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RESEARCH

Gender Identification, Phenotypic Variation, and Heritability in F_1 Fig (*Ficus Carica* L.) Progenies Derived from a Controlled Cross

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Abstract

The aim of this study was to investigate the effectiveness of gender-specific cleaved amplified polymorphic sequence (CAPS) markers in distinguishing male and female progenies at the early juvenile stage, heritability, and diversity of the examined plant traits in the *Bursa Siyahı* × *Osmaniye02* cross-population. After the PCR products of the progenies were cut with the PciI enzyme, one of the fragments (242 bp) representing the female allele (CGT and TGT) in the DNA fragments was detected in all female progenies, while a 186 bp fragment (CAT allele) was detected only in the male progenies. Significant differences were found between the progenies, depending on the parents involved in the *Bursa Siyahı* × *Osmaniye02* population. The results of principal component analysis (PCA) showed that length of central lobe (LCL), leaf area (LA), leaf length (LL), leaf width (LW), number of leaves per shoot (LN), plant diameter (PD), and plant height (PH) were the most important variables to discriminate between progenies. These results indicated that PH, LN, tendency to suckers (TS), LCL, LW, LA, petiole color (PC), and leaf color (LC) traits had high heritability values (>0.90) for male and female fig progenies. In addition, the positive heterosis values of male and female progenies were highest for internode length (IL), density of hairs on the leaf (DH), leaf shape (LS), and NL. As a result, when all these progenies bear fruit, the quality traits will be investigated and the studies on the particularly persistent progenies of this cross combination will be continued.

Keywords Gender distinction · Marker-assisted selection · Morphological diversity · Heterosis

Introduction

Fig (*Ficus carica* L.) culture has been widely practiced in Mediterranean countries since ancient times. There are two subgroups of species, *F. carica* var. *domestica* (edible fig) and *F. carica* var. *caprificus* (caprifig), which are common in the natural population (Aksoy 1998; Caliskan et al. 2021). Cultivated fig species are mainly diploid (2n=26), with an estimated genome size of about 356 Mb and high heterogeneity (Mori et al. 2017).

Türkiye, with its rich genetic resources of fruit, is one of the regions of origin of figs. The carbonized figs, which date back to 6100–7000 BC, are the most important evidence of this (Çalışkan and Dalkılıç 2022). Fig cultivation is widespread in the Mediterranean basin with its hot and dry climate. In this basin, many cultivated fig cultivars have been improved through natural selection. In addition, interest in figs is increasing in the global market due to their rich content of phytochemical, their beneficial effects on human health, and their definition as a sacred fruit (Çalışkan and Polat (2012); Rasool et al. 2023; Alzahrani et al. 2024).

In each ecological region, there are different fig genotypes with unique characteristics that are typically valued in local markets (Gozlekci 2011; Şimşek et al. 2020). The southern Aegean and Mediterranean regions of Türkiye offer significant ecological advantages for early fig cultivation

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(Çalışkan et al. 2024). In Türkiye, the 'Bursa Siyahı' and 'Sarılop' are two important fig cultivars used for production and export. However, over 95% of locally grown figs, including these cultivars, belong to the deciduous fig group. With these figs, caprification is crucial for fruit set and yield. The caprification process in fig cultivation accounts for about 12% of total production costs (Çobanoğlu et al. 2005) and can transfer diseases such as *Fusarium* from caprifig fruits to edible figs. Improving parthenocarpic cultivars is seen as an important solution to these challenges (Flaishman et al. 2022). Most figs grown worldwide are parthenocarpic, i.e. they can produce fruit without the process of caprification. However, breeding programs are essential to develop parthenocarpic cultivars that mature at the early and mid-season for the production of fresh figs in Türkiye.

Studies on crossing of figs were begun in the USA, in 1944, by Condit (1947) and continued by Storey (1975). 'Conadria' cultivar was developed by Doyle and Ferguson (1997) and 'Sierra' and 'O'Rouke' cultivars by Johnson et al. (2010a, b). In addition, new cultivars such as 'Early FigARO', 'Late FigARO', 'WOW', and 'Brown Candy' were released from the crossing program that started in Israel in 2004 (Peer et al. 2022). Previous studies reported that the progenies, when planted directly in the field, undergo a 5 to 7 year period of juvenile sterility. The development of the cultivar is very labor intensive and time consuming, typically taking 10 to 15 years, resulting in significant costs (Storey 1975; Flaishman et al. 2022). In figs, a 1:1 (caprifig: edible fig) distribution of individuals in the F_1 population derived from crossing studies can be achieved (Storey 1975; Awamura et al. 1996). Early elimination of male individuals from breeding programs for female figs therefore significantly improves the efficient use of labor, time, and breeding areas. In dioecious fruit species such as figs, where male and female individuals cannot be phenotypically distinguished during the juvenile phase, early gender determination is crucial for the efficiency of breeding programs. In several other deciduous crops− such as pistachio (Yakubov et al. 2005; Kafkas et al. 2015), papaya (Urasaki et al. 2002), date palm (Maryam et al. 2016) and kiwi (Zhang et al. 2015)−sex-linked molecular markers have been effectively used for gender determination at the early-stage. Among these technologies, CAPS markers have proven to be particularly effective tools due to their co-dominant inheritance, high reproducibility, and cost-effectiveness. In figs, CAPS markers targeting sex-linked genomic regions provide a non-invasive and rapid method for gender identification prior to syconium development (Mori et al. 2017; İkten and Yılmaz 2019). In particular, the restriction enzymes PciI and HpyCH4IV have shown great potential for the differentiation of male and female genotypes based on specific allele patterns. The use of molecular tools in breeding programs offers significant advantages by minimizing the time, effort, and cost of of traditional gender identification methods. This technology is crucial for accelerating plant breeding (Coskun and Gulsen 2024).

The aim of this study was to investigate the efficacy of sex-linked CAPS markers in discriminating male and female progeny of early juvenile individuals in a cross population, heritability, and variation in the plant traits studied. We hypothesized that: (a) the gender ratio in the progeny of *Bursa Siyahı* × *Osmaniye02* is approximately 1:1; (b) there is significant variation among the progeny of *Bursa Siyahı* × *Osmaniye02*; (c) the progeny of *Bursa Siyahı* × *Osmaniye02* segregate without being sex-dependent for most vegetative traits; (d) heterosis between the male and female progenies is increased due to the heterogeneous structure of the *Bursa Siyahı* × *Osmaniye02* cross.

Materials and methods

Plant Material

The progenies constituting the project material were obtained from the *Bursa Siyahı* (♀) × *Osmaniye02* (♂) cross combination. 'Bursa Siyahı' is the most important fresh fig for export in Türkiye due to its excellent characteristics such as black skin color, large fruits, and suitability for transportation. 'Osmaniye02' is a persistent male fig (caprifig) selected from the natural population in the Eastern Mediterranean region of Türkiye. The crossing process was carried out at the end of August 2021. For this purpose, pollen was collected from profichi fruits in June 2021 and stored at 4 °C until use. The ripe fruits after artificial pollination were harvested in October and the seeds obtained from the fruits were stored in the refrigerator at 4 °C until February 2022. In February, the seeds were sown in vials by applying 2000 ppm GA_3 for 24 h to ensure uniform germination and growth (Kılıç and Çalışkan 2022). The 357 germinated progenies were planted in 2 L pots in the greenhouse under controlled conditions in May. Male and female individuals were planted at 4 × 1 m intervals in the experimental area, irrigated and fertilized with the fertigation system. The soil structure of the study area was sandy-loamy, contained 39.5% sand, 25.3% clay, and 6.10% lime, and had a pH of 7.81. In terms of total salt content, the soil belonged to class of non-saline soils (0.035–0.041%).

The temperature, precipitation, and humidity values during the study season were presented in Table 1. The lowest temperatures in the study area were recorded in January (6 °C) and February (7 °C), and the highest in July and August (33 °C and 34 °C, respectively). Total precipitation amounted to 903 mm, with the lowest precipitation in

Table 1 Monthly temperature, precipitation and humidity values during the study period in Antakya/Hatay

Month	Temperature (°C)			Precipitation (mm)	Humidity (%)
	Minimum	Maximum	Mean		
January	6	13	9	171	77
February	7	14	10	112	75
March	9	18	13	117	72
April	12	22	17	67	69
May	16	27	21	44	67
June	20	30	25	19	64
July	23	33	28	5	65
August	24	34	28	6	66
September	22	31	26	35	68
October	19	27	22	61	72
November	13	21	16	70	74
December	9	15	11	136	76

July (5 mm) and August (6 mm). The relative humidity was between 64% and 77%.

DNA Isolation and PCR

Genomic DNA was isolated from fresh leaf tissue of 357 progenies and 18 standard fig cultivars (11 edible and 7 caprifigs) using the CTAB method (Doyle and Doyle 1987). DNA quality and concentration were determined by 1.0% agarose gel electrophoresis and NanoDrop spectrophotometry.

A pair of primers (Fig FM_f: 5′-CAATACCAAAATGA TATGCACGA-3′, and Fig FM_r: 5′-TGGCATATACAGT GAGAT-GGATG-3′) designed by Mori et al. (2017) were used for the amplification of the gender-associated CAPS locus. In this context, PCR conditions were performed as follows: 1.5 µl PCR buffer, 0.2 mM dNTPs, 1.5 mM $MgCl_2$, 10 pmol primer, 0.8 U DNA Taq polymerase, 25 ng DNA, and the total volume was 15 µl (İkten and Yılmaz 2019).

The PCR program consisted of an initial denaturation at 94 °C for 3 min, followed by 35 cycles of denaturation at 94 °C for 30 s, annealing at 55 °C for 30 s, and extension at 72 °C for 30 s. A final extension was performed at 72 °C for 5 min. After PCR amplification, each PCR product was digested with the restriction enzymes PciI and HpyCH4IV. For this purpose, a total volume of 10 µl containing 1 µl of 10x buffer, 7 µl of PCR product, 1 U of restriction enzyme, and 1 µl of sterile water was used. Both restriction reactions were incubated at 37 °C for two hours before running on a 2% TBE agarose gel. To evaluate the molecular results, the gel images obtained were scored by the imaging unit for gender differentiation based on their appearance and male and female figs were distinguished from each other.

Phenotypic Analyses

As defined by the fig descriptor (IPGRI and CIHEAM 2003) and Caliskan et al. (2023), a total of 18 morphological traits (Table 2), six subjective and 12 objective, were evaluated in 289 progenies (129 males and 160 females) during the 2023–2024 season at their fourth year of age. The plant lengths of progenies were determined by measuring them individually with a tape measure after leaf fall. Plant thickness was determined by measuring the plants individually with a digital caliper 30 cm above the soil level in the pot after leaf falls. The length of the internodes was measured using a digital caliper at three points: at the tip, middle, and at the base of the same shoots. The tendency to form a root shoot was determined by counting the bottom shoots that formed on each progeny.

Three fully mature leaves were collected from the 3rd to 5th nodes at the shoot tip of each progeny for leaf measurements. The number of leaves on the annual shoot was calculated by counting all leaves before leaf fall in the progeny. The number of lobes in the leaves of the progeny was determined by counting the number of lobes on the leaf. Leaf length (cm), leaf width (cm), and petiole length (mm) were measured with a ruler, and petiole thickness (mm) was measured with a digital caliper. In addition, leaf shape, leaf color, leaf dentation, density of hairs on the leaf surface, leaf venation, and leaf color were subjectively observed.

Table 2 Plant characteristics and abbreviations analyzed in the Fig progenies

No	Character	Unit	Abbreviation	No	Character	Unit	Abbreviation
1	Plant height	cm	PH	10	Petiole length	mm	PL
2	Plant diameter	mm	PD	11	Petiole thickness	mm	PT
3	Internode length	mm	IL	12	Petiole color	Code	PC
4	Leaf number per shoot	Number	LN	13	Leaf margin dentation	Code	LMD
5	Tendency to suckers	Number	TS	14	Density of hairs on leaf	Code	DH
6	Length of central lobe	cm	LCL	15	Leaf venation	Code	LV
7	Leaf length	cm	LL	16	Leaf color	Code	LC
8	Leaf width	cm	LW	17	Leaf shape	Code	LS
9	Leaf area	cm^2	LA	18	Number of lobes	Number	NL

Heritability Analysis

We calculated the degree of broad-sense heritability (H^2) for the traits of each offspring based on the equations established by Acquaah (2009) as follows:

$$H^2 = V_G/V_P \;\; V_P = V_G + V_E \; V_E = (V_{P1} + V_{P2})/2$$

where VG represents the total genetic variation, while VP indicates the total phenotypic variation in the progeny. VE represents environmental variation, and VP1 and VP2 represent the variation in the parents.

The H value for each variable was categorized as low (<0.2), medium (0.2–0.5), and high (>0.5).

Heterosis was analyzed using the method described by Kalhoro et al. (2015):

$$\text{Heterosis} = \frac{F1 - MP}{MP} \times 100$$

The potence ratio was evaluated according to Smith's (1952) definition to determine the degree of dominance:

$$P = \frac{F_1 - MP}{0.5\,(P_2 - P_1)}$$

In this context, F_1 refers to the mean value of an offspring, while MP represents the value of the mid-parent. P_1 is the mean value of the lower parent and P_2 is the mean value of the higher parent. The type of dominance observed can be characterized by the potence ratio: Complete dominance is indicated by a potence ratio of +1, partial dominance is indicated by a potence ratio that falls between −1 and +1, and overdominance is indicated by a potence ratio exceeding ± 1. A potency ratio of zero (0) indicates no dominance. The positive and negative signs indicate the direction of dominance in relation to one of the two parents (Ghosh et al. 2018).

Statistical Analysis

The mean, minimum and maximum change intervals and variation coefficients of the data obtained from the morphological measurements of the progeny were analyzed using the SAS package program (SAS 2005). In addition, principal component analysis (PCA) of all morphological data was performed using JMP Pro 16. The data of subjective observations were converted into numerical information specified in Fig Descriptor and then used for PCA analyzes.

Results and Discussion

Gender Determination and Distribution in Progenies

The quantity and quality of DNA isolated with Nanodrop from 357 fig progenies were determined. The A260/A280 ratio ranged from 1.69 to 2.01 in all individuals with an average of 1.91. DNA concentrations ranged from 373 to 982 ng/µl in all progenies with an average of 603.9 ng/µl. These results showed that the DNA quantity and quality reached optimum levels and that the CTAB protocol was successful in isolating the fig DNA.

After the PCR product was cut with the PciI enzyme, one of the cut pieces (242 bp) representing the female allele (CGT and TGT) was found in all female plants in the DNA fragments obtained (Supplementary Fig. 1). Since the individuals were heterozygous, a 242 bp band was also observed in the male progenies. In contrast, the 186 bp fragment (CAT allele) appeared in the male plants and was not found in the female plants. The 73 bp fragment was detected in both male and female genotypes. Bands of 73 bp, 186 bp, and 242 bp were detected in the male progenies, while the female progenies had bands of 73 bp and 242 bp. The discriminating band was 186 bp. According to the obtained data, 145 of the 329 genotypes that were successfully showed a band profile indicating male gender and 184 showed a band profile indicating female gender. The band profiles obtained with this enzyme in the cultivars used as controls were confirmed.

As a result of the restriction PCR amplicons with the HpyCH4IV enzyme, 3 different bands were formed. 129 bp and 186 bp bands were present in all male and female genotypes. Since the male genotypes were heterozygous, a 315 bp band was formed. However, the 315 bp band was not formed in female genotypes. The presence or absence of a 315 bp fragment was a key factor in determining gender. According to the obtained data, 166 of the 355 genotypes that were successfully showed a banding profile indicative male gender and 189 showed a banding profile indicative female gender.

According to the results of both restriction enzymes, there was generally a significant similarity in gender differences, but in some genotypes, two different enzyme restriction results led to differences. Genotypes 74, 130, 177, and 344 were female according to PciI restriction enzyme results, and male according to HpyCH4IV restriction enzyme results. Similar to these results, İkten and Yılmaz (2019) indicated that the results of the HpyCH4IV restriction enzyme may lead to false results, while the results of the PciI restriction enzyme provide more accurate results. Our results showed that 163 of 357 genotypes were male

(45.66%) and 190 (53.22%) were female. The gender of the 4 genotypes was different for two restriction enzymes. The results were consistent with those reported by Storey (1975) and Awamura et al. (1996), who showed that male and female progeny were predominantly distributed in a 1:1 ratio in fig crossing studies.

Phenotypic Characteristics of Progenies

Means, ranges, standard deviations and coefficients of variation of vegetative traits of male and female fig progenies from crosses of *Bursa Siyahı* × *Osmaniye02* crosses were showed in Table 3. The data indicated significant variation among individuals from this cross combination. PH varied between 71 cm and 261 cm (mean 158.33 cm), PD between 11.11 mm and 49.50 mm (mean 23.90 mm), and IL between 2.0 mm and 18.67 mm (mean 5.25 mm) in male individuals, while PH ranged between 28.70 cm and 332.0 cm (mean 153.51), PD between 12.04 mm and 50.30 mm (mean 23.66), and IL between 1.76 mm and 17.93 mm (mean 5.13 mm) in female figs. The average values for PH, PD, and IL traits were slightly higher in male progenies than in female progenies. The mean LN per shoot was 4.21 for male progeny (ranged from 1.80 to 7.40) and 4.31 (ranged from 1.10 to 6.90) for female progeny. The mean value for TS (3.15) in male progenies was higher than in females (2.70). In addition, the coefficients of variation among the traits were highest for TS in male (67.54%) and female (67.90%) individuals.

The mean values for LCL, LL, LW, and LA indicating leaf size were close to each other in male (10.58 cm, 15.88 cm, 19.70 cm, and 320.63 cm^2, respectively) and female (10.03 cm, 15.94 cm, 19.56 cm, and 318.34 cm^2, respectively) individuals. However, the CV value (22.99%) indicating variation in the LCL trait was higher in male individuals, while the CV value (34.77%) of the LA value was higher in female individuals. In crossbred individuals, PL varied between 4.66 and 13.00 mm (mean 8.21 mm) and PT varied between 2.0 and 7.43 mm (3.86 mm) in males, while PL varied between 2.83 and 13.33 mm (mean 8.11 mm) and PT varied between 0.58 and 6.2 mm (mean 3.66 mm) in females. The data indicated that the leaf size traits of the male and female progenies were essentially the same as those of the parents. The results for leaf size in this study were similar to those of Yakushiji et al. (2012). In addition, the presence of progenies with larger leaves than the parents may result in progenies that are valuable in terms of fruit size. Indeed, previous studies reported significant positive correlations between fruit weight and leaf size traits in male (Caliskan et al. 2017) and female figs (Khadivi et al. 2018).

The TS was moderate (between 3 and 7) in 56 male (43.42%) and 86 female (52.43%) progenies (Table 4). The PC trait was predominantly green in male (79 progeny, 61.24%) and female (100 progeny, 62.50%) individuals. For the LMD traits, male and female progenies mainly showed low (41.09% and 45.00%, respectively) and moderate (46.51% and 45.62%, respectively) dent formation. The male progenies had a slightly hairier (DH) leaf surface than the females. In the male progenies, the LV trait was mostly slightly apparent (69 progeny, 53.49%), whereas in females, it was both apparent (61 progeny, 38.12%) and slightly apparent (60 progeny, 37.50%). The LC was green

Table 3 Means, ranges, standard deviation, and coefficients of variation for plant characteristics of parents and their progenies. BS: 'Bursa Siyahı' and OS2: 'Osmaniye02'. Other abbreviations were showed in Table 2

Variable	BS (♀)	OS2(♂)	Male				Female			
			Mean	Range	SD	CV	Mean	Range	SD	CV
PH	260	210	158.33	71–261	39.00	24.64	153.51	28.70–332.0	41.08	26.76
PD	40	35	23.90	11.11–49.50	6.75	28.24	23.66	12.04–50.30	7.05	29.83
IL	4.46	2.87	5.25	2.0–18.67.0.67	1.80	34.25	5.13	1.76–17.93	2.20	43.01
LN	7.0	5.1	4.21	1.80–7.40	1.14	27.17	4.31	1.10–6.90	1.14	26.62
TS	3	2	3.15	1–5.0	2.12	67.54	2.70	0–5.0	1.83	67.90
LCL	12.56	6.92	10.58	8.13–14.37	2.43	22.99	10.03	8.46–14.30	1.96	19.62
LL	24.05	19.62	15.88	10.37–21.17	2.45	15.43	15.94	9.66–24.66	2.73	17.13
LW	22.96	18.21	19.70	11.20–29.17.20.17	3.66	18.62	19.56	10.0–29.66.0.66	3.68	18.84
LA	529.10	354.89	320.63	118.34–562.79.34.79	8.96	31.52	318.34	132-75-723.55	9.11	34.77
PL	9.11	3.67	8.21	4.66–13.00.66.00	1.84	22.47	8.11	2.83–13.33	2.16	26.69
PT	7.50	2.77	3.86	2.0–7.43.0.43	0.92	23.98	3.66	0.58–6.2	0.87	23.79
PC	Green	Green	1.62	1.0–5.0	0.48	30.33	1.62	1.0–5.0	0.48	29.80
LMD	2	2	1.68	1.0–5.0	0.67	40.01	1.64	1.0–5.0	0.64	39.26
DH	Sparse	Sparse	1.67	1.0–7.0	0.71	42.99	1.58	1.0–7.0	0.72	45.79
LV	Apparent	Apparent	2.15	1.0–3.0	0.66	30.94	2.13	1.0–3.0	0.78	36.78
LC	Green	Green	1.98	1.0–3.0	0.21	10.83	1.98	1.0–3.0	0.22	11.23
LS	5 (B)	5 (C)	1.35	1.0–7.0	0.69	51.09	1.49	1.0–7.0	0.94	62.97
NL	5	5	6.33	3.0–7.0	0.97	15.41	6.23	3.0–7.0	0.99	15.96

Table 4 Frequency distribution of the measured qualitative properties in the male and female Fig progeny. Abbreviations were showed in Table 2

Variable	Distribution	Male/Code				Female/Code				
		1	3	5	7	1	3	5	7	9
TS	Frequency	65	56	8		65	86	9		
	Percent (%)	50.38	43.42	6.20		41.75	52.43	5.62		
PC	Frequency	50	79			60	100			
	Percent (%)	38.76	61.24			37.50	62.50			
LMD	Frequency	53	60	16		72	73	15		
	Percent (%)	41.09	46.51	12.40		45.00	45.62	9.38		
DH	Frequency	62	48	19		88	49	23		
	Percent (%)	48.06	37.21	14.73		55.00	30.62	14.38		
LV	Frequency	20	69	40		39	60	61		
	Percent (%)	15.50	53.49	31.01		24.38	37.50	38.12		
LC	Frequency	5	122	2		7	153			
	Percent (%)	3.88	94.57	1.55		4.38	95.62			
LS	Frequency	88 (A)	40 (B)	1 (C)		101 (A)	52 (B)	3(C)	1(D)	3(G)
	Percent (%)	68.22	31.00	0.78		64.33	33.12	1.91	0.63	1.91
NL	Frequency	1	40	88		3	56	101		
	Percent (%)	0.78	31.00	68.22		1.88	35.00	63.12		

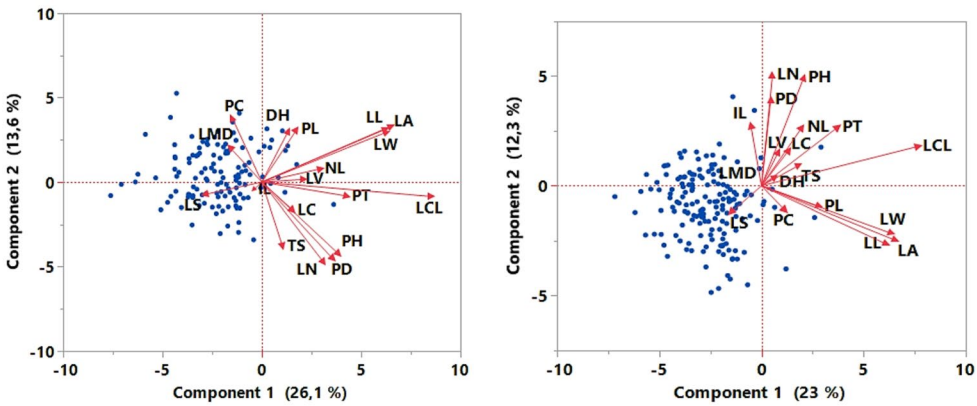

Fig. 1 PCA results for the investigated morphological characteristics of the male (left) and female (right) progeny in the *Bursa Siyahı* × *Osmaniye02* cross combination. Abbreviations were presented in Table 2

in the majority of individuals, regardless of gender. The coefficient of variation of the LS for male and female individuals (51.09% and 62.97%, respectively) was one of the most distinguishing traits. Although the parents exhibited a 5-lobed B leaf shape (LS), their male and female progenies predominantly displayed a 7-lobed A shape (6.22% and 64.33%, respectively). Interestingly, the LS and NL were more diverse in female progeny than in the male progeny. These results indicated that the parents had a heterogeneous genetic structure for fig leaf traits. Similar to these results, Yakushiji et al. (2012) reported that when *F. carica* with 5-lobed leaves and *F. erecta* with single-lobed leaves were crossed within *Ficus* species, the number of leaf lobes in the progeny varied between 3 and 5.

PCA Results

PCA results were analyzed separately to evaluate the differences in morphological characteristics between male and female individuals (Fig. 1). These results showed that the contributions of some studied traits in PCA were at different levels. In the male progeny, PC1 and PC2 accounted for 39.7% of the total variance, compared to 35.3% in the female progeny. In the male population, the critical variables in the positive part of PC1 were LCL, LA, LL, and LW, while LS was the important trait in the negative part. In PC2, the significant variables in the positive part were PC, DH, PL, and LA, while LN, PD, PH, and TS were important characteristics in the negative part. Similar to these results, LCL, LW, LA, and LL were significant traits for PC1 and LN, PH, and PD for PC2 in the female population. These results revealed that the vegetative traits of fig progeny did not show significant differences as a function of gender. These results were consistent with those of Caliskan et al. (2023), who reported that leaf length, leaf width, leaf area and length of the central lobe, petiole length, and thickness were significant traits for distinguishing between male and female figs.

Phenotypic Correlations

Correlation analyses were conducted separately for male and female offspring from the same parental cross to assess whether gender influenced the relationships between morphological traits. Significant correlations were found between plant characteristics of the male and female populations in the *Bursa Siyahı* × *Osmaniye02* crossing (Fig. 2). In both genders, leaf-related traits, including central lobe length (LCL), leaf length (LL), leaf width (LW), leaf area (LA), petiole length (PL), petiole thickness (PT), and petiole color (PC), showed strong positive correlations with each other, confirming that leaf morphological development is closely integrated regardless of gender. In contrast, lobe number (NL) showed negative correlations with several vegetative traits in both genders, suggesting that increases in lobe numbers tend to be accompanied by decreases in other vegetative dimensions. Despite these similarities, significant differences were observed between male and female offspring. In males, the strongest and most consistent correlations were limited to leaf traits, while general vegetative parameters such as plant height (PH), plant diameter (PD), and internode length (IL) showed only weak associations with leaf size. This suggested that overall plant vigor and stem development in male offspring were partially independent of leaf morphology. In contrast, PH, PD, and IL in female offspring showed stronger correlations with leaf size and petiole traits, indicating a more integrated vegetative growth pattern. Similarly, branching-related traits such as leaf margin denticulation (LMD) and leaf hair density (DH) were more closely associated with leaf size traits in female offspring than in males. These results indicated that gender did not fundamentally alter the strong relationships between leaf morphological traits, but did influence the level of coupling between leaf, stem, and branch development. This difference highlighted the potential role of gender in the growth of fig offspring and may have implications for breeding strategies based on vegetative performance. Similar gender-based differences and trait correlations have been observed in other economically important dioecious species. Huan et al. (2016) indicated that male saplings of *Morus alba*, show stronger correlations among leaf number, leaf area, and aboveground biomass than females, reflecting greater resource allocation to vegetative growth under certain architectural constraints. Nawaz et al. (2018)reported that females of *Hippophae rhamnoides* outperform males in some fruit-related vegetative traits, whereas males have advantages in plant height, leaf area, and stem dry weight. These results indicated that the gender-specific patterns observed in figs are not unique and occur in other dioecious fruit and vegetative species. For breeding programs, this suggests that selecting for traits like large leaf area or robust stem diameter may produce different correlated responses depending on whether male or female progenies are targeted, highlighting the importance of considering sex in selection indices.

Heritability, heterosis, and Potence Ratio

This study showed important information on the inheritance of vegetative traits in male and female figs. H^2 values ranged from 0.19 (PT) to 1.00 (PC) in male progeny and from 0.09 (PT) to 1.00 (PC) in female progeny (Table 5). The results showed that H^2 values for all traits, except PT and LS, were mostly high in both genders. Interestingly, the H^2 value of the LS trait had low H^2 values (0.54 and 0.56, respectively) in the populations of both genders. This could be because the LS trait showed variability in fig progenies even on the same shoot. Couranjou (1995) reported that traits with low H^2 values ($0.5 < H < 0.6$) can be affected

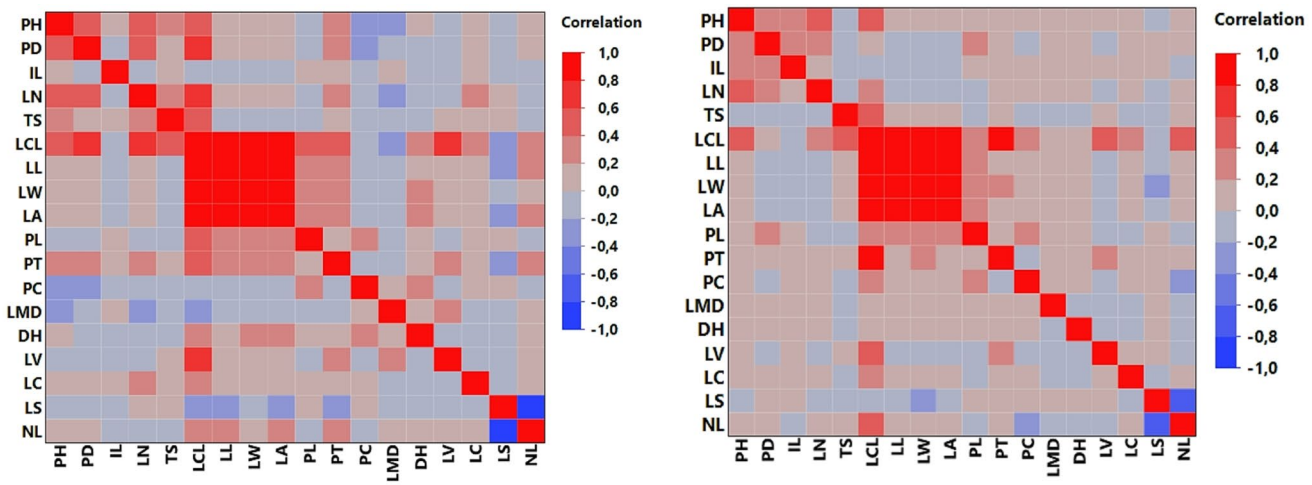

Fig. 2 Heatmap of the correlation coefficients between morphological traits for male (left) and female (right) progeny in the *Bursa Siyahı* × *Osmaniye02* cross combination. Abbreviations were presented in Table 2

Table 5 Heritability, heterosis, and potence coefficients of plant characteristics between progeny and parents

Variable	Male			Female		
	Heritability	Heterosis	Potence	Heritability	Heterosis	Potence
PH	0.94	−32.33	−3.04	0.93	−31.62	−2.97
PD	0.72	−34.42	−6.37	0.65	−30.26	−5.59
IL	0.99	48.83	2.21	0.99	62.84	2.84
LN	0.87	−31.58	−1.78	0.88	−28.95	−1.63
TS	0.91	23.03	1.45	0.87	3.83	0.24
LCL	0.94	9.07	0.32	0.91	3.42	0.12
LL	0.69	−27.53	−2.72	0.73	−27.35	−2.70
LW	0.93	−3.01	−0.29	0.93	−3.70	−0.35
LA	0.98	−27.57	−1.35	0.99	−27.72	−1.36
PL	0.67	22.86	0.57	0.71	21.27	0.53
PT	0.19	−23.92	−0.50	0.09	−27.83	−0.58
PC	1.00	−3.00	0	1.00	−2.00	0
LMD	0.75	−8.38	−0.92	0.74	−10.34	−1.14
DH	0.79	43.30	−3.03	0.79	35.94	−2.51
LV	1.0	−23.62	−4.01	0.82	−24.55	−4.18
LC	1.0	−0.78	0	1.00	−0.93	0
LS	0.54	35.15	0	0.56	49.37	0
NL	0.76	26.87	0	0.78	24.70	0

by ecological conditions. The H2 value of the LV trait was higher in male progenies (1.00) than in female progenies (0.82). This means that males mainly carried the trait. These results showed that PH, LN, TS, LCL, LW, LA, PC, and LC of male and female fig progenies had high H^2 values (>0.90) show quantitative heritability. Previous studies indicated that differences in heritability values may vary depending on the genetic distance between parents (Karaat and Serce 2020; Altan et al. 2022).

Heterosis is defined as the increased vigor of F_1 progeny resulting from the mating of inbred parents. In general, the performance of the F_1 cross exceeds the performance of the inbred parents for several traits (Merrick et al. 2023). Heterosis rates were generally similar for all traits, regardless of gender, but there were some differences in their effect ratios (Table 5). Heterosis rates for male and female progeny were highest for IL (48.83% and %62.84, respectively), DH (43.30% and 35.94%, respectively), LS (35.15% and 49.37%, respectively), and NL (26.87% and 24.70%, respectively). The positive heterosis for these traits shows that the additive gene effect controls them. The positive heterosis value for the TS trait was higher in male offspring (23.03%) than in female offspring (3.83%). The lowest heterosis was observed for PH, PD, LN, LL, and LA traits. The heterotic responses of the studied characteristics in the male and female offspring were variable and had negative values. These results showed that variability can result from additive, dominant, or epistatic gene effects (Melchinger et al. 2007; Kaeppler 2012).

The potency ratio for the examined traits of the offspring showed different degrees of dominance effects. The potency ratio in male and female progeny showed over-dominance in PH, PD, IL, LN, LL, DH, and LV and partial dominance in LCL, LW, PL, PT, and LMD (Table 5). While TS showed an over-dominance in the male offspring, it showed a partial dominance in female offspring. However, the potence ratio could not be calculated for PC, LC, LS, and NL traits, as the mean values the parents were close to each other. These results showed that investigated plant traits in the male and female progenies were controlled by over-dominance gene effects (50% and 44%, respectively) and partly dominance gene effects (28% and 33%, respectively). Overdominance is an intra-allelic interaction in which more than one allele may be present, occurring at different frequencies in the offspring (Kaeppler 2012; Ghosh et al. 2018). In addition, differences in dominance in offspring can also result from the degree of heritability caused by parental heterozygosity (Altan et al. 2022).

Conclusion

In this study, gender differentiation of individuals of the *Bursa Siyahı* × *Osmaniye02* cross was performed and some vegetative characteristics were investigated. Our results confirmed that male and female individuals can be distinguished within a few months after crossing based on the results of the PciI restriction enzyme and thus can be used for marker-assisted selection. Although the vegetative characteristics of the male and female individuals resembled their parents to a certain extent, they showed considerable differences. These results revealed that it is important to examine plant traits

such as leaf size, number of leaf lobes, and plant height in fig breeding studies. These results demonstrated the importance of examining plant traits such as leaf size, number of leaf lobes, and plant height in fig breeding studies. In addition, heterosis rates of progeny were highest in IL, DH, LS, and NL traits, regardless of gender. The potence ratio indicated that most traits exhibited over- and partial dominance gene effects in both male and female progeny. Future studies will focus on the quality traits as the progeny bear fruit and continue morphological and molecular research, especially on the persistent progeny of this cross.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

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