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NL Journal of Agriculture and Biotechnology

(ISSN: 3048-9679)

Volume 1 Issue 1 October 2024

Research Article

Comparative Study of Seed, Seedling, and Mother Shrub Traits of Amygdalus Scoparia in Diverse Populations of Isfahan Province

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DOI: 10.71168/NAB.01.01.104

Received Date: September 01- 2024 **Publication Date:** September 15- 2024

Abstract

Introduction: Amygdalus scoparia is a highly significant wild species native to the semi-arid and arid regions of Iran. Investigating the geographical variation of morphological traits of this species within its natural range is a crucial step in the genetic and conservation studies of these forest resources. This study was designed and conducted with this aim.

Materials and Methods: To examine the geographical variation of traits in this species, 10 natural populations of Amygdalus scoparia from various ecological and geographical conditions across Isfahan Province were selected. From each population, 21 to 25 mother shrubs were identified, and seeds from each shrub were collected from four directions of the crown. To determine the hundred-seed weight, 400 seeds were randomly selected from each shrub, and their fresh weight, dry weight, and dimensions were measured. For leaf traits, 20 healthy and expanded leaves were selected, and their morphological traits including length, width, area, and leaf perimeter were measured. Additionally, 10 mother shrubs from each population were randomly chosen, and after seed preparation, seeds were sown in a nursery using a randomized complete block design with 3 replications. In this experimental design, 100 mother plants were randomly placed in each block as 100 genotypes, and for each mother plant, 10 seeds were sown in a row of 10 in polyethylene pots. At the end of the growing period, the number of leaves, stems, seedling branches, stem length and diameter, main root length, seedling height, and collar diameter were measured.

Results: Based on the results, significant differences were observed among the populations for all studied traits. The hundred-seed weight, leaf area, and number of stems showed the highest variation among the studied traits. Drier regions exhibited smaller seed sizes and leaf dimensions compared to more humid areas. The study indicated that among the traits examined, seed width had the strongest correlation with seed weight. Additionally, results showed that with increasing longitude, decreasing precipitation, and rising temperatures from west to east in Isfahan, seedling height decreased. Furthermore, findings revealed that seedling height increased from east to west of Isfahan Province, while leaf dimensions decreased from north to south. This suggests a bidirectional geographical variability in the seedling stage, with latitude having a more substantial impact on the observed diversity than longitude.

Conclusion: Overall, the findings of this study demonstrate significant differences in a wide range of seed, mother shrub, leaf, and seedling morphological traits among natural populations of Amygdalus scoparia in Isfahan Province. Considering these findings, it is emphasized that the seed origin should be considered in afforestation operations with this species. It can be concluded that Amygdalus scoparia has a high ability to adapt to the environmental conditions of Isfahan Province.

Keywords: Geographical Variability, Genotype, Ecological Conditions, Morphological Traits

Introduction

Amygdalus scoparia (Spach) is a native species of Iran and Central Asia [18]. This species has multiple uses and advantages, including soil cover to prevent soil erosion [8], as a rich germplasm source for improving edible almonds [26], production of gum [10], oil [11], honey, fodder, and food [22], and raw materials for various industries [25]. Generally, plant species like Amygdalus scoparia that are distributed across vast steppe and semi-arid regions of Iran, including the Zagros ranges and provinces such as Fars, Isfahan, Yazd, Markazi, Qom, Kerman, South Khorasan, Hormozgan, Bushehr, and sporadically in parts of Golestan (Maraveh-Tappeh), Alborz (mountains around Karaj), Tehran (Siah-Kouh), and Balochistan (Bamzan) [27,14,5], have adapted to diverse ecological environments due to varied climatic and soil conditions, disturbance regimes, and the complex interactions among ecosystem components. Consequently, they have developed genetically distinct populations in different habitats [8]. These genetic distinctions follow environmental diversity patterns and manifest through various phenological, morphological, physiological, molecular, and biochemical means [1]. Understanding these patterns and utilizing the natural capacities of each local population can increase the success of reforestation and ecological restoration programs. Therefore, studying the geographical variations in growth and phenotypic traits of forest trees is crucial [15]. Such information is essential for various fields, including seed science, forest tree physiology, forestry and afforestation, species selection in agroforestry, and genetic conservation [17]. Moreover, the recent decline in natural forests highlights the importance of afforestation efforts. The success of any afforestation project is directly influenced by two fundamental stages: 1) selecting a species suitable for the soil and climate conditions, and [2] not abandoning the project and continuously monitoring the growth and performance of the afforestation [7].

One of the fundamental tasks in forest resource management and development is selecting an appropriate seed source for seed collection and seedling production. Various studies have shown that seed characteristics exhibit significant variations among different populations. For instance, research on Greek pine (Pinus yunnanensis) revealed that seed size correlates with geoclimatic variables such as latitude, longitude, altitude, temperature, precipitation, and seed origin [6]. Within a species, seed, leaf, seedling traits, and growth rates can vary among different populations, and this has been the subject of numerous studies [3]. Additionally, leaves are crucial for tree production and adaptation to various environmental conditions. The diversity among genotypes and populations based on leaf morphology has been studied in many tree species, including rowan (Sorbus torminalis) [9]. Several studies have provided strong evidence of tree growth improvement through the selection and improvement of specific traits in leaf morphology, anatomy, and physiology. For example [19], found that leaf size correlates with geoclimatic variables (latitude, longitude, altitude, temperature, and precipitation). They examined 22 different traits of seedlings across the entire distribution range of Greek pine. Among the provenances, significant differences were found in germination, leaf color on three dates, stem color, percentage of secondary needle formation, terminal buds, needle length, winter damage, current type of terminal bud, number of lateral buds, first-year mortality, primary needles, stem deviation, and height growth. Iran is one of the primary regions for various wild almond species, and the seed and leaf traits of some have been investigated in various studies. Most of these studies have compared seed and leaf morphological traits among numerous wild almond species, including Amygdalus scoparia [20,26]. Research on intra-species variation in morphological traits of mother trees, seeds, and leaves from several Amygdalus scoparia populations collected across Iran has used multivariate statistics [2]. All these studies have reported extensive phenotypic diversity among different almond species and natural populations of Amygdalus scoparia based on seed and leaf traits. Considering the wide distribution range of Amygdalus scoparia and its multiple functions, extensive studies on morphological, physiological, phenological, biochemical, and molecular diversity within its natural habitats and various populations are needed to formulate necessary measures for corrective actions, management of regeneration, and restoration of degraded habitats and to develop conservation strategies for its valuable populations. This study aims to assess the impact of dominant geoclimatic factors on morphological differences and the relationship between site-specific seed traits and morphological traits of Amygdalus scoparia from various populations across Isfahan Province. This will provide essential prerequisites for the management and conservation of this species.

Material and Methods

Isfahan Province, located in central Iran with its capital city being Isfahan, is the sixth largest province, the third most populous, and ranks first in urbanization in the country [29]. Covering an area of approximately 106,786 square kilometers, the province spans from 30 degrees 43 minutes to 34 degrees 27 minutes north latitude and from 49 degrees 36 minute to 55 degrees 31 minutes east longitude. Isfahan Province is bordered by Yazd and South Khorasan to the east, Semnan, Qom, and Markazi to the north, Lorestan and Chaharmahal and Bakhtiari to the west, and Kohgiluyeh and Boyer-Ahmad and Fars to the south.

Geographically, the province is bordered by the Kavir Desert to the east and north and the Zagros Mountains to the west and south. This natural setting creates both limitations and advantages for the province [16]. Approximately 2% of Isfahan Province's area is covered by forest. The almond-bane type is one of the most prevalent forest landscapes in Isfahan. Generally, this type shows better resistance to changes in altitude and all climatic elements across the province, resulting in its widespread presence in most parts of the province and various climatic regions (Figure 1).

In Isfahan Province, Amygdalus scoparia is distributed in two ecological zones: Zagros and Irano-Turanian. Most of its habitats fall within the rainfall isohyets of 150 to 250 millimeters, though it is also found in areas with annual rainfall below 100 millimeters and above 600 millimeters. The orientation of the terrain plays a significant role in the distribution of Amygdalus scoparia, with this light-demanding species typically being more densely distributed on southern and eastern slopes compared to northern and western slopes. The wide distribution range of Amygdalus scoparia indicates its presence across various soil types, making it one of the more adaptable forest species. Currently, its seeds are used in afforestation projects across the province.

To select the populations for this study, field experiences and consultations with experts from the Agricultural and Natural Resources Research Center and the Isfahan Provincial Department of Natural Resources and Watershed Management were utilized. Ten representative populations of Amygdalus scoparia from across the province, with varying distributions and ecological conditions, were chosen. Seed and leaf samples from these populations were collected in late spring 2020.

Figure 1. Wild almond forest habitat in Isfahan province (Natanz)

Research Methodology

In each of the 10 studied populations, including Pashtkouh in Fereydunshahr, Vank in Semnan, Zafreh in Isfahan, Ziadabad in Shahinshahr and Meymeh, Galleh Pareh in Natanz, Qaleh Tappeh in Barkhvar, Darreh Sohail in Na'in, Zowareh in Ardestan, Sensen in Kashan, and Biayzeh in Khur and Biabanak, 21 to 25 mother trees of Amygdalus scoparia (a total of 232 trees) were selected. These trees were chosen for their free pollination, suitable appearance, and seed production, and were spaced at least 100 meters apart to avoid genetic closeness. Their geographic coordinates were recorded using GPS (Table 1).

Seeds from each tree were collected from four directions around the canopy, totaling approximately 1000 seeds per tree, in late spring 2020 (approximately 232,000 seeds from all populations). After separating the fleshy part of the fruit, the seeds were labeled and stored until planting (February 2021) under suitable temperature and humidity conditions (4°C and 50% relative humidity). To determine the weight of 100 seeds, 400 healthy seeds from each tree were randomly selected, divided into four replicates of 100 seeds each, and their fresh weight was measured with a digital scale accurate to 0.01 grams in the laboratory [15]. For seed dimension analysis, 100 seeds from each tree were randomly selected, and the length, width, and thickness of each seed were measured using a digital caliper with an accuracy of 0.01 mm. Additionally, the dry weight of each seed was measured after placing the seeds in labeled aluminum foils and drying them in an oven at 105°C for 48 hours using a digital scale with an accuracy of 0.01 grams [15].

To examine leaf traits, 20 healthy leaves were randomly collected from the outer branches of each tree before leaf drop in late spring. The leaves were pressed, air-dried, mounted on graph paper, scanned using a Kodak scanner with a resolution of 100 dpi, and their traits including length, width, area, and perimeter were measured using Photoshop CS6 software. In winter 2021, 10 mother trees from each population were randomly selected, and their seeds were labeled and subjected to

cold stratification for one month using moist sterilized sand and refrigeration at a constant temperature of 4°C to break seed dormancy. After preparing the seeds for germination, they were planted in a nursery using a randomized complete block design with three replicates. In this experimental design, 10 mother trees (genotypes) from each population were selected, resulting in a total of 100 genotypes randomly placed in each of the three replicates (blocks). For each mother tree in each replicate, a row of 10 polyethylene pots, each containing 2 kg of sterilized agricultural soil and manure in a 3:1 ratio, was prepared. In February 2021, one seed was planted in each pot, totaling 3000 seeds across all three replicates. At the end of the growing season (December 2021), the number of leaves, stems, and branches, as well as the length and diameter of the stem and the length of the main root of each one-year-old seedling were measured. Seedling height was measured using a metal ruler with an accuracy of 1 mm, and collar diameter was measured with a digital caliper with an accuracy of 0.01 mm.

For statistical analysis, data on leaf, seed, and seedling traits were recorded in Excel. Normality of the data, homogeneity of variances, statistical indices, Pearson's simple correlation coefficients, analysis of variance, mean comparisons (t-test), and statistical charts were analyzed using SAS software. Weather data were obtained from the synoptic weather stations at Eastern Isfahan Airport (Qahab-e Shomali), Zowareh Ardestan Automatic Climate Station, Na'in Fully Automated Synoptic Station, Khur and Biabanak Fully Automated Synoptic Station, Semirom Fully Automated Synoptic Station, Fereydunshahr Fully Automated Synoptic Station, Kashan Fully Automated Synoptic Station, Meymeh Synoptic Station, Natanz Fully Automated Synoptic Station, and Dolatabad Barkhvar Automatic Climate Station (Table 1).

Table 1- Geoclimatic characteristics of Wild almond populations and the number of parent shrubs examined in each population

The number of parent shrubs	Average annual temperature (C°)	Average annual rainfall (mm)	Altitude above sea level (m)	Longitude	Latitude	Population
21	11	586	2590	50.7	32.56	Fereydonshahr
25	10	360	2400	51.17	31.51	Semirom
25	26	68	2078	52.67	32.72	Isfahan
25	21	120	2005	51.16	33.45	Shahinshahr
21	18	150	1610	51.25	33.30	Natanz
16	19	110	1595	51.57	32.87	Borkhar
25	18.7	100.8	1580	52.35	32.30	Naein
24	27	110	1238	52.37	33.37	Ardestan
25	28	116	982	51.58	33.98	Kashan
25	20	75	837	54.61	33.89	Khor va Biabanak

Average annual rainfall and average annual temperature were estimated using 20-year statistics (1996-2016) of the closest meteorological stations to the study areas

Results

The results of the analysis of variance (ANOVA) indicated that there are significant differences among the wild almond populations in Isfahan province regarding all seed dimension traits at a 99% confidence level (Table 2). Furthermore, the comparison of means revealed that the Khor va Biabanak population had the highest mean for 100-seed weight and seed length, while the Shahinshahr population had the highest mean for 100-seed weight, seed width, and seed diameter.

Specifically, the weight of 100 seeds in the Khor va Biabanak population reached its maximum value among the studied populations at 61.43 grams, which is the highest value compared to a reduction of 47.76% in the Isfahan population, where it reached its minimum at 22.73 grams. Additionally, the seed width and diameter in the Shahinshahr population (10.67 mm and 7.83 mm, respectively) were the highest, whereas these values decreased by 22.68% and 13.67%, respectively, in the Fereydonshahr population, reaching their minimums of 8.25 mm and 6.76 mm.

Moreover, the mean seed length across the studied populations indicated that the Khor va Biabanak population had the longest seeds, which decreased to a minimum of 11.74 mm in the Semirom and Naein populations, showing a reduction of 28.41%. The highest coefficient of variation was observed for the 100-seed weight, and the lowest for seed diameter (Table 2).

Table 2 - Comparison of the average seed size in populations of wild almond in Isfahan province

Seed diameter (mm)	Seed length (mm)	Seed width (mm)	100 seeds weight (gr)	Study Populations
6.76 ^{f}	13.75 ^{e}	8.25 ^{f}	36.24 ^{c}	Fereydounshahr
6.89 ^{e}	11.76 ^{g}	8.70 ^{e}	34.65 ^{c}	Borkhar
6.77 ^{f}	11.74 ^{g}	8.28 ^{f}	33.19 ^{d}	Semirom
8.15 ^{b}	11.74 ^{g}	10.53 ^{b}	61.43 ^{a}	Khor va biabanak
7.83 ^{a}	14.47 ^{c}	10.67 ^{a}	57.98 ^{a}	Shahinshahr
7.66 ^{c}	14.19 ^{d}	9.73 ^{d}	47.81 ^{b}	Ardestan
7.39 ^{d}	14.71 ^{b}	8.62 ^{e}	48.31 ^{b}	Kashan
6.94 ^{e}	13.74 ^{e}	8.62 ^{e}	35.24 ^{c}	Natanz
6.89 ^{e}	11.74 ^{g}	8.70 ^{e}	32.68 ^{c}	Naein
6.78 ^{f}	12.39 ^{f}	8.35 ^{f}	32.09 ^{c}	Isfahan
1059.07**	1508.08**	1435.84**	47.44**	F-value
0.000	0.000	0.000	0.000	Significance
8.134	9.905	9.943	19.686	CV

** Significance at the 99% level, Mean of each column that have same letters do not have a statistically significant difference at the 5% probability level

Leaf Dimensions

The analysis of variance (ANOVA) revealed significant differences among the wild almond populations in Isfahan province for all leaf dimension traits at a 99% confidence level (Table 3). The results of the mean comparison indicated that the Isfahan population had the lowest values for all leaf traits, including leaf length, width, perimeter, and area (2.34 cm, 0.33 cm, 5.14 cm, and 46.0 cm^2, respectively). Similarly, the Fereydonshahr population also showed significantly lower average values for leaf length, width, and perimeter (2.33 cm, 0.32 cm, and 5.13 cm, respectively) compared to other populations.

Although the Semirom population had the lowest average leaf length, area, and perimeter among the Isfahan populations, it had the highest average leaf width (0.61 cm) (Table 3). Additionally, the comparison of means showed that the Khor va Biabanak population had significantly higher average leaf length, area, and perimeter, while the Kashan population had significantly higher average leaf length and perimeter compared to other populations (Table 3).

The range of variation in the average leaf traits revealed the highest variability in leaf area (66.91%), followed by leaf length (50.64%), leaf width (47.54%), and leaf perimeter (39.58%). The highest coefficient of variation was observed for leaf area, while the lowest was for leaf length.

Table 3 - Comparison of the average traits of leaf dimensions of parent shrubs in wild almond populations of Isfahan province

leaf area (cm2)	leaf diameter (cm)	leaf width (cm)	leaf length (cm)	Study Populations
0.83 d	5.13 d	0.32 d	2.33 d	Fereydounshahr
0.78 d	7.29 bc	0.51 bc	3.28 bc	Borkhar
0.46 e	5.14 d	0.61 a	2.35 d	Semirom
1.39 a	8.49 a	0.53 b	3.88 a	Khor va biabanak
0.94 bc	7.51 b	0.49 bc	3.42 b	Shahinshahr
0.92 c	7.53 b	0.48 c	3.41b	Ardestan
1.01 b	8.15 a	0.52 b	4.72 a	Kashan
0.83 d	7.05 c	0.49 bc	3.20 c	Natanz
0.78 d	7.29 bc	0.51 bc	3.26 bc	Naein
0.46 e	5.14 d	0.33 d	2.34 d	Isfahan
**111.3	79.88**	78.58**	69.44**	F-value
0.000	0.000	0.000	0.000	Significance
46.868	26.066	29.191	26.061	CV

** Significance at the 99% level, Mean of each column that have same letters do not have a statistically significant difference at the 5% probability level

Seedling Traits

The analysis of variance showed that at a 99% confidence level, there are significant differences among the seedling traits from the studied populations for all vegetative traits examined (Table 4). Mean comparisons revealed that seedlings from the Fereydunshahr population exhibited the highest values for all aerial traits, including stem length, number of stems, number of branches, number of leaves, and fresh and dry stem weight. However, they had the lowest values for root length and fresh and dry root weight (Tables 4 and 5). Stem length in the Fereydunshahr and Barkhar populations was prioritized, while the Ardestan and Semirom populations exhibited the weakest performance in terms of stem growth length. The neck diameter of the Khur and Biyabank, Isfahan, and Barkhar populations differed significantly from other populations. The Khur and Naein populations had fewer stems and branches. Higher stem-to-root ratios were observed in the Fereydunshahr, Isfahan, and Shahinshahr populations, while lower ratios were found in the Naein and Khur and Biyabank populations. Among the studied populations, the Fereydunshahr population had the shortest main root length. In terms of fresh root weight, the Khur and Biyabank, Barkhar, and Naein populations showed the highest values, and for dry root weight, the Khur and Biyabank and Shahinshahr populations had the highest values. Fresh and dry stem weights were highest in the Fereydunshahr and Barkhar populations. The Fereydunshahr population also had the highest number of leaves, while the lowest number of leaves was recorded in the Kashan population. Among the vegetative traits of almond seedlings, the highest coefficient of variation was observed for the number of branches, and the lowest for neck diameter. Additionally, among the mean weights of fresh and dry stem and root, the highest coefficient of variation was associated with dry stem weight, and the lowest with dry root weight (Tables 4 and 5).

Table 4 - Comparison of the average growth traits of wild almond seedlings in populations of Isfahan province

leaf number	Number of branches	Number of stems	Stem diameter (mm)	Root length (cm)	Stem length (cm)	Study Populations
64.00 bc	0.32 c	1.10 d	2.97 bc	20.27 ab	15.88 c	Khor va biabanak
54.3 cd	0.31 d	1.35 d	2.69 b	21.32 a	16.99 c	Naein
63.00 bc	2.17 a	2.66 a	2.67 b	13.73 e	23.12 a	Natanz
36.7 e	0.62 ab	1.93 c	2.67 b	14.59 e	22.40 a	Kashan
67.9 b	0.61 ab	2.49 ab	2.72 b	17.02 b	19.88 b	Shahinshahr
70 b	0.40 bc	2.15 bc	2.86 c	18.32 bc	23.25 a	Borkhar
51.40 d	0.65 ab	2.43 ab	2.88 a	21.03 ab	21.44 ab	Isfahan
64.00 bc	0.33 c	2.45 ab	2.71 b	20.29 ab	15.78 c	Semirom
54.30 cd	0.45 d	1.92 c	2.68 b	22.32 a	16.97 a	Ardestan
88.20 a	0.45 d	2.66 a	2.68 b	13.63 e	23.42 a	Fereydounshahr
110.28**	32.62**	37.75**	**16.55	20.54**	21.52**	F-value
0.000	0.000	0.000	0.000	0.000	0.000	Significance
59.13	72.47	62.02	14.34	53.88	47.491	CV

** Significance at the 99% level, Mean of each column that have same letters do not have a statistically significant difference at the 5% probability level

Table 5 - Comparison of the average fresh and dry weight of wild almond seedlings in the studied populations of Isfahan province

Stem to root ratio (S-R)	Root dry weight (gr)	Stem dry weight (gr)	Stem wet root (gr)	Stem wet weight (gr)	Study Populations
1.11 d	0.28 a	0.32 c	2.97 bc	20.27 ab	Khor va biabanak
1.12 d	0.23 cd	1.35 d	2.69 b	21.32 a	Naein
1.11 d	0.21 d	2.66 a	2.67 b	13.73 e	Natanz
1.50 b	0.23 cd	1.93 c	2.67 b	14.59 e	Kashan
1.53 b	0.27 a	2.49 ab	2.72 b	17.02 b	Shahinshahr
1.50 b	0.24 bc	2.15 bc	2.86 c	18.32 bc	Borkhar
1.52 b	0.26 ab	2.43 ab	2.88 a	21.03 ab	Isfahan
1.31 c	0.20 d	2.45 ab	2.71 b	20.29 ab	Semirom
1.15 cd	0.23 bc	1.92 c	2.68 b	22.32 a	Ardestan
2.7 a	0.21 d	2.66 a	2.68 b	13.63 e	Fereydounshahr
182.70**	77.87**	37.75**	16.55**	20.54**	F-value
0.000	0.000	0.000	0.000	0.000	Significance
40.99	33.56	62.02	14.34	53.88	CV

**Significance at the 99% level, Mean of each column that have same letters do not have a statistically significant difference at the 5% probability level

Correlation of Seed and Leaf Traits with Geoclimatic Data of the Region

Simple correlation coefficients between seed and leaf traits and geoclimatic data (longitude, latitude, elevation above sea level, average annual temperature, and average annual rainfall) are presented in Table 6. Correlations among various traits of the mother trees, seeds, and seedling leaves are provided in Table 7. In the studied populations, except for the seed length-to-width ratio, all seed traits showed significant positive correlations with the average annual rainfall. Seed length was the only seed trait that showed a significant positive correlation with latitude. The leaf area of the mother trees showed a significant positive correlation with the average annual rainfall, while all leaf traits of the seedlings showed a significant positive correlation with latitude. Traits such as leaf length, width, and circumference of the mother trees exhibited significant negative correlations with the average annual temperature. None of the seed and leaf traits of the seedlings showed significant correlations with the traits of the mother trees. However, except for the seed length-to-width ratio, the remaining seed traits showed significant positive correlations with each other. The leaf area of the mother trees showed a significant positive correlation with seed length, width, seed weight, and leaf circumference only with seed width.

Table 6 - Simple correlation coefficients between geoclimatic variables and characteristics of wild almond seeds and leaves in the studied populations in Isfahan province

Leaf environ-ment	Leaf width	Leaf length	Leaf area	Seed length to width ratio	Seed thick-ness	Seed width	Seed length	100 grains weight	Variable
0.90**	0.87**	0.92**	0.89**	0.41	0.55	0.64	**0.84	0.69	Y
0.052	0.04	0.06	0.024	0.50	-0.03	-0.06	0.20	-0.04	X
-0.33	0.73	0.63	0.52	0.46	0.25	0.33	0.08	0.24	ASL
-0.85*	-0.79*	-0.80*	-0.64	-0.17	-0.23	-0.31	0.41-	-0.28	T
0.66	0.58	0.68*	0.79*	0.09	0.80*	0.85**	**0.84	0.87*	R

* and ** respectively indicate significant correlation at 0.05 and 0.01 probability levels. Y, X, ASL, T and R respectively represent the Longitude, Latitude, Altitude above Sea Level, Average Annual Temperature and Average Annual Rainfall of Seed Origin.

Table 7- Simple correlation coefficients between parent trees and seed traits of the studied wild almond populations in Isfahan province

TLW	TLW	TLP	TLA	RLW	SWD	ST	SL	SW	TCD	TH	trait
											TH
										0.97**	ACD
									0.21	0.01	SW
								0.81**	0.28	0.06	SL
							0.76**	0.98**	0.28	0.09	ST
						0.95**	0.90**	0.98**	0.16	-0.05	SWD
					-0.01	-0.24	0.05	-0.18	0.21	0.16	L:W
				0.22	0.91**	0.86**	0.93**	0.88**	0.52	0.32	SW
			0.84*	0.22	0.84*	0.70	0.89**	0.80*	0.23	0.01	LA
		0.92*	0.73	0.03	0.74*	0.72	0.89**	0.74*	0.27	0.06	LP
	0.96**	0.93**	0.71	0.07	0.67	0.56	0.68	0.67	0.30	0.10	LW
0.95**	0.99**	0.93**	0.76*	0.05	0.76*	0.67	0.75*	0.76*	0.28	0.06	LL

* and ** respectively indicate significant correlation at 0.05 and 0.01 probability levels. TH: Tree Height, ACD: Average Crown Diameter, SW: Seed Width, SL: Seed Length, ST: Seed Thickness, SWD: Weight of each Seed, L:W: Seed Length to Width Ratio, SS: 100 Seed Weight, LA: Leaf Area, LP: Leaf Perimeter, LW: Leaf Width, LL: Leaf Length of Mother Trees.

Correlation of Traits in Almond Seedlings with Geoclimatic Data

In the studied populations, the number of leaves, fresh and dry stem weight of the seedlings showed a significant negative correlation with latitude and annual rainfall average, while they showed a significant positive correlation with fresh and dry root weight, leaf area, circumference, length, and width. The height of the almond seedlings exhibited a significant negative correlation with longitude, while the number of branches per seedling showed a significant positive correlation with the average annual temperature and a significant negative correlation with elevation above sea level. The stem-to-root ratio also demonstrated a significant positive correlation with the average annual temperature. Additionally, all leaf traits of the seedlings showed significant positive correlations with each other (Table 8).

Table 8- Simple correlation coefficients between geoclimatic variables and seedling traits of the studied populations of wild almond in Esfahan province

Average annual temperature	Average annual rainfall	Altitude above sea level	Longitude	Latitude	Seedling traits
-0.49	0.81*	-0.49	-0.45	0.83*	LW
0.51	0.83*	-0.54	-0.41	0.83*	LL
-0.51	0.83*	-0.53	-0.42	0.81*	LP
-0.46	0.82*	-0.46	-0.48	0.81*	LA
-0.93**	-0.33	-0.77*	-0.21	-0.82*	S:R
-0.27	-0.47	-0.63	-0.03	-0.82*	RDW
-0.67*	0.84*	0.45	-0.39	0.65*	SDW
-0.67	0.15	0.62	-0.44	0.78*	RFW
0.7	0.82*	0.62	0.25	0.57*	SFW
0.92**	0.17	0.77*	-0.43	-0.78	BN
-0.69	-0.42	0.52	0.65	0.24	RL
0.53	-0.62	-0.58	-0.32	-0.73	SN
-0.12	0.75	0.16	0.34	0.39	CRD
0.44	0.65	-0.33	-0.80*	-0.09	SH

* and ** respectively indicate significant correlation at 0.05 and 0.01 probability levels. LW: Leaf Width, LL: Leaf Length, LP: Leaf Perimeter, LA: Leaf Area, S:R: Stem to Root ratio, LN: Leaf Number, RDW: Root Dry Weight, SDW: Stem Dry weight, RFW : Root Fresh Weight, SFW: Stem Fresh Weight, BN: Branch Number, RL: Root Length, SN: Stem Number, CRD: Collar Diameter, SH: Stem Height.

Discussion

This study observed significant differences across a wide range of seed, leaf, and seedling traits among various almond populations. The highest diversity in seed, leaf, and one-year-old seedling traits were related to 100-seed weight, leaf area, and the number of stems, respectively [4]. reported the highest coefficient of variation for seed traits, particularly seed weight, among different almond species, including almond. Seed propagation, gametophytic incompatibility, and natural hybrids may contribute to the diversity observed in almond populations and potentially ensure adaptation to diverse environments [26]. Plants require water throughout their lifecycle, and since water is unevenly distributed, its abundance or scarcity in the environment is reflected in prominent vegetative traits. In Isfahan Province, the dryness gradient (decreasing rainfall and increasing temperature) increases from the northwest to the south of the province with decreasing latitude, and from the west to the east with increasing longitude. Significant positive correlations were observed between the dimensions of the leaves of mother trees and seedlings with latitude, and significant positive correlations between seed dimensions, leaf area of mother trees, and leaf dimensions of seedlings with annual average rainfall. Additionally, significant negative correlations were found between the length, width, and circumference of mother tree leaves and the annual average temperature, indicating adaptive strategies of almond to cope with drought.

Comparing the leaf dimensions of seedlings grown under uniform environmental conditions and without soil moisture limitations in the nursery with the leaf dimensions of almond populations in their native habitats (with varying environmental conditions) showed similarity in these traits. This suggests that the similarity in these traits between seedlings and mother trees is largely controlled by genetic factors of the mother trees. The correlation between morphometric traits and geoclimatic data indicates that some seed and leaf traits of almond populations in Isfahan Province may exhibit clinal distribution, and natural selection along environmental gradients may continuously drive changes in allele frequencies of loci controlling adaptive traits [15], in their study of seed, leaf, and seedling traits of the neem tree (Azadirachta indica) in relation to geoclimatic factors, concluded that seedlings of this species utilize adaptive mechanisms in the early growth stages under water scarcity. Plants exhibit a broad range of adaptations to water scarcity. Reduced leaf area, increased root density, and length are among the most important and common drought adaptation traits [12]. Climatic stresses due to lower annual rainfall in the southern and eastern distribution areas of almond in Isfahan Province suggest that smaller leaves of mother trees and seedlings are an adaptation to the climatic conditions of these areas. Reducing leaf area and length-to-circumference ratio allows the plant to transfer more heat and moisture. Thus, in sunny and stressful environments, smaller leaves experience less thermal stress [23]. Smaller leaf dimensions in drier regions of the distribution and the positive correlation of leaf dimensions with annual average rainfall have been reported in previous studies [26,2].

The Khur population, despite being in the driest habitat studied, had the shortest main root length. It was expected that due to higher dryness in this habitat, almond seedlings would have a longer main root to access soil moisture. However, it appears that the optimal conditions in the nursery regarding moisture, temperature, and other factors may have altered allocation patterns in this population. Plants under different climatic conditions allocate biomass to various organs to maximize growth rates and optimize light, water, nutrients, and carbon dioxide uptake. According to the optimal allocation hypothesis, when plant access to nutrients and moisture increases, almond seedlings allocate fewer resources to the root system and more to the biomass of aerial parts [28]. Therefore, drought adaptation in the roots of seedlings from this population should be considered in other morpho-anatomical traits such as root diameter, number of branches, amount of lateral roots, and root architecture.

Seeds from the southern and eastern regions of the province were smaller and lighter, showing a significant positive correlation with annual average rainfall. When resources are limited, the plant may allocate its resources to a greater number of smaller seeds or a smaller number of larger seeds. Smaller seed dimensions and weight in drier areas likely indicate better adaptation of these seeds to environmental conditions. Larger seeds, with their smaller surface-to-volume ratio, require more time to absorb water, whereas smaller seeds can absorb maximum water in less time. Reduced soaking time is advantageous for seed germination and allows seedlings to utilize soil moisture conditions before facing drought. Additionally, smaller seeds are more likely to be in microclimates within the habitat, which often enhance water absorption and minimize seed desiccation [13]. The concept of provenance in forestry, indicating the origin of planting material distinct due to evolutionary processes, is suitable for explaining the results of this study. The study showed that seedling height increased from east to west, and leaf dimensions decreased from north to south, indicating a bidirectional geographic variation in seedlings with latitude and longitude, but the impact of latitude was significantly greater than longitude. Studies based on ISSR markers in almond populations from various locations in Iran also showed significant differences in molecular polymorphism and heterozygosity among populations, which could be distinguished by distance [21]. The correlations among some seed, leaf, and seedling traits with latitude, annual average rainfall, and annual average temperature suggest that selective pressures due to increasing drought are likely influencing the observed variation, reflecting adaptations for slower growth of certain traits. Such mechanisms can be considered as plant strategies against drought stress. Given Iran's location in the arid belt and the ongoing climate changes that exacerbate drought conditions, selecting drought-resistant genotypes is one of the best approaches to enhance survival, growth, and health in reforestation and afforestation projects. However, drought resistance traits in plants vary, and the diversity of habitat traits in almonds also challenges the selection of the most suitable provenances for dry habitats. Therefore, combining morphological, physiological, biochemical, and molecular studies in future research will facilitate the selection of the best provenances for targeted habitats.

Conclusion

Overall, the results of this study indicate clear and significant statistical differences in all seed traits among the studied populations. Significant differences were also observed across a wide range of morphological traits of mother trees, leaves, and seedlings from different almond populations in Isfahan Province. This suggests that on the one hand, morphological variables of seeds, leaves, and seedlings can be used to differentiate almond populations, and on the other hand, confirms the high adaptability of the almond species to the environmental conditions of the region.

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Citation: Soheil Soheili Esfahani. “Comparative Study of Seed, Seedling, and Mother Shrub Traits of Amygdalus Scoparia in Diverse Populations of Isfahan Province”. NL Journal of Agriculture and Biotechnology 1.1 (2024): 22-34.