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Study of Juvenile Period and Correlation of Traits in Pistachio: Promising Male and Female Genotypes

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ABSTRACT

Pistachio is one of the most important nut crops in the world. Its yield is greatly influenced by drought, salinity, and environmental fluctuations. In the present study, 30 male and female genotypes were selected from seedling trees originating from open pollination of five pistachio cultivars (‘Akbari’, ‘Badami’, ‘Sarakhs’, ‘Kirmizi’, and ‘Siirt’) to investigate factors associated with the juvenile and adult growth phases in pistachio and to identify genotypes characterized by a short juvenile period. The genotypes were evaluated for vegetative and reproductive traits. The results revealed a wide range of variation in the morphological traits and juvenile periods among the studied genotypes. The S16-4 genotype, parented by the ‘Siirt’ cultivar, was characterized by white nuts and a green kernel. It exhibited the shortest juvenile period among the studied genotypes. Among the male genotypes, BZ11-3 displayed the longest flowering period (21 d) and favorable yield, while the S16-2 genotype, distinguished by its upright growth habit and relatively long flowering period (13 d), was also notable. Correlation analysis between vegetative and reproductive traits indicated that, in female genotypes, rachis length was positively correlated with leaf length ($r = +0.59$) and leaf width ($r = +0.57$). In male genotypes, pollen weight showed a negative correlation with the number of leaflets ($r = -0.51$) and a positive correlation with shoot length ($r = +0.56$). Based on the results of this study, it can be postulated that a shorter juvenile period in pistachio trees was associated with more efficient reserve utilization and greater dry matter accumulation. Therefore, factors such as larger leaf dimensions and higher leaf area that promote vegetative growth and increase carbohydrate storage capacity may shorten the juvenile period.

Introduction

Iran is one of the world’s largest producers and exporters of pistachios. Pistachio trees are relatively drought tolerant, which has made them a well-suited crop for Iran’s predominantly arid and semi-arid regions. However, climate change has emerged as one of the most serious environmental challenges facing global agriculture, with direct effects on plant growth, yield, and survival. Rising temperatures, increased frequency of floods and droughts, and greater vulnerability to pests and diseases are among the primary consequences of climate change that threaten agricultural systems. Pistachio trees are particularly sensitive to climatic fluctuations, especially temperature extremes. Recent studies examining the effects of climate change on pistachio cultivation have reported a declining trend in the accumulation of cold hours and chilling requirement units. This reduction in winter chill is expected to disrupt bud break and flowering synchronization, ultimately leading to reduced pistachio yields in the coming years (Ahmadi et al., 2021; Ravari et al., 2023).

Although pistachio is classified as both a glycophyte and a phreatophyte species, its yield is strongly influenced by salinity and drought stress. The inability to meet the species' chilling requirements under warmer winter conditions, combined with increasing limitations on irrigation water, has contributed to a gradual shift in pistachio cultivation from lower to higher latitudes. As a result, pistachio breeding programs have increasingly focused on identifying and developing genotypes with enhanced tolerance to salinity, drought, and temperature stress, either for use as rootstocks or as cultivars (Karimi, 2025; Tous and Ferguson, 1996).

In Iran, several pistachio cultivars are of major commercial importance, including 'Akbari', 'Ahmad Aghaei', 'Kale Ghochi', and 'Fandoghi' (Karimi, 2025). The 'Akbari' cultivar, which is characterized by large, almond-shaped nuts, shows good resistance to high summer temperatures but requires a long chilling period and is susceptible to the common pistachio psylla (*Agonoscena pistaciae*). The 'Ahmad Aghaei' cultivar is valued for its high yield potential, attractive white nuts, and large nut size; however, it exhibits a pronounced tendency toward alternate bearing. The 'Fandoghi' (Owhadi) cultivar produces medium-sized nuts, is resistant to psylla, shows a low tendency for alternate bearing, and yields moderately. In contrast, the 'Kalle Ghochi' cultivar produces large nuts and relatively high yields but is sensitive to spring frost, salinity, drought, and high summer temperatures (Al-Khayri et al., 2019).

Among the various breeding strategies used in fruit trees, selection is one of the most widely applied approaches. Pistachio trees exhibit high genetic diversity within both natural and hybrid populations, largely due to their high degree of heterozygosity. This genetic variability increases the likelihood of identifying superior genotypes with the capacity to adapt to adverse environmental conditions. Indeed, several commercially important pistachio cultivars have originated from the selection of seedling trees derived from open-pollinated seeds (Al-Khayri et al., 2019). For example, the 'Sirora' cultivar was developed in Australia through selection from the 'Red Aleppo' population, while the widely cultivated 'Kerman' and 'Joley' cultivars were selected from seedling trees and released by the USDA Station in Chico, California, and the University of California, respectively. Similarly, the male cultivars 'Peter' and 'Chico' were developed through the selection of promising seedlings (Al-Khayri et al., 2019).

In Iran, drought, salinity, spring cold, and the failure of some cultivars to meet their chilling requirements are among the most important factors contributing to pistachio yield reduction. Consequently, the introduction of tolerant cultivars to replace sensitive ones has been proposed as a key strategy to mitigate these constraints. The present study was designed to select superior pistachio genotypes that had previously been evaluated under the environmental conditions of Rafsanjan (Hakimnejad et al., 2019). These genotypes were obtained through open pollination of three Iranian cultivars, 'Akbari', 'Badami', and 'Sarakhs,' which have reportedly exhibited resistance to salinity and drought stress, as well as two Turkish cultivars, 'Siirt' and 'Kirmizi', which are known to have lower chilling requirements than Iranian cultivars.

The objective of this study was to investigate factors associated with the juvenile and adult growth phases of pistachio and to identify genotypes characterized by a short juvenile period, strong adaptation to adverse environmental conditions, and the capacity to produce nuts with desirable commercial traits.

Materials and Methods

Plant materials

Nuts obtained from open pollination of five pistachio cultivars, i.e., 'Akbari', 'Sarakhs', 'Badami', 'Siirt', and 'Kirmizi', were collected and sown in black plastic pots in 2007. After the seedlings reached a height of approximately 25 cm, they were transplanted to the pistachio collection of Vali Asr University in Rafsanjan, with a spacing of three meters between trees within each row and six meters between rows. The pistachio collection is located in Rafsanjan City, Kerman Province, Iran. The meteorological data and soil characteristics of the study area are provided in Table S1. The seedling trees were irrigated once every 30 d, and no fertilizers or pesticides were applied throughout the study period. From 2007 to 2019, during the first stage of selection, the genotypes were evaluated under the prevailing environmental conditions based on their growth and eco-physiological parameters (Hakimnejad et al., 2019; Saghafi et al., 2019). During this stage, the juvenile period of each genotype was also recorded. As the trees reached reproductive maturity and began to flower, data on reproductive traits were collected for each genotype. At the end of the first selection stage, 14 female genotypes and 16 male genotypes (TS2) were identified as promising candidates based on their performance. In the second selection stage, these selected genotypes were compared with the main commercial pistachio cultivars of Iran, i.e., 'Akbari', 'Ahmad Aghaei', 'Kale Ghochi', and 'Fandoghi', with respect to their reproductive characteristics.

Morphological trait measurements

In this study, 29 traits related to female genotypes and 13 traits related to male genotypes were measured according to the pistachio descriptor (Karimi et al., 2009a; IPGRI, 1997) (Table 1). Three branches bearing bud inflorescences were selected and marked around each genotype in late winter, and each branch was considered as a replicate.

Table 1. Traits range of variability, mean, maximum, minimum and coefficient of variation for the measured traits.

No	Traits	Abbreviation	unit	Female				
				Min	Max	Range	Mean	C.V
1	Leaf length	LL	cm	13.8	19.3	6.5	16.55	11.81
2	Leaf width	LW	cm	11.7	20.3	8.6	16.0	14.31
3	Leaf length/ Leaf width	LL/LW		0.93	1.29	0.36	1.11	7.96
4	Number of leaflets	NL		3.0	5	2.0	4.0	22.32
5	Terminal leaflets length	TLL	cm	8.0	13	5.0	10.5	14.0
6	Terminal leaflets width	TLW	cm	4.0	7.33	3.33	5.66	16.43
7	Terminal leaflets length/ Terminal leaflets width	TLL/TLW		1.59	2.31	0.72	1.95	15.56
8	Rachis length	RL	cm	7.67	14.33	6.66	11.0	21.74
9	Number of fruit per rachis	NF		12.0	33	21.0	22.50	22.10
10	Fruit length	FL	mm	15.06	28.29	13.23	21.67	9.36
11	Fruit width	FW	mm	8.88	15.78	6.9	12.33	7.10
12	Fruit thickness	FT	mm	8.80	16.40	7.6	12.60	8.62
13	Fruit fresh weight (10 fruits)	FFW	g	7.73	30.13	22.4	18.93	12.02
14	Nut fresh weight (10 nuts)	NFW	g	4.67	17.66	12.99	11.16	7.33
15	Nut dry weight (10 nuts)	NDW	g	3.44	12.55	9.11	7.99	6.93
16	Nut length	NL	mm	13.53	23.14	9.61	18.32	5.78
17	Nut width	NW	mm	7.25	13.83	6.58	10.54	5.19
18	Nut thickness	NT	mm	8.17	13.73	5.56	10.95	6.01
20	Kernel length	KL	mm	11.95	20.39	8.44	16.17	11.40
21	Kernel width	KW	mm	6.60	11.60	5.0	9.10	62.85
22	Kernel thickness	KT	mm	5.93	11.08	5.15	8.50	7.14
23	Kernel fresh weight (10 kernels)	KFW	g	2.24	12.0	9.76	7.12	7.91
24	Kernel dry weight (10 kernels)	KDW	g	1.58	5.95	4.37	3.76	9.38
25	Split nuts percentage	SNP	%	6.67	90.0	82.33	48.33	16.75
26	Blank nuts percentage	BNP	%	0.0	26.67	26.67	13.33	79.0
27	Indehiscent nuts percentage	INP	%	5.67	70.0	64.33	37.83	31.71
28	Ounce	OU		22	83.0	61.0	52.50	8.34
29	Kernel percentage	KP	%	28.85	75.83	46.98	52.34	18.05
	Male							
1	Leaf length	LL	cm	13.0	18.67	5.67	15.84	10.31
2	Leaf width	LW	cm	8.67	16.67	8.0	12.67	13.47
3	Leaf length/ Leaf width	LL/LW		0.94	1.74	0.8	1.34	14.83
4	Number of leaflets	NL		5	7	2	6	23.60
5	Terminal leaflets length	TLL	cm	4	9.5	5.5	6.75	16.49
6	Terminal leaflets width	TLW	cm	2.67	5.67	3.0	4.17	23.18
7	Shoot length	SL	cm	4.17	33.30	29.13	18.74	39.41
8	Bud number	BN		5.67	20.67	15.0	13.17	38.70
9	Flower bud number	FBN		2.67	17.33	14.66	10.0	61.62
10	Performance percentage	PER	%	35.59	89.17	53.58	62.38	28.42
11	Flower period	FP	d	3	21	18	12.0	61.71
12	Inflorescences weight	RW	g	0.71	3.34	2.63	2.03	43.93
13	Pollen weight	PW	mg	70	200	130	135	28.19

Ten fully developed leaves were collected from each branch in late June to evaluate leaf and leaflet characteristics of both male and female genotypes. Leaves located at the third, fourth, and fifth nodes were used for measurements. The dimensions of leaves and terminal leaflets were measured using a ruler. For female genotypes, fruits from each marked branch were harvested separately after full maturity and ripening. From each branch, ten fruits were randomly selected, and their characteristics, including fresh and dry weights of fruits, nuts, and kernels, as well as their dimensions, were measured using a digital scale and a ruler. The percentages of split, indehiscent, and blank nuts were recorded from a sample of 100 fruits per branch. In addition, kernel percentage was calculated based on the following formula:

$$KP = \frac{KDW}{NDW} \times 100$$

KP = Kernel percentage, NDW = Nut dry weight, KDW = Kernel dry weight

In male genotypes, 10 inflorescences were harvested from each branch in mid-March before pollen shedding, and their weight and pollen weight were measured. Also, yield percentage for each genotype was calculated based on the following formula:

$$PER = \frac{FBN}{BN} \times 100$$

PER = Performance percentage in male genotypes, BN = number of buds per shoot, FBN = number of flower buds per shoot.

Data analysis

This experiment was conducted in a completely randomized design with three replications, each replication containing one branch. Analysis of variance (ANOVA) was carried out using SAS software, version 9.0 (SAS Institute Inc., USA). Mean comparisons and the determination of significant differences among treatments were performed using the least significant difference (LSD) test ($P \leq 0.05$). In addition, correlations among traits were assessed using Pearson's correlation coefficients. Cluster analysis was further conducted using Ward's method based on squared Euclidean distance as the similarity criterion, i.e., employing SPSS software, version 27.

Results

Juvenile period and fruit harvesting time

A wide range of variation was observed among the studied genotypes with respect to the duration of the juvenile period and the timing of fruit harvest. In general, male genotypes derived from all cultivars exhibited a shorter juvenile period than female genotypes, i.e., they began flowering within 5–6 years. Among all genotypes, S16-4, S16-1 originating from Siirt cultivar and H6-4, had the shortest juvenile period, producing flowers in the fifth year after planting. These were followed by genotypes obtained from the 'Badami' and 'Akbari' cultivars. Conversely, the longest juvenile period was recorded for genotypes derived from the 'Kirmizi' cultivar, which began flowering after 9–10 years. The results further indicated that the genotypes S16-4, S16-1, and H6-4, which exhibited the shortest juvenile period, also possessed the largest leaf dimensions.

Among the studied female genotypes, SA4-3 and SA10-8, both derived from the 'Sarakhs' cultivar, were identified as early-ripening types, with fruit harvested at the end of July. Despite their early ripening, these genotypes produced relatively small nuts. In contrast, the H6-4 genotype was classified as late-ripening, with fruit harvested in mid-October. The remaining genotypes were medium-ripening types, with harvesting taking place from mid to late September.

Morphological characteristic of female genotypes

Maximum, minimum, mean values, and coefficient of variation among measured traits

The maximum, minimum, mean, range of variability, and coefficient of variation (CV %) for each measured trait are presented in Table 1. The genotypes exhibited considerable variability across all measured traits (Fig. 1). Among these traits, the highest coefficients of variation were observed for blank nuts percentage (79%), indehiscent nuts percentage (31.71%), number of leaflets (22.32%), and number of fruits per rachis (22.10%). Conversely, the lowest coefficients of variation were recorded for nut dry weight (6.93%), nut length (5.78%), nut width (5.19%), and nut thickness (6.01%).

Analysis of variance and mean comparisons for female genotypes

The results of the analysis of variance revealed significant differences among the female genotypes for all studied characteristics. Based on these results, the greatest leaf and terminal leaflet dimensions were observed in the H6-4 and S16-4 genotypes, whereas the smallest values were recorded in SA10-8. Similarly, the largest fruit dimensions were found in H6-4 and S16-4, while the smallest were associated with SA4-3. However, no significant difference was detected between the H6-4 genotype and the cultivars 'Kale Ghochi' (KGH) and 'Fandoghi' (FA), nor between S16-4 and the cultivar 'Ahmad Aghaei' (AA) or the genotype BZ13-5. The highest number of fruits per rachis was recorded in the BZ13-2 genotype, whereas the lowest was observed in SA8-2. Likewise, the greatest fruit fresh weight and nut fresh weight were obtained in the H6-4 and S16-4 genotypes, while the lowest values were recorded in SA4-3. With respect to fruit and nut fresh weights, no significant difference was observed between H6-4 and the cultivar 'Akbari' (AA), nor between S16-4 and 'Fandoghi' (FA). All of the aforementioned genotypes exhibited lower nut dry weight than the 'Akbari' cultivar, although no significant difference was detected between H6-4 and 'Kale Ghochi' (KGH) or between S16-4 and 'Fandoghi' (FA). Regarding nut length, all noted genotypes produced shorter nuts than 'Akbari'; however, the differences were not significant between H6-4 and 'Kale Ghochi' (KGH) or between S16-4 and 'Ahmad Aghaei' (AA). In addition, all genotypes produced nuts with smaller thickness compared to 'Kale Ghochi' (KGH) and 'Akbari' (AA).

The highest kernel dry weight was observed in the H6-4 genotype, while the lowest values were recorded in SA4-3 and SA10-8. Although kernel dry weight in H6-4 was lower than in 'Kale Ghochi' (KGH) and 'Akbari' (AA), no significant difference was detected between H6-4 and 'Fandoghi' (FA). The highest percentage of split nuts was observed in the A20-5 genotype, whereas the lowest values were found in SA4-3 and H6-4. Based on mean comparisons, the A4-3 (23.33%) and H6-4 (26.66%) genotypes exhibited the highest percentages of blank nuts, while the H6-3, SA8-2, SA10-8, BZ13-1, BZ13-2, and BZ13-6 genotypes showed no blank nuts. The number of nuts per ounce varied among genotypes, ranging from 28 in H6-4 (representing the largest nuts) to 83 in SA4-3 (the smallest nuts). No significant difference was observed between H6-4 and 'Kale Ghochi' (KGH) or between S16-4 and 'Fandoghi' (FA) for this trait. Kernel percentage also differed among genotypes, with the highest values recorded in BZ13-2 and BZ13-6 and the lowest in A19-7. No significant difference was detected between S16-4 or H6-4 and the cultivar 'Fandoghi' (FA) with respect to kernel percentage (Table 2).

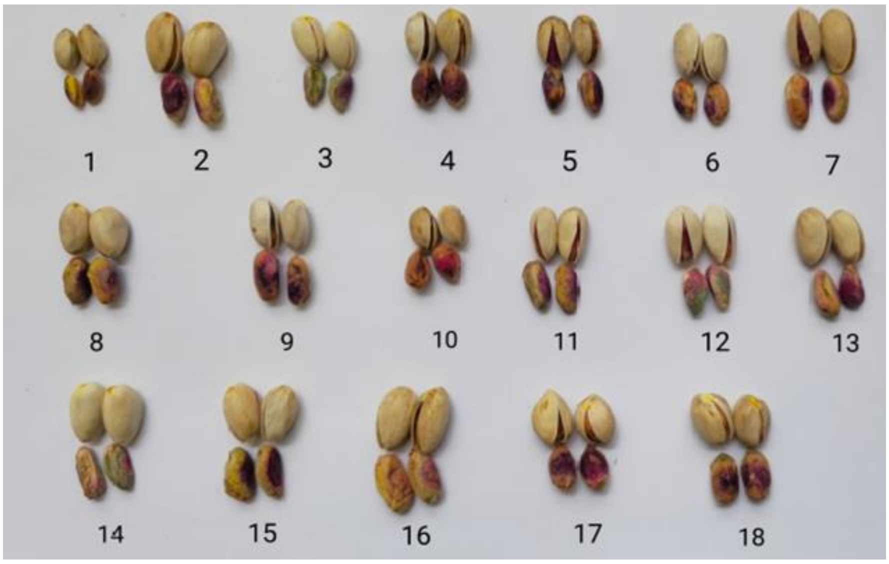

Fig. 1. Nuts and kernels in the studied genotypes, compared with commercial cultivars. 1; SA4-3, 2; H6-4, 3; H6-3, 4; SA8-2, 5; SA10-8, 6; BZ13-1, 7; BZ13-2, 8; BZ13-3, 9; BZ13-5, 10; BZ13-6, 11; BZ13-7, 12; S16-4, 13; A19-7, 14; A20-5, 15; AA ('Ahmad Aghaei'), 16; AK ('Akbari'), 17; FA ('Fandoghi'), 18; KHG ('Kalle Ghochi').

Correlation between traits in female genotypes

The correlation coefficients among traits in female genotypes are presented in Table 3. A significant positive correlation was found between rachis and leaf length, as well as terminal leaflet dimensions. Specifically, rachis length was positively correlated with leaf length (r= +0.59), leaf width (r= +0.57), terminal leaflet length (r= +0.60), and terminal leaflet width (r= +0.52).

Nut dry weight showed strong positive correlations with fruit length (r= +0.76), fruit width (r= +0.86), and fruit thickness (r= +0.84). Similarly, kernel dry weight was positively correlated with fruit and nut dimensions. The percentage of splitting nuts was positively correlated with fruit length (r = +0.47).

In contrast, the number of nuts per ounce exhibited strong negative correlations with several fruit and nut traits, including fruit length (r= –0.79), fruit width (r= –0.91), fruit thickness (r= –0.76), nut dry weight (r= –0.85), nut length (r= –0.79), nut width (r= –0.84), nut thickness (r= –0.71), kernel length (r= –0.81), kernel thickness (r= –0.73), kernel dry weight (r= –0.80), and splitting percentage (r= –0.50) (Table 4).

Table 2. Mean comparisons of morphological traits in the studied female genotypes.

	LL (cm)	LW (cm)	LL/LW	NL	TLL (cm)	TLW (cm)	TLL/TLW	RL (cm)	NF	FL (mm)	FW (mm)	FT (mm)	FFW (g)	NFW (g)
SA4-3	15.00^{cde}	13.33^{ghi}	1.17^{abc}	5.00^{a}	8.00^{fg}	4.33^{de}	1.86^{abc}	11.16^{a-d}	20.66^{cde}	15.53^{g}	8.86^{h}	8.80^{f}	7.72^{h}	4.67^{i}
H6-4	20.66^{a}	20.33^{a}	1.02^{def}	3.33^{ab}	12.33^{ab}	6.66^{ab}	1.85^{abc}	14.33^{a}	14.00^{f-i}	23.87^{bc}	15.39^{ab}	15.44^{a}	23.70^{bc}	15.70^{ab}
H6-3	19.33^{ab}	17.00^{a-f}	1.15^{a-d}	4.33^{ab}	11.66^{abc}	6.33^{abc}	1.85^{abc}	8.25^{d}	15.00^{e-h}	17.57^{efg}	12.03^{fg}	11.96^{cd}	13.55^{g}	8.78^{gh}
SA8-2	18.00^{abc}	17.33^{a-e}	1.04^{c-f}	4.33^{ab}	11.33^{a-d}	5.00^{cde}	2.30^{a}	12.33^{abc}	7.60^{i}	16.29^{fg}	12.89^{def}	12.84^{c}	15.98^{fg}	9.60^{fgh}
SA10-8	15.00^{cde}	11.66^{i}	1.28^{a}	5.00^{a}	7.33^{g}	4.33^{de}	1.73^{bc}	7.66^{d}	12.00^{hi}	15.06^{g}	11.11^{g}	10.48^{def}	13.74^{g}	13.07^{cde}
BZ13-1	17.00^{b-e}	16.00^{b-g}	1.07^{c-f}	3.00^{b}	11.00^{a-e}	6.33^{abc}	1.73^{bc}	11.16^{a-d}	24.33^{bc}	19.10^{def}	12.25^{efg}	10.89^{de}	15.13^{fg}	8.32^{h}
BZ13-2	15.33^{cde}	13.33^{ghi}	1.16^{a-d}	3.33^{ab}	9.00^{d-g}	5.66^{bcd}	1.58^{c}	10.00^{bcd}	33.33^{a}	23.06^{bc}	12.10^{fg}	9.86^{ef}	16.59^{efg}	9.81^{fg}
BZ13-3	15.00^{cde}	15.66^{b-h}	0.095^{f}	3.00^{b}	9.66^{c-g}	5.00^{cde}	1.97^{abc}	8.00^{d}	14.66^{e-h}	20.87^{bcd}	14.20^{bcd}	11.86^{cd}	15.32^{fg}	10.07^{fg}
BZ13-5	16.66^{b-e}	18.00^{abc}	0.92^{f}	3.33^{ab}	11.66^{abc}	7.16^{a}	1.63^{bc}	9.83^{cd}	18.66^{c-g}	23.37^{bc}	13.50^{c-f}	12.16^{cd}	14.00^{fg}	10.44^{f}
BZ13-6	17.00^{b-e}	14.66^{c-i}	1.60^{a-d}	5.00^{a}	9.00^{d-g}	4.33^{de}	2.11^{ab}	9.83^{cd}	14.33^{e-h}	19.00^{ef}	12.04^{fg}	14.66^{ab}	13.82^{g}	8.38^{h}
BZ13-7	15.33^{cde}	13.66^{ghi}	1.12^{b-e}	4.33^{ab}	10.00^{b-f}	4.33^{de}	1.68^{bc}	10.16^{bcd}	16.66^{e-h}	22.53^{bc}	13.26^{c-f}	12.02^{cd}	13.44^{g}	9.60^{fgh}
S16-4	19.33^{ab}	18.33^{ab}	1.06^{c-f}	3.00^{b}	13.00^{a}	7.33^{a}	1.84^{abc}	13.6^{ab}	17.66^{d-h}	24.46^{b}	13.91^{bcd}	13.30^{bc}	21.49^{cd}	13.73^{cd}
A19-7	14.00^{e}	12.33^{hi}	1.14^{a-d}	5.00^{a}	8.33^{fg}	4.00^{e}	2.08^{ab}	7.66^{d}	12.66^{ghi}	23.22^{bc}	13.69^{cde}	13.31^{bc}	16.19^{fg}	10.31^{f}
A20-5	17.66^{a-d}	14.33^{d-i}	1.23^{ab}	5.00^{a}	9.33^{c-g}	5.00^{cde}	1.91^{abc}	10.33^{bcd}	15.00^{e-h}	24.51^{b}	12.77^{def}	12.04^{cd}	17.35^{ef}	11.87^{e}
AA	13.83^{e}	14.00^{e-i}	0.98^{ef}	4.33^{ab}	9.00^{d-g}	5.16^{cde}	1.75^{bc}	11.16^{a-d}	20.33^{c-f}	25.69^{ab}	13.80^{cde}	15.13^{ab}	22.49^{bcd}	14.28^{c}
AK	17.50^{a-d}	17.66^{a-d}	0.99^{ef}	5.00^{a}	11.00^{a-e}	5.50^{bcd}	2.00^{abc}	9.83^{cd}	23.33^{bcd}	28.28^{a}	14.36^{abc}	16.36^{a}	25.50^{b}	17.66^{a}
FA	14.50^{de}	14.83^{b-i}	0.98^{f}	4.33^{ab}	8.83^{efg}	4.40^{de}	2.02^{abc}	8.66^{cd}	19.33^{c-f}	20.54^{cde}	14.20^{bcd}	14.69^{ab}	19.75^{de}	12.85^{de}
KGH	16.66^{b-e}	13.00^{ghi}	1.28^{a}	4.33^{ab}	10.83^{a-e}	5.16^{cde}	2.09^{ab}	10.33^{bcd}	28.00^{ab}	24.52^{b}	15.77^{a}	16.29^{a}	30.12^{a}	17.08^{ab}

	NDW (g)	NL (mm)	NW (mm)	NT (mm)	KL (mm)	KW (mm)	KT (mm)	KFW (g)	KDW (g)	SNP (%)	BNP (%)	INP (%)	Ounce	KP (%)
SA4-3	3.43^{m}	13.53^{h}	7.25^{j}	8.68^{i}	11.95^{h}	21.36^{a}	5.92^{k}	2.24^{j}	1.58^{f}	6.66^{e}	23.33^{a}	76.66^{a}	83.33^{a}	46.90^{cd}
H6-4	10.99^{b}	20.66^{bc}	13.09^{ab}	11.33^{def}	17.54^{abc}	10.42^{b}	9.50^{c-f}	8.68^{c}	5.00^{b}	36.66^{e}	26.66^{a}	36.33^{b}	28.00^{h}	45.58^{cd}
H6-3	6.17^{ijk}	14.14^{gh}	10.52^{f-i}	10.46^{fg}	13.28^{fgh}	7.65^{b}	8.17^{hi}	4.30^{i}	2.64^{d}	80.00^{abc}	0.00^{d}	20.00^{c-g}	49.00^{c}	43.81^{cde}
SA8-2	6.05^{jk}	16.93^{e}	11.29^{def}	10.86^{f}	15.59^{c-g}	9.77^{b}	9.30^{d-g}	6.60^{e-h}	4.00^{c}	16.66^{e}	0.00^{d}	83.33^{a}	43.00^{d}	66.41^{ab}
SA10-8	5.88^{jkl}	14.43^{fgh}	4.40^{j}	9.54^{gh}	13.79^{e-g}	7.28^{b}	7.42^{ij}	2.50^{j}	1.87^{f}	66.66^{bc}	0.00^{d}	23.33^{b-f}	59.00^{b}	31. 78^{ef}
BZ13-1	6.38^{hij}	15.68^{efg}	10.84^{ef}	8.76^{hi}	13.79^{e-h}	7.93^{b}	6.90^{jk}	3.71^{i}	2.52^{de}	63.33^{c}	0.00^{d}	26.66^{b-e}	38.33^{def}	39.46^{de}
BZ13-2	5.101	18.82^{cd}	10.84^{efg}	8.16^{i}	1.66^{b-e}	8.00^{b}	6.00^{k}	6.00^{h}	3.82^{c}	66.66^{bc}	0.00^{d}	33.33^{bcd}	42.66^{d}	75.83^{a}
BZ13-3	7.20^{fgh}	18.71^{cd}	10.63^{f-i}	12.25^{cd}	17.33^{bcd}	8.36^{b}	10.12^{a-d}	6.51^{fgh}	4.13^{c}	83.33^{abc}	8.33^{bcd}	8.33^{g}	42.00^{d}	57.36^{bc}
BZ13-5	7.96^{ef}	19.84^{bc}	9.77^{hij}	12.07^{cde}	17.54^{abc}	8.28^{b}	8.86^{e-h}	6.01^{gh}	4.22^{c}	76.66^{abc}	6.66^{bcd}	20.00^{c-g}	35.00^{efg}	53.30^{bc}
BZ13-6	5.48^{kl}	15.98^{ef}	10.66^{e-h}	10.99^{ef}	14.83^{c-h}	8.77^{b}	9.27^{d-g}	6.01^{gh}	3.97^{c}	65.00^{c}	0.00^{d}	35.00^{bc}	49.00^{c}	73.22^{a}
BZ13-7	7.36^{fg}	18.92^{bc}	9.69^{ij}	11.29^{def}	16.26^{b-f}	8.14^{b}	8.69^{fgh}	5.80^{h}	3.97^{c}	72.33^{bc}	10.00^{bc}	17.66^{d-h}	40.00^{de}	54.42^{bc}
S16-4	8.32^{de}	21.06^{b}	11.47^{cde}	12.05^{cde}	17.50^{a-d}	9.52^{b}	9.80^{b-e}	7.43^{de}	3.82^{c}	80.00^{abc}	10.00^{bc}	10.00^{fg}	34.00^{fg}	46.70^{cd}
A19-7	6.93^{ghi}	20.70^{b}	11.29^{def}	11.33^{def}	14.02^{e-h}	7.97^{b}	8.41^{ghi}	4.50^{i}	2.00^{ef}	20.66^{de}	0.00^{d}	79.33^{a}	40.00^{de}	28.85^{f}
A20-5	7.19^{fgh}	20.24^{bc}	11.46^{cde}	10.77^{f}	14.51^{c-h}	9.16^{b}	8.76^{e-h}	6.98^{ef}	3.68^{c}	90.00^{a}	0.00^{d}	10.00^{fg}	36.00^{ef}	51.89^{bcd}
AA	9.85^{c}	21.24^{b}	11.11^{def}	13.07^{abc}	18.48^{ab}	9.41^{b}	10.23^{a-d}	8.40^{c}	5.40^{ab}	78.33^{abc}	0.00^{d}	21.66^{b-g}	27.00^{hi}	54.87^{bc}
AK	12.55^{a}	23.14^{a}	11.98^{cd}	13.44^{ab}	20.39^{a}	9.82^{b}	10.80^{ab}	9.71^{b}	5.95^{a}	91.66^{a}	4.33^{cd}	5.66^{g}	22.00^{i}	47. 44^{cd}
FA	9.11^{cd}	17.30^{de}	12.34^{bc}	12.48^{bc}	16.38^{b-e}	10.43^{b}	10.43^{abc}	8.00^{cd}	5.09^{b}	70.00^{bc}	13.33^{b}	16.66^{efg}	30.00^{gh}	55.80^{bc}
KGH	10.73^{b}	20.16^{bc}	13.83^{a}	13.37^{a}	18.18^{ab}	11.60^{ab}	11.07^{a}	12.00^{a}	5.86^{a}	66.66^{bc}	0.00^{d}	33.33^{bcd}	26.00^{hi}	55.34^{bc}

Means with a common letter in each column are not significantly different (LSD test, P = 0.05); SA (Sarakhs), BZ (Badami), S and H (Siirt), A and AK (Akbari), AA (Ahmad Aghaei), FA (Fandoghi) and KGH (Kalle Ghochi).

Table 3. Bivariate correlation among morphological traits in female genotypes.

	LL	LW	TLL	TLW	CL	FL	FW	FT	NDW	NL	NW	NT	KL	KW	KT	KFW	KDW	SNP	Ounce
LL	1																		
LW	.791**	1																	
TLL	.816**	.867**	1																
TLW	.633**	.722**	.851**	1															
RL	0.594**	0.578*	0.600**	0.523*	1														
FL	0.088	0.247	0.332	0.345	0.210	1													
FW	0.224	0.401	0.496*	0.289	0.175	0.720**	1												
FT	0.235	0.324	0.334	0.021	0.192	0.593**	0.800**	1											
NDW	0.239	0.417	0.439	0.280	0.231	0.764**	0.868**	0.840**	1										
NL	0.070	0.268	0.330	0.273	0.245	0.951**	0.768**	0.608**	0.759**	1									
NW	0.372	0.315	0.431	0.150	0.253	0.569*	0.850**	0.802**	0.756**	0.579*	1								
NT	0.031	0.253	0.313	0.072	0.014	0.626**	0.804**	0.839**	0.818**	0.673**	0.585*	1							
KL	0.127	0.431	0.458	0.369	0.282	0.811**	0.802**	0.688**	0.823**	0.827**	0.576*	0.751**	1						
KW	-0.089	-0.124	-0.184	-0.252	0.293	-0.225	-0.390	-0.174	-0.180	-0.254	-0.327	-0.136	-0.205	1					
KT	0.157	0.336	0.360	0.049	0.088	0.540*	0.830**	0.881**	0.803**	0.606**	0.682**	0.959**	0.728**	-0.202	1				
KFW	0.237	0.330	0.440	0.211	0.307	0.742**	0.860**	0.829**	0.844**	0.740**	0.811**	0.807**	0.869**	-0.097	0.827**	1			
KDW	0.161	0.367	0.382	0.211	0.277	0.690**	0.793**	0.799**	0.824**	0.673**	0.694**	0.772**	0.911**	-0.133	0.805**	0.947**	1		
SNP	0.078	0.123	0.191	0.344	-0.236	0.477*	0.339	0.232	0.395	0.343	0.226	0.383	0.450	-0.536*	0.383	0.362	0.434	1	
Ounce	-0.220	-0.407	-0.491*	-0.368	-0.195	-0.79**	-0.913**	-0.76**	-0.85**	-0.79**	-0.84**	-0.71**	-0.81**	0.526*	-0.73**	-0.82**	-0.80**	-0.50*	1

**, Correlation is significant at the 0.01 level (2-tailed); *, Correlation is significant at the 0.05 level (2-tailed).

Table 4. Mean comparisons of morphological traits in the studied male genotypes.

Genotype	Traits												
	LL	**LW**	**LL/LW**	**TLL**	**TLW**	**NL**	**SL**	**BN**	**FBN**	**PER**	**FP**	**IW**	**PW**
A19-3	16.83^{a-d}	13.83^{cd}	1.21^{bc}	8.00^{bcd}	4.83^{ab}	5.00^{bc}	4.16^{j}	5.66^{e}	2.66^{h}	47.63^{bc}	5.00^{g}	0.70^{g}	70^{h}
K17-3	16.50^{a-d}	13.33^{cd}	1.24^{b}	7.00^{de}	5.00^{ab}	5.00^{bc}	19.66^{cde}	8.33^{cde}	3.00^{gh}	35.96^{c}	3.00^{i}	2.01^{b}	120^{f}
K17-4	16.33^{a-d}	13.00^{cde}	1.26^{b}	7.50^{cde}	5.00^{ab}	5.00^{bc}	20.50^{cd}	8.66^{cd}	4.66^{d-g}	54.23^{b}	5.00^{g}	1.83^{b}	140^{e}
K17-5	17.66^{abc}	14.00^{cd}	1.26^{b}	7.00^{de}	4.50^{bc}	5.66^{b}	11.00^{hi}	8.33^{cde}	3.66^{e-h}	43.90^{bc}	6.00^{f}	1.78^{bc}	80^{g}
S16-1	15.16^{c-f}	14.66^{abc}	1.04^{bcd}	7.00^{de}	3.33^{d}	5.00^{bc}	14.50^{efg}	8.00^{cde}	4.33^{e-h}	54.16^{b}	4.00^{h}	1.14^{def}	120^{f}
S16-2	17.83^{ab}	16.33^{ab}	1.09^{bcd}	9.50^{a}	5.16^{ab}	5.00^{bc}	17.33^{def}	6.33^{de}	3.00^{gh}	46.66^{bc}	13.00^{b}	1.26^{def}	120^{f}
S16-3	15.83^{b-e}	14.16^{bc}	1.11^{bcd}	7.50^{cde}	5.16^{ab}	5.00^{bc}	16.50^{efg}	7.66^{cde}	3.33^{fgh}	44.03^{bc}	5.00^{g}	2.03^{b}	170^{c}
S16-5	18.66^{a}	14.66^{abc}	1.27^{b}	8.33^{abc}	3.66^{cd}	7.00^{a}	12.83^{ghi}	10.33^{bc}	5.00^{c-e}	48.53^{bc}	5.00^{g}	1.43^{cd}	110^{i}
SA4-4	14.66^{def}	8.66^{f}	1.74^{a}	4.00^{f}	1.33^{e}	7.00^{a}	14.00^{fgh}	20.66^{a}	17.33^{a}	83.80^{a}	5.00^{g}	0.91^{fg}	70^{h}
BZ13-4	13.66^{ef}	11.83^{de}	1.16^{bcd}	8.00^{bcd}	4.33^{bcd}	5.00^{bc}	12.66^{hi}	7.66^{cde}	6.33^{bcd}	84.26^{a}	5.00^{g}	1.29^{def}	170^{c}
BZ13-9	16.00^{b-e}	13.16^{cd}	1.21^{bc}	8.00^{bcd}	5.33^{ab}	5.00^{bc}	11.00^{hi}	5.66^{e}	4.33^{e-h}	77.36^{a}	4.00^{h}	1.33^{de}	180^{b}
BZ10-5	13.50^{ef}	13.83^{cd}	0.98^{cd}	8.00^{bcd}	5.00^{ab}	3.00^{de}	33.33^{a}	12.66^{b}	6.66^{bc}	52.60^{bc}	10.00^{c}	3.33^{a}	180^{b}
BZ10-4	13.00^{f}	10.83^{ef}	1.21^{bc}	6.30^{e}	5.33^{ab}	5.33^{bc}	25.0^{b}	10.33^{bc}	5.33^{bcd}	51.86^{bc}	8.00^{d}	1.09^{d-g}	190^{a}
BZ10-8	14.83^{def}	15.16^{abc}	0.98^{cd}	9.16^{ab}	4.66^{abc}	3.00^{e}	18.50^{cde}	8.66^{cd}	6.33^{bcd}	73.06^{a}	7.00^{e}	1.02^{efg}	160^{d}
BZ11-3	16.00^{b-e}	14.66^{abc}	1.09^{bcd}	8.33^{abc}	5.66^{a}	4.33^{cd}	21.83^{bc}	8.33^{cde}	7.33^{b}	89.16^{a}	21.00^{a}	1.02^{efg}	140^{e}
BZ12-1	15.50^{b-f}	16.66^{a}	0.93^{d}	9.00^{ab}	5.66^{a}	3.00^{e}	10.50^{i}	6.66^{de}	5.33^{bcd}	80.03^{a}	8.00^{d}	1.02^{efg}	140^{e}

Means with a common letter in each column are not significantly different (LSD test, $P = 0.05$). SA (Sarakhs), BZ (Badami), S (Siirt), A (Akbari) and K (Kirmizi).

Cluster analysis of female genotypes

Cluster analysis grouped the female genotypes into two main clusters (Fig. 2). Genotypes derived from the seeds of 'Badami' and 'Sarakhs' cultivars were placed in the first cluster, while H6-4 and S16-4 genotypes, originating from 'Siirt', were grouped in the second cluster together with the cultivars 'Ahmad Aghaei' (AA), 'Akbari' (AA), 'Kaleh Ghochi' (KGH), and 'Fandoghi' (FA) (Fig. 2).

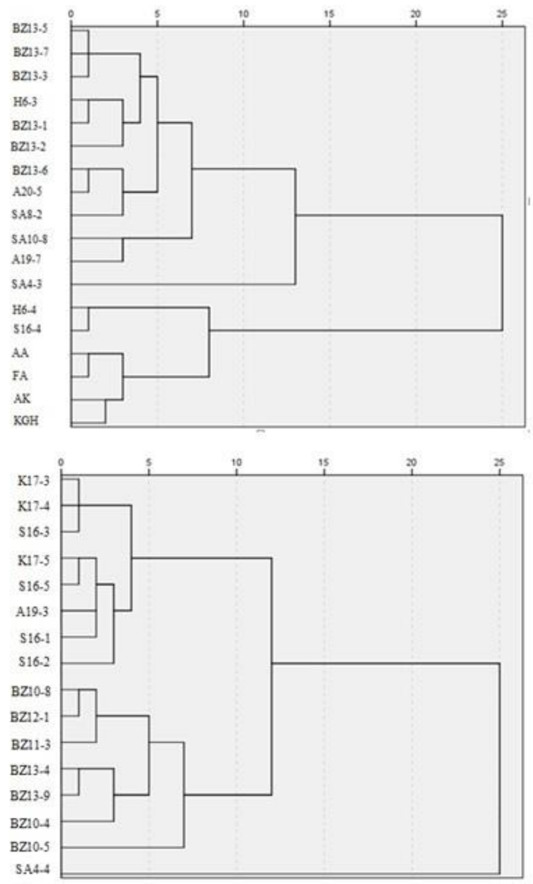

Fig. 2. Dendrogram representing morphological relationships among female genotypes (upright) and male genotypes (down right).

Morphological characteristics of male genotypes

Maximum, minimum, mean values, and coefficient of variation for measured traits

The maximum, minimum, mean values, range of variability, and coefficient of variation (CV%) for each trait are presented in Table 1. The studied genotypes exhibited a wide range of variability across all measured traits. Among these traits, the highest coefficients of variation were recorded for flower bud number (61.62%), flowering period (61.71%), inflorescence weight (43.93%), and shoot length (39.41%). Conversely, leaf length (10.31%) and leaf width showed the lowest coefficients of variation.

Analysis of variance and mean comparisons for male genotypes

The analysis of variance revealed significant differences among the genotypes for all studied characteristics. According to the obtained results, the largest leaf dimensions were recorded in S16-5 and S16-2 genotypes, whereas the smallest were observed in BZ10-4. The greatest terminal leaflet dimensions were also associated with S16-2, while the smallest were recorded in SA4-4. However, there was no significant difference between BZ12-1 and S16-2 genotypes with respect to terminal leaflet dimensions.

The numbers of leaflets varied among genotypes, i.e., the highest numbers (7 leaflets per compound leaf) were recorded in S16-5 and SA4-4, while the lowest (5 leaflets) were observed in BZ12-1. The SA4-4 genotype also had the highest number of flower buds per shoot, whereas the lowest was observed in A19-3. The duration of the flowering period ranged from 3 d in K17-3 to 21 d in BZ11-3.

The performance rate (flower buds/total buds × 100) differed significantly among genotypes, i.e., the lowest value was recorded in K17-3, while the highest rates were observed in SA4-4, BZ13-4, BZ12-1, and BZ11-3. According to the mean comparison results, the highest inflorescence weight (3.33 g) and pollen weight per inflorescence (190 mg) were recorded in BZ10-5 and BZ10-4 genotypes, respectively, whereas A19-3 had the lowest values for both inflorescence weight (0.7 g) and pollen weight (70 mg) (Table 3).

Correlation between traits in male genotypes

The correlation coefficients among traits in male genotypes are presented in Table 5. The number of flower buds per shoot was negatively correlated with terminal leaflet length (r= –0.64), terminal leaflet width (r= –0.71), and leaf width (r= –0.69). Inflorescence weight (r= +0.57) and pollen weight (r= +0.56) were positively correlated with shoot length. Pollen weight showed a negative correlation with leaf length (r= –0.59) and leaf number (r= –0.51), but a positive correlation with terminal leaflet width (r= +0.52) (Table 5).

Table 5. Bivariate correlation among morphological traits in male genotypes.

	BN	FBN	PER	FP	SL	LL	LW	LL/LW	TLL	TLW	NL	IW	PW
BN	1.000												
FBN	0.904**	1.000											
PER	0.270	0.632**	1.000										
FP	-0.046	0.089	0.345	1.000									
SL	0.273	0.121	-0.008	0.463	1.000								
LL	-0.340	-0.396	-0.424	-0.045	-0.517*	1.000							
LW	-0.683**	-0.693**	-0.343	0.314	-0.002	0.532*	1.000						
LL/LW	0.659**	0.647**	0.150	-0.337	-0.362	0.113	-0.758**	1.000					
TLL	-0.735**	-0.643**	-0.078	0.357	0.049	0.305	0.851**	-0.790**	1.000				
TLW	-0.738**	-0.714**	-0.195	0.416	0.317	0.027	0.509*	-0.691**	0.662**	1.000			
NL	0.511*	0.447	-0.024	-0.353	-0.463	0.323	-0.536*	0.881**	-0.656**	-0.708**	1.000		
IW	0.086	-0.189	-0.428	-0.084	0.573*	-0.083	0.137	-0.268	0.066	0.221	-0.282	1.000	
PW	-0.198	-0.158	0.224	0.128	0.568*	-0.598*	-0.032	-0.487	0.264	0.529*	-0.512*	0.285	1.000

**, Correlation is significant at the 0.01 level (2-tailed); *, Correlation is significant at the 0.05 level (2-tailed).

Cluster analysis of male genotypes

Based on the results of cluster analysis, male genotypes were also divided into two main clusters (Fig. 2). The first cluster comprised genotypes K17-3, K17-4, K17-5, S16-1, S16-2, S16-3, and S16-5, which originated from seeds of the 'Kirmizi' and 'Siirt' cultivars. The second cluster included genotypes BZ13-4, BZ13-9, BZ10-4, BZ10-5, BZ10-8, BZ11-13, and BZ12-1, all derived from the 'Badami' cultivar. The genotype SA4-11 was placed outside these two groups, forming a separate branch (Fig. 2).

Discussion

Pistachio is one of the tree species characterized by a long juvenile period, the duration of which depends on genotype, nutritional status, and environmental conditions. However, little information is available regarding the juvenile period of different pistachio cultivars. In the present study, significant differences were observed among genotypes in terms of juvenile period, which is consistent with previous findings in both pear and pistachio (Pan et al., 2023; Vargas and Romero, 1998). In pears, for example, it has been reported that seedlings of *Pyrus pyrifolia* and *Pyrus bretschneideri* have shorter juvenile periods than those of *Pyrus communis*. Similarly, Vargas and Romero (1998), who investigated juvenile period and vigor in families derived from crosses among several pistachio cultivars, reported differences among families with respect to juvenile period. Specifically, the 'Mateur' and 'Batoury' families with male genotype C, as well as 'Larnaka' with B genotype, exhibited shorter juvenile periods.

In the present study, the female genotypes S16-4, derived from the cultivar Siirt and H6-4, showed the shortest juvenile periods and were also characterized by the greatest trunk diameters and leaf dimensions. The duration of the juvenile phase is known to be influenced by multiple factors, including species, temperature, light, soluble carbohydrate content, and endogenous hormones (Umoh et al., 2022; Pan et al., 2023). The H6-4 and S16-4 genotypes, with their larger leaves and greater leaf area, likely produced sufficient carbohydrates to promote flower bud formation. These results are in agreement with those of Bagnara (1993), who reported that in pear, a shorter juvenile period is associated with efficient reserve utilization and higher dry matter accumulation in the woody parts of the plant.

In a study on *Anthurium*, the effect of radiation on carbohydrate accumulation and its influence on the transition from the juvenile to the mature stage was investigated, and a correlation was reported between photosynthates and the transition from the vegetative to the adult phase. In addition, it was shown that a threshold level of carbohydrates is required before plants can transition from the juvenile to the mature stage (Matsoukas Ioannis et al., 2008). Similarly, studies on an *Arabidopsis thaliana* mutant have demonstrated that impaired starch synthesis and catabolism prolong the juvenile phase due to insufficient starch supply, highlighting the critical role of carbohydrates in the transition from juvenile to mature stages. Furthermore, sugars have been shown to function not only as nutrients but also as signaling molecules that regulate the plant juvenile phase. For example, sucrose produced during photosynthesis can indirectly induce the expression of the *PRODUCTION OF ANTHOCYANIN PIGMENTS 1* (*PAP1*) gene, which is involved in anthocyanin synthesis, through the miR156–SPL regulatory pathway, thereby shortening the juvenile phase (Pan et al., 2023). Additionally, sugars can facilitate the transition out of the juvenile phase by downregulating the expression of miR156 (Ahsan et al., 2019).

In a relevant study, Karimi and Saghafi (2019) evaluated the same genotypes morphologically and ecophysiologically and found that S16-5 and H6-4 exhibited the highest leaf number per shoot, total leaf area, and chlorophyll index. Therefore, growth rate, leaf area, and photosynthetic parameters, including photosynthetic rate and chlorophyll index, can be considered reliable markers for determining the juvenile period in pistachio. These findings are consistent with previous reports identifying morphological and physiological markers associated with the juvenile and adult phases in trees (Valverde et al., 2024; Pan et al., 2023; Hammami et al., 2021; Basheer-Salimia, 2007; Basheer-Salimia et al., 2005). Pan et al. (2023) also reported that during the juvenile phase, plants exhibit significant differences in external leaf morphology, trichome distribution, cell shape, and chlorophyll and soluble protein content compared with the adult phase.

Basheer-Salimia et al. (2005) investigated several morphological, anatomical, and ecophysiological markers associated with the transition from juvenility to adulthood in olive and reported that photosynthetic rate and stomatal conductance were higher during the juvenile phase than during the adult phase. They also observed that, in the juvenile phase, leaf size as well as the number and size of hairs and stomata were smaller than in the adult phase. In another study, Hammami et al. (2021) examined the relationship between vigor, architectural parameters, and the duration of the juvenile period in olive and found that plant height and the insertion angle of secondary shoots were correlated with juvenile period length. Therefore, based on our results, the H6-4 and S16-4 genotypes can be introduced as early-fruiting cultivars suitable for use as scion sources or as parental material in pistachio breeding programs aimed at developing precocious cultivars.

According to the results, the morphological traits evaluated in both female and male genotypes varied across parameters such as mean, minimum, maximum, and coefficient of variation. Leaf length ranged from 13.0 to 19.30 cm, while leaf width varied from 8.67 to 20.30 cm. Neyshaburi et al. (2021) reported a similar range for leaf length (13.08–19.99 cm) and leaf width (12.48–18.30 cm). Nut length in the present study ranged from 13.53 to 23.14 mm, whereas nut width varied from 7.25 to 13.83 mm. By comparison, Neyshaburi et al. (2021) reported nut lengths ranging from 16.6 to 23.68 mm and nut widths ranging from 10.48 to 13.70 mm. In the present study, the SA4-3 and SA8-10 genotypes, which originated from the 'Sarakhs' cultivar and were characterized by the smallest nut dimensions, were identified as the earliest ripening genotypes. These genotypes can be utilized as early-ripening cultivars suitable for fresh consumption. In addition, they may represent promising candidates for cultivation under rainfed conditions due to their potentially low water requirements. As water scarcity continues to intensify worldwide as a result of climate change, increasing attention is being directed toward fruit tree species with low water demands, particularly through the selection and cultivation of early-ripening cultivars (Galindo et al., 2018).

Among nut characteristics, the percentage of blank nuts (CV = 79.0%) and kernel width (CV = 62.85%) exhibited the highest coefficients of variation. In a similar study, Rezaei et al. (2019) reported that the greatest coefficient of variation among measured quantitative traits in pistachio genotypes was associated with the percentage of blank nuts, which is consistent with the present results. They also noted that morphological traits with high coefficients of variation can serve as reliable markers for assessing genetic diversity among pistachio genotypes. In the present study, the percentage of split nuts ranged from 90.0% in A20-5 to 6.66% in SA4-3. Boualem et al. (2015) reported a range of 9.62–85.75% among Algerian genotypes, while Rezaei et al. (2019) observed a broader range from 0.00 to 97.37%.

Among the genotypes evaluated, H6-4, characterized by a green kernel, exhibited the largest fruit size and the greatest kernel weight, with no significant difference compared with the cultivars 'Kaleh Ghochi' (KGH) and 'Fandoghi' (FA). However, 'Kaleh Ghochi' is known to be sensitive to spring frost, salinity, drought, and high summer temperatures (Al-Khayri et al., 2019). Therefore, the H6-4 genotype can be recommended either as a cultivar for kernel production or as a parent in pistachio breeding programs. The S16-4 genotype, derived from the 'Siirt' cultivar, showed similarities to the cultivars 'Fandoghi' (FA) and 'Ahmad

Aghaei' (AA) in most nut characteristics, except for nut length, which was greater in S16-4 than in 'Fandoghi'. This genotype exhibited the shortest juvenile period, was early bearing, and produced white, unstained shells; thus, it can be proposed as a suitable cultivar for orchard establishment.

Furthermore, Hakimnejad et al. (2019) reported that the 'Akbari' and 'Siirt' cultivars of *Pistacia vera* were well adapted to the environmental conditions of Rafsanjan, indicating their potential for use as parents in breeding programs aimed at improving pistachio rootstocks and cultivars. Correlation analysis among female genotypes revealed that nut weight was positively correlated with nut dimensions, which is consistent with the findings of Kafkas et al. (2001), who reported a positive relationship between nut weight and nut thickness. In addition, rachis length in female genotypes showed a significant correlation with leaf and terminal leaflet dimensions. Larger leaf size can provide sufficient assimilates to support the development of larger inflorescences (Steven et al., 2019). For male pistachio trees, important breeding objectives include abundant pollen production with high viability, good flowering overlap with female trees, and shoots with high performance. In the present study, the S16-2 genotype, characterized by an upright growth habit, a flowering period of 13 d, and strong performance, and the BZ11-3 genotype, which exhibited the longest flowering period (21 d) and the highest yield (89.17%), were identified as promising pollinizer genotypes for further research.

A negative correlation was observed between pollen production and leaflet number, whereas a positive correlation was found between pollen production and shoot length. Genotypes with a greater number of leaflets generally exhibited smaller total leaf area and reduced crown volume, which limited carbohydrate production and consequently decreased the number of pollen grains produced per inflorescence. This result is consistent with the findings of Torno Molina et al. (1996), who reported a linear correlation between tree crown size and total pollen production in the inflorescences of anemophilous trees. Conversely, genotypes with longer shoots typically possessed more leaves, resulting in a larger photosynthetic area and greater carbohydrate accumulation in the shoots, thereby increasing pollen production per inflorescence. Cluster analysis separated female and male genotypes according to their cultivar origin. All male genotypes derived from Turkish cultivars ('Siirt' and 'Kirmizi') were distinctly grouped apart from those originating from Iranian cultivars ('Badami' and 'Sarakhs'). Among the female genotypes, H6-4 and S16-4, clustered together with 'Akbari' and 'Ahmad Aghaei'. In a breeding study, Hakimnejad et al. (2019) examined the morphological, ecophysiological, and photosynthetic characteristics of several *Pistacia* species and reported a close genetic relationship between the cultivars 'Siirt' and 'Akbari'.

Conclusion

Information regarding the juvenile period of pistachio cultivars remains scarce. Based on the results of the present study, a clear relationship was observed between trunk diameter, leaf area, and leaf dimensions and the duration of the juvenile period in pistachio, with genotypes exhibiting larger leaf area and leaf dimensions showing shorter juvenile periods. Therefore, these traits can be used as reliable markers to identify early-bearing genotypes in pistachio breeding programs. In addition, the S16-4 female genotype, characterized by a short juvenile period and desirable nut traits, as well as the BZ11-3 and S16-2 male genotypes, which exhibited long flowering periods and upright growth habits, can be proposed as promising genotypes or used as parental material in pistachio breeding programs. Based on the findings of this study, it is recommended that the performance of these genotypes be evaluated when grafted onto different pistachio rootstocks and grown under diverse climatic conditions. Furthermore, future research should examine the effects of pollen from these promising male genotypes on yield and nut quality parameters in commercial pistachio cultivars.

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Author Contributions

Responsible for the experimental design, HK; Executed the experiment, HK, MBK, and MJ. All authors have reviewed and endorsed the final manuscript.

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Conflict of interest

The authors declare that there are no competing interests.

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Supplementary Materials

Table S1. Meteorological data and soil analysis of the studied area (Hakimnejad et al., 2019).

Soil									
Soil Texture	Sand %	Clay %	Silt %	Na^+ (meq L^{-1})	Mg^{2+} (meq L^{-1})	Ca^{2+} (meq L^{-1})	SAR	pH	Ec dS m^{-1}
S.L	76	14	10	25.9	35	15	3.97	7.7	3.11
Climate									
Maximum temp. °C	Minimum temp. °C	The number of frosty days	The coldest month of the year	The warmest month of the year	Annual evaporation rate	Average annual moisture	Average annual sunny hours (h)	Average annual rainfall (mm)	Average annual wind speed (m s^{-1})
42.1	-6	28.35	December	July	2413.15	26.42	2735.3	47.8	2.67

Table S2. Origin, parent and key traits for selection of studied genotypes.

Selected genotypes	Parent	Origin	Trunk diameter	Leaf number per shoot	Key traits for selection
SA4-3	'Sarakhs'	Iran	9.55 (cm)	11.0	Early ripening
H6-4	'Siirt'	Turkey	10.50	14.0	Precocity, late flower, regular fruiting
H6-3	'Siirt'	Turkey	7.96	11.0	Late flowering, high splitting percentage of nuts
SA8-2	'Sarakhs'	Iran	5.41	10.0	Low blank of nuts, high splitting percentage of nuts
SA10-8	'Sarakhs'	Iran	6.68	9.0	Early ripening
BZ13-1	'Badami'	Iran	6.05	10.0	High number fruit in cluster
BZ13-2	'Badami'	Iran	10.50	11.0	High number fruit in cluster
BZ13-3	'Badami'	Iran	8.59	10.0	High splitting percentage of nuts
BZ13-5	'Badami'	Iran	7.32	11.0	Relatively precocity, high number fruit in cluster
BZ13-6	'Badami'	Iran	8.28	9.0	Relatively late flower
BZ13-7	'Badami'	Iran	7.32	9.0	Relatively late flower
S16-4	'Siirt'	Turkey	10.39	13.0	Precocity, regular fruiting, green kernel color
A19-7	'Akbari'	Iran	7.96	10.0	Low blank nuts
A20-5	'Akbari'	Iran	5.41	11.0	Low blank of nuts, high splitting percentage of nuts
A19-3	'Akbari'	Iran	7.0	8.0	Late flowering
K17-3	'Kirmizi'	Turkey	7.32	10.0	High pollen weight per florescence
K17-4	'Kirmizi'	Turkey	10.19	9.0	High pollen weight per florescence
K17-5	'Kirmizi'	Turkey	6.67	9.0	Long flowering period
S16-1	'Siirt'	Turkey	11.14	13.0	Erect growth habit, precocity
S16-2	'Siirt'	Turkey	15.92	11.0	Long flowering period
S16-3	'Siirt'	Turkey	8.28	11.0	Erect growth habit, high pollen weight per florescence
S16-5	'Siirt'	Turkey	8.30	11.0	Erect growth habit,
SA4-4	'Sarakhs'	Iran	8.59	9.0	High number of bud flower per shoot
BZ13-4	'Badami'	Iran	7.35	10.0	High number of bud flower per shoot, high pollen weight / florescence
BZ13-9	'Badami'	Iran	9.87	11.0	High pollen weight per florescence
BZ10-5	'Badami'	Iran	7.32	10.0	Long flowering period, high pollen weight per florescence
BZ10-4	'Badami'	Iran	7.30	10.0	High pollen weight per florescence
BZ10-8	'Badami'	Iran	7.0	11.0	Long flowering period, high pollen weight per florescence
BZ11-3	'Badami'	Iran	6.36	11.0	Long flowering period
BZ12-1	'Badami'	Iran	7.38	11.0	Long flowering period, high pollen weight per florescence