü/Glosa (25.70) exhibited the highest number of spikelets per spike, while the lowest number of spikelets per spike was observed in the combinations Pehlivan/Köprü and Flamura-85/Esperia (21.30) among crosses in the F_1 population. In the F_2 populations, the lowest number of spikelets per spike was recorded on the cross Ginra/Midas (17.0), and the highest was observed in the cross Krasunia odeska/Aslı (24.00) (Table 2). Kalhoro et al. (2015) reported number of spikelets per spike ranging from 17.67 to 20.60, Shah et al. (2022) found number of spikelets per spike between 14.0 and 20.90, and Bayhan et al. (2023) observed number of spikelets per spike ranging from 12.33 to 17.94. Regarding number of spikelets per spike, heterosis values in the F_1 population ranged from -2.29 to 25.96 %, while heterobeltiosis values varied between -5.86 and 19.60 %. The cross Krasunia odeska/Rumeli exhibited the highest heterosis and heterobeltiosis values in the F_1 population, whereas the combination Pehlivan/Köprü displayed the lowest values. In the F_2 population, heterosis values ranged from -8.78 to 30.99 %, and heterobeltiosis values ranged from -14.76 to 26.55 %. The cross Krasunia odeska/Aslı showed the highest heterosis and heterobeltiosis values in the F_2 population, while the cross Pehlivan/Köprü exhibited the lowest values (Table 3). For number of spikelets per spike, heterosis and heterobeltiosis values were reported as follows: Kalhoro et al. (2015) -0.40 % and 1.62 %, Gungor et al. (2018) -10.75 % and 5.51 %, Shah et al. (2022) -17.45 % and 12.49 %, and Bayhan et al. (2023) -1.13 % and -11.47 %.

3.3. Grain numbers spike^{-1}

Increased number of grains per spike are an important trait directly associated with the grain yield of wheat. The number of grains per spike significantly impacts the grain yield of wheat (Wolde et al., 2019; Kumar et al., 2020; Ullah et al., 2021). The lowest number of grains per spike in the F_1 population was observed in the cultivar Masaccio (45.70) among parents, while the highest number of grains per spike was found in the cultivar Ginra (83.70). In the F_2 population, the cultivar Krasunia odeska (61.30) recorded the highest grain numbers per spike, whereas the lowest was observed in the cultivar Aslı (47.00). In the F_1 population, the maximum number of grains per spike was observed in the combination Köprü/Glosa (115.00), while the lowest was in the cross Flamura-85/Esperia (53.70). The lowest grain numbers per spike was found in the combinations Masaccio/Lucilla (42.00) and Pehlivan/Köprü (43.00), whereas the highest was observed in the combinations Glosa/Aslı (72.70) and Rumeli/Aslı (72.70) in the F_2 population. It was determined that the average number of grains per spike of crosses in both F_1 and F_2 populations was higher than that of the parental genotypes (Table 2). Kalhoro et al. (2015) reported number of grains per spike ranging from 63.80 to 69.67 among parents and from 62.40 to 76.27 among combinations, while Shah et al. (2022) reported number of grains per spike ranging from 35.35 to 49.65 within parents and from 64.40 to 84.20 within crosses.

Table 2. Mean performance of parental genotypes and F_1, F_2 populations for spike length, number of spikelets per spike, and number of grains per spike

Parental genotypes/ Crosses	Spike Length (cm)		Spikelets/Spike (no)		Grains/Spike (no)	
	F_1	F_2	F_1	F_2	F_1	F_2
Aslı/Midas	**9.96 ıjk**	9.87 ı-m	23.70 b-e	20.70 c-g	67.30 klm	45.70 lm
Aslı/Köprü	11.13 d-h	11.43 bcd	25.30 ab	22.00 bc	90.30 cd	49.30 h-m
Aslı/Lucilla	11.43 d-h	10.73 c-ı	22.70 d-h	20.30 d-h	75.00 f-k	67.30 ab
Glosa/Aslı	11.3 d-h	10.10 g-m	23.00 d-g	21.30 cde	84.30 de	**72.70 a**
Rumeli/Aslı	10.53 hıj	11.13 b-f	23.70 b-e	21.70 cd	83.30 def	**72.70 a**
Krasunia odeska/Aslı	11.4 d-h	**12.67 a**	25.00 abc	**24.00 a**	72.70 ı-l	66.00 abc
Krasunia odeska/Rumeli	11.53 d-g	10.97 b-h	24.30 a-d	23.30 ab	81.30 e-h	68.00 ab
Krasunia odeska/Glosa	12.70 bc	11.57 bc	23.00 d-g	19.30 g-k	90.70 cd	54.00 e-k
Krasunia odeska/Lucilla	11.67 def	11.07 b-g	22.3 e-h	20.30 d-h	82.70 d-g	62.30 bcd
Köprü/Glosa	13.30 ab	11.23 b-e	**25.70 a**	20.30 d-h	**115.00 a**	55.70 d-h
Ginra/Midas	11.53 d-g	**9.20 m**	22.30 e-h	**17.00 no**	76.00 e-j	46.30 klm
Lucilla/Pehlivan	11.96 cd	11.03 b-g	23.00 d-g	18.70 ı-m	74.30 g-k	53.70 e-k
Ginra/Lucilla	**14.00 a**	11.57 bc	25.00 abc	20.30 d-h	100.70 b	55.70 d-h
Glosa/Midas	11.40 d-h	9.60 j-m	22.30 e-h	20.00 e-ı	98.70 bc	68.00 ab
Pehlivan/Köprü	11.70 de	11.20 b-e	**21.30 g-j**	17.30 mno	68.00 j-m	**43.00 m**
Flamura-85/Esperia	10.93 e-h	11.20 b-e	**21.30 g-j**	20.70 c-g	**53.70 pq**	58.30 c-g
Flamura-85/Lucilla	11.70 de	9.90 ı-m	23.00 d-g	19.30 g-k	83.70 de	51.70 f-l
Rumeli/Lucilla	13.10 ab	10.47 d-j	23.30 c-f	18.30 j-n	100.30 b	51.00 g-l
Selimiye/Glosa	11.26 d-h	11.10 b-f	21.70 f-ı	18.70 ı-m	79.70 e-ı	56.30 d-h
Masaccio/Lucilla	10.50 hıj	10.47 d-j	21.70 f-ı	17.70 l-o	63.30 mno	**42.00 m**
Aslı	9.87 ıjk	10.60 c-ı	**23.30 c-f**	19.00 h-l	67.00 klm	49.30 h-m
Midas	10.73 f-j	**9.43 lm**	21.30 g-j	17.30 mno	64.30 lmn	**47.00 j-m**
Köprü	9.80 jk	10.03 h-m	22.70 d-h	20.30 d-h	82.30 d-g	59.30 c-f
Lucilla	10.70 g-j	10.0 h-m	19.70 jkl	19.00 h-l	73.70 h-k	55.30 d-h
Pehlivan	11.23 d-h	10.43 e-k	21.00 hıj	17.70 l-o	53.70 pq	49.30 h-m
Masaccio	**7.80 l**	9.47 klm	**17.30 m**	17.70 l-o	**45.70 q**	55.00 d-ı
Flamura-85	**12.06 cd**	11.43 bcd	21.70 f-ı	19.00 h-l	62.30 mno	54.70 d-j
Ginra	10.77 e-ı	10.10 g-m	22.70 d-h	**16.70 o**	**83.70 de**	**47.30 ı-m**
Krasunia odeska	10.70 g-j	**11.87 ab**	20.30 ıjk	17.70 l-o	53.30 pq	**61.30 b-e**
Rumeli	9.87 ıjk	10.00 h-m	18.30 lm	19.70 f-j	53.00 pq	56.30 d-h
Selimiye	10.70 g-j	10.57 d-j	19.70 jkl	17.70 l-o	57.30 nop	45.30 lm
Esperia	9.30 k	10.20 f-l	**17.70 m**	**21.00 c-f**	49.00 pq	55.00 d-ı
Glosa	10.53 hıj	9.97 ı-m	18.70 klm	18.00 k-o	55.70 op	49.00 h-m
F_1 and F_2 mean values	**11.65**	**10.83**	**23.18**	**20.06**	**82.05**	**56.99**
Parental mean values	**10.31**	**10.32**	**20.34**	**18.52**	**61.62**	**52.62**
General mean values	**11.12**	**10.62**	**22.06**	**19.45**	**74.00**	**55.27**
F	**	**	**	**	**	**
CV (%)	5.16	5.63	4.87	5.20	17.34	8.64
LSD (0.05)	0.94	0.98	1.75	1.65	8.54	7.79

*, ** Significant at P=0.05 and 0.01, respectively.

Heterosis values for number grains per spike, in the F_1 population ranged from -4.56 to 66.76 %, while heterobeltiosis values varied between -17.46 and 62.83 %. The highest heterosis value in the F_1 population was observed in the cross Köprü/Glosa, while the lowest heterosis value was found in the combination Flamura-85/Esperia. The highest heterobeltiosis value was detected in the cross Krasunia odeska/Glosa, while the lowest heterobeltiosis value was observed in the combination Pehlivan/Köprü in the F_1 population. In the F_2 population, heterosis values ranged from -23.86 to 47.76 %, and heterobeltiosis values ranged from -27.20 to 45.29 %. The highest heterosis and heterobeltiosis values were found in the cross Glosa/Aslı, while the lowest heterosis value was observed in the cross Masaccio/Lucilla, and the lowest heterobeltiosis value was detected in the cross Pehlivan/Köprü (Table 3). In previous studies, heterosis and heterobeltiosis values were reported as follows: Gungor et al. (2018) -25.46 % and 16.52 %, Bilgin et al. (2022) -9.60 % and 5.65 %, Choudhary et al. (2022) -23.26 % and 18.17 %, and Bayhan et al. (2023) -31.62 % and -36.71 %.

3.4. Grain weight spike^{-1}

Grain weight per spike is a crucial yield component, representing the culmination of various developmental stages. It directly influences harvest index and reflects the efficient nutrient utilization and translocation within the plant (Borojevich, 1983; Protich et al., 2012). The maximum grain weight per spike among parents in the F_1 population was recorded in the cultivar Köprü (4.12 g), while the lowest grain weight was observed in the Krasunia odeska (1.65 g). In the F_2 population, the highest grain weight per spike among parents was measured in the cultivar Köprü (3.45 g), and the lowest was recorded in the cultivar Midas (1.75 g). In the F_1 population, the highest grain weight per spike was observed in the cross Köprü/Glosa (4.97 g), while the lowest was in the cross Flamura-85/Esperia (2.29 g) among combinations. In the F_2 population, the lowest grain weight per spike was found in the cross Aslı/Midas (1.91 g), while the highest was in the cross Krasunia odeska/Rumeli (3.30 g). It was determined that the average grain weight per spike of crosses in both the F_1 and F_2 populations was higher than that of the parental genotypes (Table 3). Bilgin et al. (2011) reported grain weight per spike ranging from 1.74 to 1.99 g among parents and from 1.55 to 2.34 g among crosses, Haridy (2017) observed grain weight per spike ranging from 1.08 to 2.40 g among parents and from 1.75 to 3.68 g among combinations and Motawea (2017) found grain weight per spike ranging from 1.51 to 2.04 g among parents and from 1.49 to 2.01 g among combinations. Heterosis values for grain weight per spike, in the F_1 population ranged from -16.20 % to 85.97 %, while heterobeltiosis values varied between -31.02 % and 52.57 %. The highest heterosis value in the F_1 population was observed in the combination Krasunia odeska/Glosa, while the lowest heterosis value was found in the cross Flamura-85/Esperia. The highest heterobeltiosis values were detected in the combination Krasunia odeska/Rumeli, while the lowest heterobeltiosis value was observed in the combination Pehlivan/Köprü. In the F_2 population, heterosis values ranged from -34.37 % to 35.16 %, and heterobeltiosis values ranged from -40.41 % to 28.28 %. The highest heterosis value was found in the combination Glosa/Aslı, and the highest heterobeltiosis value was observed in the combination Krasunia odeska/Rumeli, while the lowest heterosis and heterobeltiosis values were detected in the cross Pehlivan/Köprü (Table 5). In studies conducted on grain weight per spike in terms of heterosis and heterobeltiosis values; Bilgin et al. (2011) reported values of 5.16 % and 2.89 %, Gungor et al. (2018) reported values of 46.66 % and 31.61 %, and Bayhan et al. (2023) reported values of -11.50 % and -23.63 %.

Table 3. Heterosis (Ht) and heterobeltiosis (Hb) estimates for spike length, number of spikelets per spike, and number of grains per spike

Crosses	Spike Length (cm)				Spikelets/Spike (no)				Grains/Spike (no)			
	F_1-Ht	F_1-Hb	F_2-Ht	F_2-Hb	F_1-Ht	F_1-Hb	F_2-Ht	F_2-Hb	F_1-Ht	F_1-Hb	F_2-Ht	F_2-Hb
Aslı/Midas	**-3.24**	-6.36	-1.46	-6.92	5.99	1.57	13.71	8.79	2.46	-3.30	-5.18	-7.95
Aslı/Köprü	13.21	12.50	10.82	7.86	10.14	8.64	11.93	8.17	20.87	10.01	-9.27	-16.87
Aslı/Lucilla	11.32	7.01	4.20	1.26	5.50	-2.78	7.21	5.26	6.91	1.96	28.68	21.70
Glosa/Aslı	11.12	7.61	-1.75	-4.72	9.49	-1.45	15.44	12.49	37.70	26.66	**47.76**	**45.29**
Rumeli/Aslı	6.77	4.34	8.20	5.03	13.75	1.45	12.34	8.68	39.49	25.49	37.57	29.10
Krasunia odeska/Aslı	11.03	6.87	12.74	6.71	14.55	7.31	**30.99**	**26.55**	21.41	9.47	19.26	7.57
Krasunia odeska/Rumeli	12.23	8.07	0.34	-7.62	**25.96**	**19.60**	24.89	18.65	53.81	50.69	15.63	11.10
Krasunia odeska/Glosa	19.81	17.2	6.04	-2.50	18.00	13.17	8.47	5.56	**66.43**	**62.83**	-2.00	-11.79
Krasunia odeska/Lucilla	9.22	6.69	1.25	-6.56	11.67	9.84	10.86	7.02	30.29	12.25	6.88	1.75
Köprü/Glosa	**30.88**	26.33	12.32	8.69	24.24	13.24	6.39	0.16	**66.76**	39.78	2.70	-6.22
Ginra/Midas	8.21	4.85	-5.86	-9.00	1.52	-1.45	-0.06	-1.96	2.85	-9.26	-1.97	-2.95
Lucilla/Pehlivan	9.13	6.52	8.07	5.78	13.17	9.52	1.85	-1.75	16.89	1.21	2.50	-3.06
Ginra/Lucilla	30.33	**29.92**	**15.15**	**14.20**	18.17	10.34	14.02	7.02	28.06	20.32	8.43	0.63
Glosa/Midas	7.22	5.30	-1.07	-3.69	11.67	4.62	13.17	9.06	64.40	53.60	41.65	38.74
Pehlivan/Köprü	11.27	4.12	9.45	7.34	**-2.29**	**-5.86**	**-8.78**	**-14.76**	32.17	**-17.46**	-20.76	**-27.2**
Flamura-85/Esperia	0.78	**-9.23**	3.55	-2.05	8.69	-0.93	3.42	-1.44	**-4.56**	-13.85	6.58	3.86
Flamura-85/Lucilla	2.78	-3.06	**-7.60**	**-13.33**	11.35	6.36	1.94	0.18	23.01	13.96	-5.83	-7.06
Rumeli/Lucilla	27.40	22.55	4.77	3.45	22.91	16.67	-5.22	-8.35	58.42	36.46	-8.80	-10.18
Selimiye/Glosa	6.17	5.09	8.07	4.77	13.05	10.18	4.71	1.85	41.07	38.34	18.81	14.85
Masaccio/Lucilla	13.57	-1.81	7.48	4.62	17.13	10.26	-3.60	-7.02	5.85	-13.92	**-23.86**	-24.99
Mean	**11.96**	**7.72**	**4.73**	**0.67**	**12.73**	**6.52**	**8.18**	**4.21**	**30.71**	**17.26**	**7.94**	**2.82**

3.5. Grain yield

Plant breeders consistently select superior parental genotypes to enhance wheat crop yield. The efficient selection of parent material is crucial for the success of breeding programs. In the study, the lowest grain yield in the F_1 population was measured in the cultivar Aslı (9.15 g) among parents, while the highest grain yield was recorded in the cultivar Ginra (20.53 g). In the F_2 population, the highest grain yield was found in the cultivar Rumeli (235.20 g) among parents, and the lowest was determined in the cultivar Esperia (124.40 g). Among crosses in the F_1 population, the highest grain yield was observed in the combination Rumeli/Lucilla (29.85 g), while the lowest was in the cross Lucilla/Pehlivan (5.90 g). The lowest grain yield was in the cross Aslı/Midas (155.60 g), while the highest grain yield was in the combinations Rumeli/Lucilla (428.70 g), Krasunia odeska/Rumeli (395.20 g), and Krasunia odeska/Lucilla (374.40 g) crosses in the F_2 population. The average grain yield of crosses in both F_1 and F_2 populations surpassed that of the parents (Table 3). Motawea (2017) observed grain yields ranging from 19.91 to 27.27 g among parents and from 21.50 to 40.67 g among combinations, while Shah et al. (2022) reported grain yields ranging from 15.75 to 19.30 g among parents and from 26.00 to 36.45 g among combinations. Heterosis values for grain yield in the F_1 population ranged from -59.54 to 108.54 %, while heterobeltiosis values ranged from -66.81 to 100.96 %. The highest heterosis value in the F_1 population was observed in the combination Rumeli/Lucilla, whereas the lowest heterosis value was found in the cross Lucilla/Pehlivan. The highest heterobeltiosis value was detected in the cross Krasunia odeska/Glosa, while the lowest heterobeltiosis value was observed in the combination Lucilla/Pehlivan. In the F_2 population, heterosis values ranged from -21.47 to 87.43 %, and heterobeltiosis values ranged from -25.42 to 80.58 %.

Table 4. Mean performance of parental genotypes and F_1, F_2 populations for grain weight per spike, and grain yield

Parental genotypes / Crosses	Grain Weight/Spike (g)		Grain Yield (g)	
	F_1	F_2	F_1 (g/plant)	F_2 (g/1 m)
Aslı/Midas	2.64 l-p	**1.91 qr**	12.19 j-n	**155.60 mno**
Aslı/Köprü	4.43 a-d	2.51 f-m	19.41 def	257.20 de
Aslı/Lucilla	2.75 l-o	2.69 d-j	17.58 e-h	316.00 c
Glosa/Aslı	3.37 h-k	3.18 abc	11.36 k-p	235.00 d-h
Rumeli/Aslı	3.37 h-k	2.47 g-m	14.17 g-l	236.30 d-g
Krasunia odeska/Aslı	2.95 klm	3.07 bcd	11.80 k-o	267.30 d
Krasunia odeska/Rumeli	3.83 e-h	**3.30 ab**	20.24 de	**395.20 b**
Krasunia odeska/Glosa	3.95 d-g	2.13 m-r	28.04 ab	313.90 c
Krasunia odeska/Lucilla	4.32 b-e	2.23 l-q	26.23 ab	**374.40 b**
Köprü/Glosa	**4.97 a**	2.90 c-f	7.96 opq	243.80 def
Ginra/Midas	3.05 j-m	1.98 o-r	9.15 n-q	216.50 f-k
Lucilla/Pehlivan	2.86 k-n	2.49 g-m	**5.90 q**	220.30 f-j
Ginra/Lucilla	4.66 abc	2.78 d-ı	27.01 ab	311.50 c
Glosa/Midas	3.56 f-j	2.07 n-r	8.07 opq	219.00 f-j
Pehlivan/Köprü	2.84 k-n	2.07 n-r	7.71 pq	216.60 f-k
Flamura-85/Esperia	**2.29 n-q**	2.83 c-h	15.83 f-j	224.80 e-h
Flamura-85/Lucilla	3.33 h-k	2.44 h-n	21.76 cd	340.80 c
Rumeli/Lucilla	4.84 ab	2.70 d-j	**29.85 a**	**428.70 a**
Selimiye/Glosa	3.67 f-ı	2.96 b-e	9.79 m-p	213.30 f-k
Masaccio/Lucilla	3.12 ı-l	1.98 o-r	25.24 bc	237.20 d-g
Aslı	2.28 n-q	2.35 j-p	**9.15 n-q**	188.10 j-m
Midas	1.79 qr	**1.75 r**	14.11 g-l	209.30 g-k
Köprü	**4.12 c-f**	**3.45 a**	15.05 g-k	185.20 klm
Lucilla	3.41 g-k	2.52 f-l	17.83 efg	229.90 e-h
Pehlivan	2.13 pqr	2.85 c-g	11,32 k-p	206.70 g-l
Masaccio	2.22 o-r	2.42 ı-n	14.47 g-l	222.60 f-ı
Flamura-85	3.17 ı-l	2.63 e-k	17.72 e-h	145.80 no
Ginra	3.83 e-h	2.30 k-p	**20.53 de**	234.50 e-h
Krasunia odeska	**1.65 r**	2.46 h-m	13.88 h-l	190.30 ı-l
Rumeli	2.53 m-p	2.57 f-l	10.78 l-p	**235.20 d-h**
Selimiye	3.03 j-m	2.32 j-p	12.43 j-n	202.90 h-l
Esperia	2.17 o-r	2.57 f-l	17.36 e-ı	**124.40 o**
Glosa	2.61 l-p	2.37 j-o	13.56 ı-m	175.40 lmn
F_1 and F_2 mean values	**3.54**	**2.53**	**16.46**	**271.17**
Parental mean values	**2.69**	**2.50**	**14.48**	**196.18**
General mean values	**3.20**	**2.52**	**15.68**	**241.63**
F	**	**	**	**
CV (%)	11.09	9.32	15.02	8.25
LSD (0.05)	0.58	0.38	3.84	32.50

*, ** Significant at P=0.05 and 0.01, respectively

The highest heterosis value was recorded in the cross Krasunia odeska/Rumeli, whereas the lowest heterosis value was found in the cross Aslı/Midas. The highest heterobeltiosis values were observed in the cross Rumeli/Lucilla, while the lowest heterobeltiosis value was detected in the cross Aslı/Midas (Table 5). In previous studies, heterosis and heterobeltiosis values for grain yield were reported as follows: Kalhoro et al. (2015) recorded 2.29 % and 4.45 %, Bilgin et al. (2022) reported -4.31 % and -17.14 %, Choudhary et al. (2022) observed 39.34 % and 24.07 %, and Shah et al. (2022) found 73.55 % and 66.73 %, respectively.

Table 5. Heterosis (Ht) and heterobeltiosis (Hb) estimates for grain weight per spike, and grain yield

Crosses	Grain Weight/Spike (g)				Grain Yield (g)			
	F_1-Ht	F_1-Hb	F_2-Ht	F_2-Hb	F_1-Ht	F_1-Hb	F_2-Ht	F_2-Hb
Aslı/Midas	30.70	16.48	-6.43	-18.84	4.90	-12.93	**-21.47**	**-25.42**
Aslı/Köprü	38.19	7.65	-13.01	-26.82	61.57	30.06	37.95	32.09
Aslı/Lucilla	-3.69	-19.28	10.18	6.25	30.75	-0.83	51.80	37.82
Glosa/Aslı	37.72	29.31	**35.16**	31.75	1.49	-14.18	29.71	25.57
Rumeli/Aslı	41.43	34.85	0.61	-3.76	40.69	30.18	12.45	0.58
Krasunia odeska/Aslı	49.54	28.81	27.83	25.12	2.63	-14.31	42.38	39.05
Krasunia odeska/Rumeli	**83.96**	**52.57**	**32.17**	**28.28**	66.99	50.45	**87.43**	**72.06**
Krasunia odeska/Glosa	**85.97**	43.61	-11.11	-12.76	**105.17**	**100.96**	72.06	65.53
Krasunia odeska/Lucilla	69.58	25.67	-10.41	-14.06	66.66	46.93	78.75	63.41
Köprü/Glosa	47.70	20.62	-0.64	-16.1	-44.45	-48.29	35.87	32.26
Ginra/Midas	8.68	-20.58	-0.86	-13.27	-47.01	-55.18	-2.12	-7.21
Lucilla/Pehlivan	3.17	-15.85	-6.62	-11.44	**-59.54**	**-66.81**	0.89	-4.22
Ginra/Lucilla	28.40	21.61	15.55	9.63	40.34	31.47	34.65	30.71
Glosa/Midas	61.25	36.72	0.84	-12.52	-41.32	-43.60	14.05	4.87
Pehlivan/Köprü	-9.17	**-31.02**	**-34.37**	**-40.41**	-41.65	-49.01	10.70	4.75
Flamura-85/Esperia	**-16.20**	**-27.68**	8.80	6.27	-6.33	-13.11	68.12	54.77
Flamura-85/Lucilla	1.44	-3.91	-5.25	-7.37	22.44	18.92	**81.59**	48.08
Rumeli/Lucilla	62.90	43.34	6.15	2.72	**108.54**	66.96	**85.72**	**80.58**
Selimiye/Glosa	30.19	21.48	26.04	25.00	-24.98	-28.35	12.91	5.44
Masaccio/Lucilla	11.10	-7.59	-19.94	-23.91	56.77	41.58	4.97	2.93
Mean	**33.14**	**12.84**	**2.73**	**-3.31**	**17.18**	**3.55**	**36.92**	**28.18**

4. Conclusion

The current study revealed a significant variability among parental genotypes and crosses across all examined traits. Heterosis and heterobeltiosis values were found to be positive across all examined traits in both F_1 and F_2 populations except for grain weight per spike in the F_2 population. Remarkably, the parental genotypes Rumeli and Lucilla exhibited higher yields. A comparative analysis of promising crosses for spike-related traits revealed combinations such as Ginra/Lucilla and Köprü/Glosa for spike length, Krasunia odeska/Aslı and Krasunia odeska/Rumeli for number of spikelets per spike, Krasunia odeska/Glosa, Glosa/Aslı, Glosa/Midas, and Köprü/Glosa for number of grains per spike, and Krasunia odeska/Rumeli, Glosa/Aslı, and Krasunia odeska/Aslı for grain weight per spike stood out. The Rumeli/Lucilla, Krasunia odeska/Glosa, Ginra/Lucilla, Krasunia odeska/Lucilla, and Krasunia odeska/Rumeli populations have performed prominently in grain yield.

Declaration of Author Contributions

The authors declare that they have contributed equally to the article. All authors declare that they have seen/read and approved the final version of the article ready for publication.

Declaration of Conflicts of Interest

All authors declare that there is no conflict of interest related to this article.

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To Cite	Güngör, H., 2024. Evaluation of Heterosis and Heterobeltiosis for Spike-Related Traits in F_1 and F_2 Populations of Hexaploid Bread Wheat. *ISPEC Journal of Agricultural Sciences*, 8(3): 572-582. DOI: https://doi.org/10.5281/zenodo.12579041.