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Research Article

Determination of combining ability, heterosis, hetorobeltiosis and dominance gene effect in inbred popcorn (*Zea mays* everta Sturt.) lines*

Erkan ÖZATA[1]*, Bilal UÇAR[2]

[1]Black Sea Agricultural Research Institute, Samsun, Türkiye
[2]Seed Certification and Variety Test Station, Ministry of Agriculture and Forestry, Samsun, Türkiye

***Corresponding author e-mail:** erkan.ozata@tarimorman.gov.tr

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Abstract: This study aimed to determine the effects of heterosis, heterobeltiosis and dominance on the inheritance of agronomic traits in popcorn. The study was carried out for two years (2018-2019) under ecological conditions of Samsun province. A total of 32 inbred popcorn lines were crossed with two tester lines (i.e., 'P206' and 'HP7211') during 1st year and 64 hybrids were obtained. Yield trial was carried out according to the 8 × 8 partially balanced Lattice trial design with 2 replications during 2nd year. Yield and yield components of each genotype were determined, hybrid vigor of the hybrids and general combaning abilities of the parents were examined. Heterosis, heterobeltiosis, and general combaning abilities occurred positively and negatively in all traits. Heterosis rates for grain yield trait were between -11.33 and 178.05%, whereas heterosis rates for bursting volume trait were between -0.9 and 69.9%. Heterobeltiosis rates ranged between -15.85 and 163.86% for grain yield and -14.4 and 69.1% for bursting volume. Overdominance and partial dominance genes were effective in the inheritance of the examined traits. It was also determined that 'TCK129', 'TCK 135', 'TCK136' and 'TCK144' lines can be used as genitor lines due to their high grain yield and average bursting volume. These results indicate that new commercial popcorn hybrids which can be planted in Türkiye can be developed in a short time.

Keywords: Popcorn, GCA, heterosis, heterobeltiosis, dominance effect

Kendilenmiş cin mısır (*Zea mays* everta Sturt.) hatlarında birleştirme yeteneği, heterosis, hetorobeltiosis ve dominans gen etkinliğinin belirlenmesi

Öz: Bu çalışmada, patlamış mısırın agronomik özelliklerinin kalıtımında heterosis, heterobeltiosis ve baskınlığın etkilerinin belirlenmesi amaçlanmıştır. Çalışma, Samsun ekolojik koşullarında iki yıl (2018-2019) süreyle yürütülmüştür. Çalışmanın birinci yılında 32 adet kendilenmiş patlamış mısır hattı, iki test hattı ('P206' ve 'HP7211') ile melezlenmiş ve 64 adet melez elde edilmiştir. İkinci yılda ise verim denemesi, 8 × 8 kısmi dengeli Latis deneme desenine göre 2 tekrarlamalı olarak yürütülmüştür. Denemede her genotipe ait verim ve verim öğeleri belirlenmiş, melezlerin melez gücü ve ebeveynlerin genel kombinasyon uyumları incelenmiştir. Heterosis, heterobeltiosis, genel kombinasyon uyumları tüm özelliklerde olumlu ve olumsuz yönde ortaya çıkmıştır. Denemede tane verimi özelliğinde heterozis oranları-%11.33 ile %178.05 aralığında, patlama hacmi özelliğinde heterozis oranları-%0.9 ile %69.9 aralığında belirlenmiştir. Heterobeltiosis oranları tane verimi özelliğinde-%15.85 ile %163.86 aralığında, patlama hacmi özelliğinde ise-%14.4 ile %69.1 aralığında ölçülmüştür. Çalışmada incelenen özelliklerin kalıtımınında, aşırı baskınlık ve kısmi baskınlık genlerinin etkili olduğu belirlenmiştir. Ayrıca yüksek tane verimi ve ortalama patlama hacmi kapasiteleri nedeniyle 'TCK129', 'TCK 135', 'TCK136' ve 'TCK144' hatlarının genitor hatları olarak kullanılabileceği belirlenmiştir. Bu sonuçlar kısa sürede Türkiye'de ekilebilecek yeni ticari patlamış mısır melezlerinin elde edilebileceğini göstermektedir.

Anahtar kelimeler: Cin mısır, GCA, heterosis, heterobeltiosis, dominans etkisi

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1. Introduction

Popcorn (*Zea mays* everta Sturt.) can be easily popped using popping methods (oil, air and microwave), and it is regarded as one of the most consumed snacks from past to present. Being a high-quality and concentrated food source with high fiber, protein, antioxidant and vitamin content has allowed it to take its place in breakfasts and meals. It is estimated that the popcorn market will increase from 5.5 billion US$ to 13.5 billion US$ in the next decade (Özata et al., 2024). Türkiye is ranked among the top ten countries in the world in terms of popcorn production (50-60 thousand tons) and export (25-30 thousand tons). Türkiye has the potential to rise to the top in the popcorn market with improvements in yield and quality.

Popping volume (PV), nonpopped grain ratio (NPGR), grain weight and size are controlled by many genes in popcorn breeding since they are quantitative characters. Although this situation creates some difficulties in breeding studies, the popping volume has been doubled and the nonpopped grain ratio (NPGR) has been reduced by 75% in the last 50 years (Sweley, 2013). The main goal in popcorn breeding is to develop varieties with high PV and low NPGR, stable, uniform, and fast grain moisture loss (Rinaldi et al., 2007; Dhliwayo, 2008; Effa et al., 2011; Freitas Júnıor et al., 2009). The breeder must have sufficient knowledge about the inheritance and nature of the gene action of yield and the yield-related traits in order to implement a successful breeding strategy (Alhadi et al., 2013). The ability of an improved inbred line to transfer the desired performance to its hybrid progeny is defined as the combining ability. The combining ability of parents provides information about the genetic structure, as well as gene action that plays a role in the inheritance of quantitative traits (Begum et al., 2018; Gosai et al., 2017). The basis of hybrid breeding varies according to hybrid vigour. The superior performance of a hybrid over the average of two parental strains is defined as heterosis (He), and the superior performance of a superior parent is defined as heterobeltiosis (Hb).

There are two views on the genetic control and inheritance of major agronomic traits in popcorn. The first view is that the control of PV is due to additive genes only, while the control of grain yield (GY) is primarily due to dominance genes (Larish and Brewbaker 1999; Pereira and Amaral Júnior, 2001; Freitas Júnior et al. 2006; Rangel et al. 2011; Cabral et al. 2016). The second view is that dominance genes may also effective to some extent on PV in parallel with GY. The effectiveness of dominant genes in both traits (GY and PV) enables the transfer of desirable characteristics to hybrids by maximizing the benefits of high heterosis. (Babo et al. 2006; Li et al. 2007; Freitas, et al. 2014; Coan et al. 2019; Santos et al. 2020; Guimarães et al. 2019). Although studies on the genetic gain of He, Hb, and dominance effects in the inheritance of agricultural traits of popcorn exist worldwide, no research has been found in Türkiye. Understanding genetic gains in the development of hybrids with high PV and GY is crucial for breeding studies. The assessment of potential genetic gains in popcorn, along with the analysis of genetic parameters and the investigation of heterotic and dominance effects on the genetic control of key agricultural traits, is of great importance for the reasons mentioned above. This study aimed to determine the effects of He, Hb and dominance on the inheritance of agronomic traits of popcorn.

2. Materials and Methods

2.1. Experimental site

A total of 32 inbred popcorn lines and 2 tester ('HP7211' and 'P206') lines were used in the study. The tester lines had high combination ability developed in the Batı Akdeniz Agricultural Research Institute (BAARI) popcorn breeding research. In 2018, two tester lines ('P206' and 'HP7211') and 32 popcorn inbred lines were crossed under controlled conditions and 64 popcorn hybrids were produced. The popcorn inbred lines were developed from materials obtained from different genetic sources (domestic and foreign populations and F2) between 2013 and 2018. For the construction of the test hybrid, S6 inbred lines were planted as the main parent in two different isolated areas (without corn production adjacent or at least 500 m away) and the popcorn inbred lines used as fathers (testers) were planted in the adjacent rows. The number of mother and father rows were 4 and 2, respectively. The experiment was conducted in 2019 at the Bafra trial station according to the partially balanced Lattice trial design (8 × 8) with 2 replications. Morphological and physical traits were observed in accordance with the technical instructions for agricultural value measurement experiments (TTÖDTK, 2018). Planting was done with a disc type pneumatic seeder with 70 cm row spacing and 20 cm plant spacing. Fertilizers were applied as 80 kg/ha phosphate P_2O_5 and 180 kg/ha N (nitrogen).

All cultural practices (irrigation, fertilization, hoeing, spraying, etc.) were performed as recommended. Data relating to days to start flowering, thousand grain weight, yield per hectare, popping volume, and non-popping grain rate were recorded. Thousand grain weight, grain moisture and flowering were made according to TDÖDTT (2018), while the popping volume and non-popping grain rate (%) were made according to Sweley (2013). Popping was done with 1100 W Kiwi KPM-7408 brand hot air blowing machines in the 11.8-12.5% moisture range. The data of each observed trait were analyzed by analysis of variance (ANOVA). Estimation of heterosis, potence ratio, and general combining ability were carried out as follows. Heterosis, heterobeltiosis and dominance effect determination heterosis (H1) and heterobeltiosis (H2) were calculated with the following formula (Mather and Jinks, 1971).

a) H1 (%) = (F1-MP/MP) × 100,

Where F1= mean value of the hybrid population; MP = mean of parent)

b) H2 (%) = (F1-BP/BP) × 100,

Where F1= mean value of the hybrid population; BP = better-parent

Potency ratio (D.E.) was calculated using the following formula suggested by Mather (1949) and Smith (1952).

c) D.E. = (F1– MP)/(0.5 × P2– P1),

Where F1= mean value of the hybrid population; MP = middle parent; P2= mean of highest parent; P1= mean of lowest parent. When D.E. = +1, it signifies complete dominance; when D.E. falls between -1 and +1, it indicates partial dominance; D.E. = 0 represents no dominance. If D.E. exceeds ±1, overdominance is observed. The '+' and '−' indicate the direction of dominance of one of the parents.

3. Results and Discussion

3.1. General combining ability (GCA)

Significant differences were determined among the hybrids in all traits (p<0.01). General combining ability (GCA), heterosis, heterobeltiosis and dominance effect (DE) estimations indicated that the genetic difference between the hybrids created sufficient variation. These results show that the parents are sufficiently different from each other and provide various allelic combinations. The average grain yield of the hybrids was 3.71 tonnes/ha, days to start flowering were 88 days, grain moisture was 20.1%, popping volume (PV) was 28.5 g/cm^3, non-popping grain rate (NPGR) was 14.1%, and 1000 grain weight (TGW) was 139.1 g. The GCA showed grain yield ranging from -16.49 to 27.53 tonnes/ha, flowering ranging from -7.88 to 2.4 days, grain moisture -3.78 to 2.53%, PV ranging from -8.2 to 9.04 g/cm^3, NPGR ranging from -2.84 to 3.7%, and TGW ranging from -29.54 to 31.97 g. The highest GCA in grain yield was determined from 'TCK152' × 'P206', the earliest flowering time from 'TCK122' × 'HP7211', the lowest grain moisture from 'TCK129' × 'P206'. The highest PV was noted for 'TCK125' × 'P206', the lowest NPGR was recorded for 'TCK137' × 'HP7211', and the highest TGW was observed for 'TCK141' × 'P206' (Table 1). Considering the traits examined in GCA, popcorn inbred lines showed different combining ability with both tester inbred lines. The highest grain yield combining ability was recorded for 'HP7211' tester line (Figure 1). The GCA effects were obtained in both directions (positive and negative) in terms of grain yield and PV, which are important selection criteria in popcorn. Among hybrids, 14 combinations in grain yield, 33 combinations in flowering, 1 combination in grain moisture, 29 combinations in PV, 4 combinations in NPGR, and 37 combinations in TGW showed positive comninig ability. The selection of superior genotypes that will meet the needs of the producer and consumer in popcorn is quite difficult since PV and grain yield are quantitative traits. The dominance of the negative relationship between both traits restricts simultaneous selection (Kamphorst et al., 2021; dos Santos Junior, et al., 2023). An inverse relationship between grain yield and PV in terms of GCA was noted in the current study. These results are consistent with dos Santos Junior et al. (2023), Santos et al. (2017), and Mafra et al. (2018). In addition, when grain yield and PV were evaluated together in terms of GCA, 'TCK 132' inbred line showed positive combination compatibility with both testers ('P206' and 'HP7211'). Similarly, 'TCK135', 'TCK136' and 'TCK 144' popcorn inbred lines showed positive combination ability with 'HP7211' tester line. The 'TCK 138' popcorn line had positive combination ability with 'P206' tester line. These popcorns inbred lines have high potential to be used in breeding programs aiming to obtain simultaneous gains in the future.

3.2. Heterosis

Significant differences were observed in the heterosis rates of the hybrids included in the study. The main purpose of using the check hybrid is to select the best parents in terms of certain traits for hybrid breeding. Heterosis values also varied according to the testers (Figure 2). The highest heterosis values in grain yield were determined for 'HP7211' tester, and for 'P206' tester in other traits. Positive and negative heterosis was measured in all parameters included in the study. However, almost all the hybrids examined in grain yield and PV showed positive heterosis. Our findings are similar to those of Ghosh et al. (2018) in popcorn and Flint-Garcia et al. (2009) reported that heterosis values changed positively and negatively according to the traits examined in their studies on grain maize. However, these results suggest that performing each trait in its biological context will contribute to obtaining maximum heterosis in solving the heterosis mechanism. In our study, heterosis rates varied between-11.33 and 178.05% in grain yield, -3 and 9.1% in flowering, -23.1 and 6.6% in grain moisture, and -0.9 and 69.9% in PV (Table 2). The results of our study are generally similar to the results of Kumar et al. (2023), Soni and Khanorkar (2013), Guimaraes et al. (2007), Amanullah et al. (2011) and Kumar et al. (2013). Guerrero et al. (2014) stated that in maize breeding, a heterosis level of at least 20% is desirable for effective utilization in crosses. Approximately 90% of the grain yield heterosis rates and 75% of the PV rates of the crosses were above the desired heterosis rates in maize breeding. It is thought that this difference is due to the genetic structure of the parents and environmental differences and the differences used in data analysis. Guillén-de la Cruz et al. (2009) found that as the genetic diversity of parent lines increases, the variation among their crosses also increases in both agronomic and physiological traits. As the genetic difference between inbred lines increases, the heterosis rate also increases. Using this approach, inbred lines and testers provide information about which heterotic group the inbred lines belong to. Lines that show good combination ability with the tester are thought to belong to a different heterotic group. Inbred lines 'TCK 158', 'TCK138' and 'TCK 136' had high heterosis rates for grain yield and PV with both tester groups. There are no heterotic groups defined differently from grain corn in popcorn breeding. It is thought that lines that show positive and high combining ability with both testers are from a different heterotic group.

3.3 Heterobeltiosis

Significant differences were recorded between the heterobeltiosis rates of grain yield and yield traits of the hybrids included in the study. It was determined that heterobeltiosis rates varied between-15.85 and 163.86% in grain yield, -3.6 and 8.4% in flowering, -25.7 and 3% in grain moisture, -1.4 and 69.1% in PV, -44.63 and -2.12% in NPGR, and -19.02 and 26.39% in 1000-grain weight (Table 3). The heterobeltiosis rates were lower than the heterosis rates. Utilization of heterosis or heterobeltiosis can speed up the process of generating superior hybrids. Heterosis, or hybrid vigour, is the superiority of the hybrid for a certain trait over the mean of the parents, whereas heterobeltiosis is a form of heterosis where the hybrid is superior to its best performing parent (Beche et al. 2013) Jones (1957) defined heterosis as the expression of dominance deviation, a variance from mid parent value, which may be explained by the additive effects of several desired dominant alleles, or as "overdominance," the combined effect of (two) different alleles at the same gene locus, or a combination of both. It is expected that the heterobeltiosis rate is lower than the heterosis rates in the examined traits. Positive and negative heterobeltiosis values were determined in terms of the traits examined in hybrid combinations. The highest heterobeltiosis value was obtained from grain yield. When grain yield, popping volume and flowering time traits were evaluated together, it was determined that almost all the combinations had positive heterobeltiosis values.

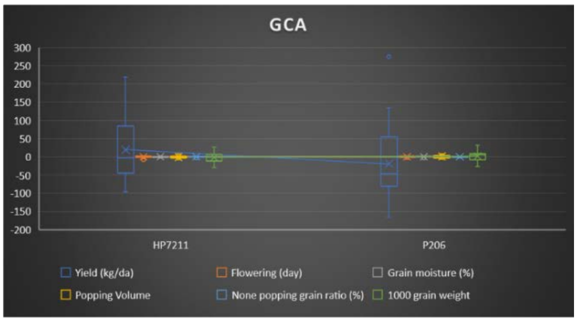

Figure 1. General combination ability of popcorn genotypes according to tester lines.

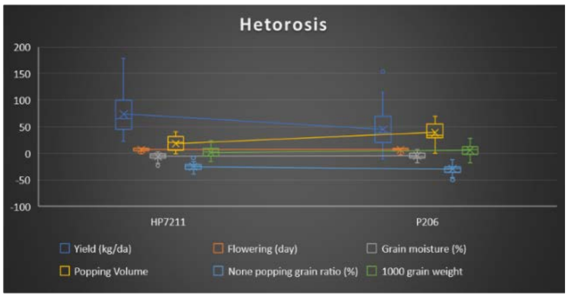

Figure 2. Heterosis value comparisons of popcorn genotypes according to tester lines.

Our findings are similar and different from previous studies (Soni and Khanorkar 2013; Kumar et al. 2023; Kumar et al. 2014). The determined differences are due to the genetic structure of the parents and environmental differences and the genetic differences of the corn types used. The 'TCK 158', 'TCK138' and 'TCK 136' inbred lines gave high heterobeltiosis rates similar to heterosis rates in grain yield and popping volume with both tester groups (Figure 3). From the definitions, heterobeltiosis helps a breeder to make more stringent selections than heterosis, as also reported by Lamkey & Edwards (1999). The obtained results are similar to Begum et al. (2017) and Khan et al. (2019) and Kumar et al., (2023).

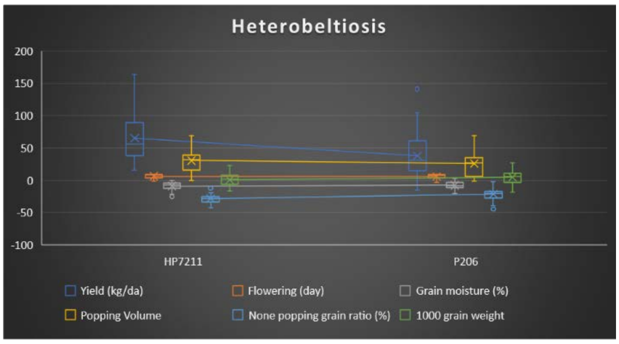

Figure 3. Heterobeltiosis value comparisons of popcorn genotypes according to tester lines.

3.4. Dominance effect

The dominance effect caused differences in the examined traits of the hybrids included in the experiment. The dominance effect was between-11.65 and 23.57% in grain yield, and it was >±1 in 59 combinations and between ±1 in 4 combinations. Positive complete and intense dominance was determined in the hybrids. Since the potency ratio was >1 in most of the combinations in the study, it suggests that the inheritance in grain yield is only due to overdominance. Our results are consistent with the studies reporting that overdominance is effective in grain yield in maize (Ghosh et al., 2018, Alhadi et al., 2013, Srdić et al., 2008).

The dominance effect of the flowering ranged between-15.38 and 4.80%, and it was determined to be >±1 in 59 hybrids and between ±1 in 5 hybrids (Table 4). Our findings revealed that intense and complete dominant genes are effective in the inheritance of flowering time. Indeed, our findings are similar to the results of El-Badawy (2012) and Ghost et al., (2018), who reported that complete dominance is effective in flowering. Grain moisture dominance effect varied between -5.28 and 3.39%, and it was determined that it was > ±1 in 48 hybrids, between ±1 in 16 hybrids and that excessive, complete and ineffective genes were effective, respectively. Both dominance situations show that dominant and partial dominance effects are intense in grain moisture. The obtained results are similar to the results of Begum et al. (2017), Rahman et al., (2019) and Kumar et al., (2023). Popping volume dominance effect was between-14.91 and 16.43%, and it was determined that it was > ±1 in 58 combinations and between ±1 in 6 hybrids. It was determined that in most hybrids, overdominance and partial dominance genes were effective in terms of PV. Dong et al. (2007) reported that partial dominance and overdominance were effective on popping volume inheritance. Lima et al. (2019), Oliveira et al. (2019), Santos et al. (2020) and Santos Junior et al. (2023) stated that dominance effects had a greater effect on PV inheritance. The results obtained are in accordance with the above-mentioned studies. The NPGR varied between-5.15 and 6.73%, and the NPGR dominance effect was determined to be > ±1 in 34 hybrids and ±1 in 30 hybrids. Overdominance was determined in half of the combinations, and partial dominance was determined in the other half. The results obtained from our study are similar to the results of Mosa et al. (2024). The dominance effect in 1000-grain weight varied between-24.62 and 26.64% and was determined to be > ±1 in DE 63 combinations and between ±1 in 1 hybrid. It was determined that overdominance and partial dominance were effective on 1000 grain weight. The results obtained in our study are consistent with Cabral et al. (2016) and Kumar et al. (2021). In addition, it was determined that, similar to heterosis and heterobeltiosis rates, dominance effect also differed from the tester lines (Figure 4). The fact that overdominance and partial dominance conditions differed in testers suggests that they contain different heterotic groups due to their genetic structures.

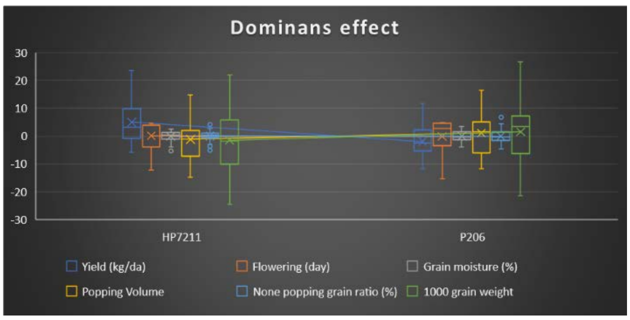

Figure 4. Dominance effect rates comparisons of popcorn genotypes with according to tester lines.

Table 1. General combination ability of traits examined in popcorn.

Female Line	×	Tester Line	Yield (tonnes/ha)		Flowering (day)		Grain moisture (%)		Popping Volume (%)		None popping grain ratio (%)		1000 grain weight (g)	
TCK120	×	HP7211	2.398	n.s.	2.12	*	0.23	n.s	1.10	**	0.51	n.s	6.75	**
TCK120	×	P206	-6.474	*	2.12	*	2.13	n.s	0.90	*	2.41	*	14.81	**
TCK121	×	HP7211	-3.478	n.s	2.12	*	-0.43	n.s	-1.34	**	0.39	n.s	26.32	**
TCK121	×	P206	1.556	n.s.	2.12	*	-1.03	n.s	2.17	**	-0.01	n.s	9.01	**
TCK122	×	HP7211	3.393	n.s.	-7.88	**	2.53	*	-4.32	**	-0.27	n.s	21.65	**
TCK122	×	P206	-12.286	**	2.12	*	-1.93	n.s	-1.64	**	0.96	n.s	-2.19	**
TCK123	×	HP7211	-4.404	n.s.	2.12	*	-2.88	*	0.69	n.s	-0.12	n.s	-6.29	**
TCK123	×	P206	-12.829	**	2.12	*	1.03	n.s	8.09	**	-0.21	n.s	4.56	**
TCK124	×	HP7211	0.961	n.s.	2.12	*	-1.08	n.s	0.90	**	-0.28	n.s	7.70	**
TCK124	×	P206	-0.5992	n.s	1.12	n.s	1.93	n.s	8.23	**	-0.92	n.s	17.06	**
TCK125	×	HP7211	-2.548	n.s.	2.12	*	-0.18	n.s	-1.13	**	0.18	n.s	2.65	**
TCK125	×	P206	-6.177	n.s	-3.88	**	-0.58	n.s	9.04	**	-0.41	n.s	-0.05	n.s
TCK126	×	HP7211	-3.569	n.s	-1.88	*	-0.28	n.s	-1.34	**	0.45	n.s	3.20	**
TCK126	×	P206	-3.126	n.s.	-1.88	*	0.28	n.s	4.07	**	-1.71	n.s	10.21	**
TCK127	×	HP7211	-9.267	**	1.12	*	-0.93	n.s	2.67	**	-0.84	n.s	17.29	**
TCK127	×	P206	-16.498	**	-3.88	**	-1.83	n.s	0.90	*	0.60	n.s	5.95	**
TCK128	×	HP7211	-4.969	n.s.	1.12	**	-0.03	n.s	5.19	**	0.11	n.s	4.16	**
TCK128	×	P206	-5.068	n.s	2.12	n.s	-2.33	n.s	2.22	**	-0.44	n.s	12.36	**
TCK129	×	HP7211	-7.323	*	1.12	*	-0.93	n.s	6.04	**	-0.21	n.s	2.27	**
TCK129	×	P206	13.502	**	2.12	n.s	-3.78	**	0.29	n.s	0.12	n.s	6.39	**
TCK130	×	HP7211	-9.618	**	2.12	*	-0.73	n.s	-0.11	n.s	2.29	*	-11.57	**
TCK130	×	P206	-8.701	**	2.12	*	1.38	n.s	8.97	**	-0.64	n.s	-11.92	**
TCK131	×	HP7211	-1.59	n.s.	2.12	*	-0.18	n.s	1.71	**	1.10	n.s	22.16	**
TCK131	×	P206	-8.267	*	2.12	*	-0.33	n.s	4.59	**	-0.05	n.s	1.45	*
TCK132	×	HP7211	16.869	**	-1.88	*	-0.08	n.s	0.95	**	1.56	n.s	-8.63	**
TCK132	×	P206	1.801	n.s.	2.12	*	0.38	n.s	0.90	*	-2.51	**	25.95	**
TCK133	×	HP7211	8.773	*	2.12	*	0.93	n.s	-3.16	**	-1.99	*	-2.79	**
TCK133	×	P206	2.881	n.s	2.12	*	-0.83	n.s	0.90	*	3.70	**	-2.44	**
TCK134	×	HP7211	-4.908	n.s	2.12	*	0.08	n.s	-3.36	**	-0.38	n.s	-29.54	**
TCK134	×	P206	6.658	*	2.12	*	0.78	n.s	-0.31	n.s	0.83	n.s	-25.84	**
TCK135	×	HP7211	16.653	**	-1.88	*	-0.33	n.s	6.61	**	0.56	n.s	-12.29	**
TCK135	×	P206	6.254	n.s	2.12	*	1.68	n.s	-6.21	**	-0.19	n.s	5.58	**
TCK136	×	HP7211	15.426	**	1.12	n.s	1.63	n.s	8.20	**	-2.69	**	-12.29	**
TCK136	×	P206	6.305	n.s	2.12	*	0.38	n.s	-6.51	**	0.20	n.s	-7.05	**
TCK137	×	HP7211	9.471	*	-1.88	*	-0.23	n.s	0.56	*	-2.84	**	-25.86	**
TCK137	×	P206	-5.21	n.s	2.12	*	0.68	n.s	-0.92	**	-1.31	n.s	6.40	**
TCK138	×	HP7211	10.758	*	-3.88	**	1.18	n.s	-1.76	n.s	0.52	n.s	1.48	*
TCK138	×	P206	10.426	**	-3.88	**	0.13	n.s	0.95	**	-0.81	n.s	26.87	**
TCK139	×	HP7211	21.902	**	-0.88	n.s	-0.73	n.s	-5.09	**	0.52	n.s	-16.17	**
TCK139	×	P206	-4.365	n.s	-5.88	**	-0.23	n.s	2.94	**	-1.17	n.s	6.33	**
TCK141	×	HP7211	1.447	n.s.	-4.88	**	-0.18	n.s	-1.88	**	-0.69	n.s	-24.48	**
TCK141	×	P206	-15.134	**	-4.88	**	0.33	n.s	-5.40	**	-1.92	*	31.97	**
TCK143	×	HP7211	4.799	n.s.	-3.88	**	-0.83	n.s	-4.18	**	-0.44	n.s	-18.54	**
TCK143	×	P206	1.018	n.s	-4.88	**	1.28	n.s	0.15	n.s	-1.37	n.s	-10.96	**
TCK144	×	HP7211	13.625	**	-2.88	**	-2.73	*	0.95	**	0.36	n.s	-10.37	**
TCK144	×	P206	12.811	**	2.12	**	0.78	n.s	-4.58	**	-1.37	n.s	-8.66	**
TCK145	×	HP7211	-4.598	n.s.	-1.88	*	-1.13	n.s	-1.47	**	-1.69	n.s	5.46	**
TCK145	×	P206	-13.716	**	-0.38	*	0.98	n.s	1.31	**	-0.07	n.s	-7.36	**
TCK146	×	HP7211	-3.32	n.s.	0.12	n.s	-0.18	n.s	2.52	**	0.86	n.s	8.25	**
TCK146	×	P206	-5.33	n.s	2.12	*	-1.38	n.s	0.64	n.s	-0.41	n.s	-25.82	**
TCK148	×	HP7211	-6.752	*	0.12	n.s.	-1.58	n.s	0.15	n.s	0.63	n.s	-2.55	**
TCK148	×	P206	-0.438	n.s	2.12	*	1.33	n.s	-5.19	**	-0.34	n.s	3.93	**
TCK151	×	HP7211	-1.429	n.s.	0.12	n.s	1.18	n.s	-5.09	**	0.16	n.s	-1.54	*
TCK151	×	P206	-11.683	**	0.12	n.s.	1.93	n.s	-3.29	**	1.03	n.s	3.57	**
TCK152	×	HP7211	2.598	n.s	-4.88	**	0.88	n.s	0.50	n.s	0.60	n.s	-7.18	**
TCK152	×	P206	27.532	**	0.12	n.s	-0.18	n.s	-4.58	**	-0.54	n.s	5.42	**
TCK153	×	HP7211	7.707	*	2.12	*	1.48	n.s	-5.19	**	0.11	n.s	6.91	**
TCK153	×	P206	-4.888	n.s	2.12	*	1.83	n.s	0.94	**	0.82	n.s	-7.63	**
TCK154	×	HP7211	-0.689	n.s.	2.12	*	0.88	n.s	-5.70	**	-0.09	n.s	-12.26	**
TCK154	×	P206	-3.975	n.s	2.12	*	-2.38	n.s	7.23	**	1.86	n.s	-18.45	**
TCK158	×	HP7211	0.037	n.s	2.12	*	1.28	n.s	-6.20	**	0.46	n.s	17.74	**
TCK158	×	P206	6.282	n.s	-3.88	**	-0.13	n.s	-3.29	**	1.23	n.s	-18.50	**
TCK159	×	HP7211	-6.57	*	2.12	*	0.23	n.s	-8.2	**	1.30	n.s	-10.30	**
TCK159	×	P206	-7.718	*	2.40	*	0.23	n.s	-4.63	**	1.70	n.s	7.33	**
Mean			371		88		20.1		28.50		14.1		139.1	
GCA			27.532 to -16.498		2.4 to -7.88		2.53 to -3.78		9.04 to -8.2		3.7 to -2.84		31.97 to -29.54	
Total significant cross			29		54		4		54		8		63	
Positive			14		33		1		29		4		37	
Negative			15		21		3		26		4		26	
CV (0.05)			12.39		1.15		8.55		13.97		9.57		0.6	

Table 2. Heterosis rates of some yield and components of popcorn genotypes.

Female Line	×	Tester Line	Yield (%)	Flowering (%)	Grain moisture (%)	Popping Volume (%)	None popping grain ratio (%)	1000 grain weight (%)
TCK120	×	HP7211	30.59	9.1	-4.2	23.3	-22.96	8.98
TCK120	×	P206	31.78	9.1	4.7	69.9	-21.26	15.04
TCK121	×	HP7211	66.32	9.1	-7.3	27.9	-26.70	10.66
TCK121	×	P206	48.67	9.1	-10.1	69.6	-14.10	23.60
TCK122	×	HP7211	44.67	9.1	-14.4	32.4	-20.60	2.33
TCK122	×	P206	6.79	-3.0	6.6	66.2	-20.24	20.12
TCK123	×	HP7211	52.79	9.1	-18.8	-0.9	-21.47	7.35
TCK123	×	P206	4.45	9.1	-0.5	66.1	-34.21	-0.66
TCK124	×	HP7211	56.67	7.9	-10.4	31.5	-28.80	16.65
TCK124	×	P206	33.86	9.1	3.8	65.6	-26.87	9.75
TCK125	×	HP7211	45.35	1.8	-6.1	2.7	-30.43	3.92
TCK125	×	P206	33.07	9.1	-8.0	61.7	-32.72	5.99
TCK126	×	HP7211	46.19	4.2	-6.6	0.4	-30.02	11.55
TCK126	×	P206	69.94	4.2	-4.0	58.9	-28.46	6.40
TCK127	×	HP7211	65.86	1.8	-9.6	29.7	-31.94	16.83
TCK127	×	P206	-11.33	7.9	-13.9	56.3	-28.15	8.35
TCK128	×	HP7211	53.48	9.1	-16.2	38.4	-25.08	7.05
TCK128	×	P206	37.83	7.9	-5.4	52.5	-25.71	13.12
TCK129	×	HP7211	117.71	7.9	-23.1	36.1	-26.70	5.76
TCK129	×	P206	39.86	9.1	-9.6	49.8	-26.70	8.68
TCK130	×	HP7211	22.21	9.1	-8.7	22.4	-27.75	-4.80
TCK130	×	P206	19.77	9.1	1.2	47.4	-36.04	-4.69
TCK131	×	HP7211	100.37	9.1	-6.1	5.4	-27.23	5.15
TCK131	×	P206	24.07	9.1	-6.8	42.3	-21.54	20.41
TCK132	×	HP7211	28.13	9.1	-3.5	31.2	-8.38	-2.35
TCK132	×	P206	67.38	4.2	-5.6	40.4	-14.43	23.23
TCK133	×	HP7211	131.26	9.1	-0.9	22.3	-15.18	2.26
TCK133	×	P206	72.02	9.1	-9.2	38.8	-33.37	1.85
TCK134	×	HP7211	88.27	9.1	-4.9	7.8	-21.12	-15.15
TCK134	×	P206	18.26	9.1	-1.6	33.3	-50.41	-18.06
TCK135	×	HP7211	118.23	9.1	2.6	20.4	-22.51	-5.07
TCK135	×	P206	86.53	4.2	-6.8	33.3	-28.15	8.17
TCK136	×	HP7211	105.90	9.1	-3.5	32.4	-39.56	-5.07
TCK136	×	P206	86.75	7.9	2.4	33.3	-34.43	-1.23
TCK137	×	HP7211	59.79	9.1	-2.1	5.0	-38.22	-15.17
TCK137	×	P206	37.22	4.2	-6.4	33.2	-26.19	8.78
TCK138	×	HP7211	125.98	1.8	0.2	40.4	-29.72	24.07
TCK138	×	P206	104.48	1.8	-4.7	33.1	-30.60	5.12
TCK139	×	HP7211	70.80	-0.6	-8.7	33.3	-32.46	8.78
TCK139	×	P206	40.86	5.5	-6.4	33.1	-41.22	-8.01
TCK141	×	HP7211	44.28	0.6	-3.8	14.1	-30.89	-15.18
TCK141	×	P206	-5.46	0.6	-6.1	33.1	-12.35	27.89
TCK143	×	HP7211	132.19	0.6	-9.2	24.2	-30.89	-5.13
TCK143	×	P206	64.01	1.8	0.7	31.5	-41.26	-9.69
TCK144	×	HP7211	38.52	9.1	-1.6	7.8	-23.93	-4.69
TCK144	×	P206	114.73	3.0	-18.1	31.2	-36.58	-2.34
TCK145	×	HP7211	31.37	6.1	-0.7	5.0	-26.70	-2.45
TCK145	×	P206	0.64	4.2	-10.6	29.7	-26.70	8.17
TCK146	×	HP7211	63.77	9.1	-11.8	9.6	-21.29	9.17
TCK146	×	P206	36.71	6.7	-6.1	29.7	-45.79	-15.10
TCK148	×	HP7211	57.75	6.7	0.9	13.2	-22.51	1.13
TCK148	×	P206	40.69	9.1	-12.7	27.6	-29.88	6.01
TCK151	×	HP7211	38.26	6.7	0.2	34.2	-24.08	5.69
TCK151	×	P206	9.38	6.7	3.8	22.3	-33.14	1.94
TCK152	×	HP7211	178.05	0.6	-6.1	4.1	-22.66	-2.31
TCK152	×	P206	80.27	6.7	-1.2	20.5	-29.15	7.12
TCK153	×	HP7211	97.36	9.1	1.6	5.5	-21.53	-2.65
TCK153	×	P206	38.61	9.1	3.3	14.1	-28.15	8.23
TCK154	×	HP7211	92.78	9.1	-1.2	0.5	-16.06	-10.70
TCK154	×	P206	42.53	9.1	-16.5	14.1	-36.17	-6.03
TCK158	×	HP7211	86.65	9.1	0.7	21.0	-19.35	-10.73
TCK158	×	P206	153.83	1.8	-5.9	9.5	-21.64	16.28
TCK159	×	HP7211	74.22	4.2	-4.2	7.5	-18.15	8.48
TCK159	×	P206	22.42	9.1	-1.4	0.4	-38.19	-4.32
	Mean		59.63	6.52	-5.29	28.70	-27.48	3.73
	Positive		62	62	14	63	0	40
	Negative		2	2	62	1	64	24

Table 3. Heterobeltiosis rates of some yield and components of popcorn genotypes.

Female Line	×	Tester Line	Yield (%)	Flowering (%)	Grain moisture (%)	Popping Volume (%)	None popping grain ratio (%)	1000 grain weight (g)
TCK120	×	HP7211	23.93	8.4	-7.5	22.7	-24.55	7.70
TCK121	×	HP7211	57.84	8.4	-10.5	31.8	-25.37	9.36
TCK122	×	HP7211	37.29	8.4	-17.3	30.9	-26.37	1.13
TCK123	×	HP7211	45.00	8.4	-21.6	0.0	-25.04	6.09
TCK124	×	HP7211	48.68	7.2	-13.4	37.7	-32.34	15.28
TCK125	×	HP7211	37.93	1.2	-9.3	21.8	-33.89	2.70
TCK126	×	HP7211	38.73	3.6	-9.8	30.6	-28.81	10.24
TCK127	×	HP7211	57.39	1.2	-12.7	7.3	-30.35	15.45
TCK128	×	HP7211	45.65	8.4	-19.1	31.8	-23.36	5.79
TCK129	×	HP7211	106.60	7.2	-25.7	39.7	-41.29	4.52
TCK130	×	HP7211	15.97	8.4	-11.8	13.6	-42.57	-5.92
TCK131	×	HP7211	90.15	8.4	-9.3	7.3	-33.21	3.91
TCK132	×	HP7211	21.60	8.4	-6.8	9.1	-35.82	-3.50
TCK133	×	HP7211	119.46	8.4	-4.3	33.6	-12.94	1.05
TCK134	×	HP7211	78.66	8.4	-8.2	5.0	-19.40	-16.15
TCK135	×	HP7211	107.10	8.4	-0.9	20.5	-30.35	-6.19
TCK136	×	HP7211	95.40	8.4	-6.8	69.1	-27.72	-6.19
TCK137	×	HP7211	51.64	8.4	-5.5	65.4	-30.85	-16.17
TCK138	×	HP7211	114.45	1.2	-3.2	64.8	-31.34	22.61
TCK139	×	HP7211	62.09	-1.2	-11.8	58.2	-35.32	7.50
TCK141	×	HP7211	36.92	0.0	-7.0	51.8	-33.51	-16.18
TCK143	×	HP7211	120.34	0.0	-12.3	46.7	-34.33	-6.24
TCK144	×	HP7211	31.46	8.4	-5.0	39.7	-34.33	-5.81
TCK145	×	HP7211	24.67	5.4	-4.1	32.7	-26.51	-3.60
TCK146	×	HP7211	55.41	8.4	-14.8	32.7	-27.86	7.88
TCK148	×	HP7211	49.70	6.0	-2.5	32.5	-25.43	-0.06
TCK151	×	HP7211	31.21	6.0	-3.2	32.5	-20.24	4.45
TCK152	×	HP7211	163.86	0.0	-9.3	30.6	-30.35	-3.46
TCK153	×	HP7211	87.30	8.4	-1.8	29.1	-26.80	-3.79
TCK154	×	HP7211	82.94	8.4	-4.5	21.8	-26.37	-11.75
TCK158	×	HP7211	77.13	8.4	-2.7	13.6	-25.21	-11.78
TCK159	×	HP7211	65.34	3.6	-7.5	9.0	-22.22	7.21
TCK120	×	P206	25.06	8.4	1.1	27.3	-10.93	13.68
TCK121	×	P206	41.09	8.4	-13.2	-1.4	-26.54	22.14
TCK122	×	P206	1.34	-3.6	3.0	2.3	-19.77	18.71
TCK123	×	P206	-0.88	8.4	-3.9	29.1	-44.63	-1.83
TCK124	×	P206	27.03	8.4	0.2	35.5	-18.34	8.45
TCK125	×	P206	26.28	8.4	-11.1	5.0	-24.87	4.74
TCK126	×	P206	61.27	3.6	-7.3	21.8	-17.04	5.14
TCK127	×	P206	-15.85	7.2	-16.8	19.9	-18.15	7.07
TCK128	×	P206	30.80	7.2	-8.6	4.5	-12.50	11.79
TCK129	×	P206	32.72	8.4	-12.7	32.7	-17.58	7.40
TCK130	×	P206	13.66	8.4	-2.3	23.6	-26.78	-5.81
TCK131	×	P206	17.74	8.4	-10.0	4.5	-22.50	18.99
TCK132	×	P206	58.84	3.6	-8.9	12.7	-34.36	21.78
TCK133	×	P206	63.25	8.4	-12.3	3.6	-4.45	0.65
TCK134	×	P206	12.23	8.4	-5.0	0.0	-25.59	-19.02
TCK135	×	P206	77.01	3.6	-10.0	7.0	-18.15	6.90
TCK136	×	P206	77.22	7.2	-1.1	68.8	-29.18	-2.39
TCK137	×	P206	30.22	3.6	-9.5	65.3	-12.39	7.50
TCK138	×	P206	94.04	1.2	-8.0	61.0	-28.57	3.88
TCK139	×	P206	33.67	4.8	-9.5	55.6	-19.77	-9.10
TCK141	×	P206	-10.28	0.0	-9.3	49.1	-20.12	26.39
TCK143	×	P206	55.64	1.2	-2.7	41.6	-2.12	-10.75
TCK144	×	P206	103.78	2.4	-20.9	38.2	-34.41	-3.49
TCK145	×	P206	-4.50	3.6	-13.6	32.7	-20.88	6.90
TCK146	×	P206	29.73	6.0	-9.3	32.6	-25.34	-16.10
TCK148	×	P206	33.51	8.4	-15.7	32.5	-19.77	4.76
TCK151	×	P206	3.80	6.0	0.2	30.9	-28.73	0.74
TCK152	×	P206	71.07	6.0	-4.5	29.1	-4.08	5.86
TCK153	×	P206	31.54	8.4	-0.2	27.0	-12.07	6.96
TCK154	×	P206	35.26	8.4	-19.3	20.0	-21.70	-7.14
TCK158	×	P206	140.88	1.2	-9.1	13.6	-39.47	14.92
TCK159	×	P206	16.17	8.4	-4.8	0.0	-30.98	-5.45
	Mean		51,49	5,88	-8.52	28.12	-25.25	2.51
	Positive		60	62	4	63	0	39
	Negative		4	2	60	1	64	25

Table 4. Dominance effect rates of some yield and components of popcorn genotypes.

Female Line	×	Tester Line	Yield (%)	Flowering (%)	Grain moisture (%)	Popping Volume (%)	None popping grain ratio (%)	1000 grain weight (g)
TCK120	×	HP7211	3.47	3.84	0.35	2.00	0.92	5.63
TCK120	×	P206	-3.63	4.63	2.82	1.64	4.39	12.34
TCK121	×	HP7211	2.79	4.63	-0.56	-2.43	0.71	21.93
TCK121	×	P206	-1.24	3.84	-1.61	3.95	-0.01	7.51
TCK122	×	HP7211	4.26	3.84	-2.68	-7.85	-0.50	18.04
TCK122	×	P206	-8.28	-15.38	3.39	-2.97	1.75	-1.82
TCK123	×	HP7211	-1.98	3.84	-4.01	1.26	-0.22	-5.24
TCK123	×	P206	-8.72	4.63	1.27	14.70	-0.37	3.80
TCK124	×	HP7211	2.32	1.84	-1.48	1.64	-0.52	6.42
TCK124	×	P206	-3.25	4.63	2.54	14.96	-1.67	14.22
TCK125	×	HP7211	-0.49	-8.16	-0.21	-2.05	0.32	2.21
TCK125	×	P206	-3.39	4.63	-0.98	16.43	-0.74	-0.04
TCK126	×	HP7211	-0.95	-3.38	-0.35	-2.43	0.82	2.67
TCK126	×	P206	-1.31	-4.16	0.22	7.39	-3.10	8.51
TCK127	×	HP7211	-5.87	-8.16	-1.27	4.86	-1.53	14.41
TCK127	×	P206	-11.65	2.63	-2.74	1.64	1.09	4.96
TCK128	×	HP7211	-2.43	3.84	-3.24	9.43	0.19	3.46
TCK128	×	P206	-2.51	2.63	-0.20	4.04	-0.80	10.30
TCK129	×	HP7211	12.35	2.63	-5.28	10.98	-0.37	1.89
TCK129	×	P206	-4.31	3.84	-1.47	0.52	0.22	5.33
TCK130	×	HP7211	-5.41	4.63	-0.99	-0.20	4.16	-9.64
TCK130	×	P206	-6.15	3.84	1.77	16.32	-1.15	-9.93
TCK131	×	HP7211	0.28	3.84	-0.21	3.12	2.00	18.47
TCK131	×	P206	-5.07	4.63	-0.63	8.35	-0.09	1.21
TCK132	×	HP7211	15.04	3.84	0.56	1.72	2.85	-7.19
TCK132	×	P206	2.99	-3.38	-0.28	1.64	-4.57	21.63
TCK133	×	HP7211	8.57	3.84	1.34	-5.75	-3.62	-2.33
TCK133	×	P206	3.85	4.63	-1.33	1.64	6.73	-2.03
TCK134	×	HP7211	6.87	4.63	0.14	-6.11	-0.70	-24.62
TCK134	×	P206	-2.38	3.84	0.92	-0.57	1.51	-21.53
TCK135	×	HP7211	14.87	3.84	2.39	12.02	1.03	-10.24
TCK135	×	P206	6.55	-3.38	-0.63	-11.29	-0.34	4.65
TCK136	×	HP7211	13.89	3.84	0.56	14.90	-4.89	-10.24
TCK136	×	P206	6.59	2.63	2.12	-11.83	0.36	-5.87
TCK137	×	HP7211	9.12	3.84	0.99	1.01	-5.15	-21.55
TCK137	×	P206	-2.62	-3.38	-0.49	-1.68	-2.39	5.34
TCK138	×	HP7211	10.15	-8.16	1.69	-3.20	0.95	1.23
TCK138	×	P206	9.89	-7.38	0.01	1.73	-1.47	22.40
TCK139	×	HP7211	19.07	-12.16	-0.99	-9.26	0.94	-13.47
TCK139	×	P206	-1.94	-1.38	-0.49	5.34	-2.13	5.28
TCK141	×	HP7211	2.71	-10.16	0.49	-3.42	-1.25	-20.40
TCK141	×	P206	-10.56	-9.38	-0.42	-9.82	-3.49	26.64
TCK143	×	HP7211	5.39	-10.16	-1.13	-7.60	-0.80	-15.45
TCK143	×	P206	2.36	-7.38	1.63	0.27	-2.49	-9.14
TCK144	×	HP7211	12.45	3.84	1.13	1.73	0.65	-8.64
TCK144	×	P206	11.80	-5.38	-4.01	-8.32	-2.48	-7.22
TCK145	×	HP7211	-2.13	-1.16	1.41	-2.67	-3.06	4.55
TCK145	×	P206	-9.43	-3.38	-1.75	2.38	-0.13	-6.14
TCK146	×	HP7211	-1.11	3.84	-1.90	4.58	1.57	6.87
TCK146	×	P206	-2.72	0.63	-0.42	1.17	-0.75	-21.52
TCK148	×	HP7211	1.20	0.63	1.90	0.27	1.15	-2.13
TCK148	×	P206	-3.85	3.84	-2.39	-9.43	-0.62	3.28
TCK151	×	HP7211	0.40	-0.16	1.69	-9.25	0.29	-1.28
TCK151	×	P206	-7.80	0.63	2.54	-5.98	1.87	2.98
TCK152	×	HP7211	23.57	-9.38	-0.21	0.90	1.09	-5.98
TCK152	×	P206	3.63	-0.16	1.06	-8.33	-0.99	4.52
TCK153	×	HP7211	7.71	3.84	2.11	-9.43	0.20	5.76
TCK153	×	P206	-2.36	4.63	2.40	1.70	1.49	-6.36
TCK154	×	HP7211	1.00	3.84	1.27	-10.35	-0.17	-10.21
TCK154	×	P206	-1.63	4.63	-3.51	13.15	3.39	-15.38
TCK158	×	HP7211	6.57	4.63	1.83	-11.28	0.85	14.78
TCK158	×	P206	1.58	-8.16	-0.35	-5.98	2.25	-15.41
TCK159	×	HP7211	-3.71	-4.00	0.35	-14.91	2.36	-8.58
TCK159	×	P206	-5.37	4.80	0.28	-8.42	3.08	6.11
	Mean		1,55	0,01	-0.08	-0.05	-0.02	0.00
	x>1		29	37	20	31	18	34
	-1<x<+1		30	22	16	27	16	29
	-1>x		4	5	28	6	30	1

4. Conclusion

Positive and negative heterosis and heterobeltiosis values were obtained for all traits examined in the study. According to the results, heterosis rates for grain yield and popping volume traits were -11.33-178.05%, -0.9-69.9%, respectively. Similalry, heterobeltiosis rates grain yield and popping volume traits were -15.85-163.86% and -14.4-69.1%, respectively. Positive heterosis rates were obtained above the desired (>20%) heterosis values in for grain yield and popping volume traits, which are the most important selection criteria. It is thought that high heterosis values are related to the genetic variability of inbred lines. In addition, overdominance and partial dominance were effective in grain yield and popping volume. The highest GCA value in grain yield trait in the experiment was obtained from 'TCK152' × 'P206' hybrid with 27.53 tons/ha, and from 'TCK125' × 'P206' hybrid with 9.04% in popping volume. Different lines ranked first in grain yield and popping volume traits, which are the main selection criteria in popcorn breeding. However, 'TCK129', 'TCK 135', 'TCK136' and 'TCK144' inbred lines had higher grain yield GCA and above average popping volume values. These results indicate that in a short time, new commercial popcorn hybrids can be developed which can be planted in Türkiye. This suggests that popcorn inbred lines that stand out in both traits have the highest genetic differences. There are no defined heterotic groups in popcorn. Identification of heterotic groups through genetic studies will contribute to increasing heterosis success.

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Conflict of interest

The authors declare no conflicts of interest.

Authorship contribution statement

E.Ö: Methodology, Planning and conducting the experiment, performing statistical analyses, Writing-Original draft preparation, Writing- Reviewing and Editing. B.U: Conducting the experiment, taking observations and measurements.

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