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Pomological Characteristics of Argan Tree [*Argania spinosa* (L.) Skeels] Genetic Resources in Morocco

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SILVICULTURE

ABSTRACT

Background: The argan tree [*Argania spinosa* (L.) Skeels], native to Morocco, faces significant threats from climate change, leading to a shrinking natural distribution area. This study aimed to assess the diversity within argan tree populations and identify morphological differences and similarities among them by examining their fruits, seeds, and almonds.

Results: Researchers analyzed 32 morphological characteristics from 13 populations (40 samples each, totaling 520 materials) across diverse Moroccan coastal and inland habitats. Analysis of variance and multiple tests revealed significant morphological changes and high diversity among the populations. Notably, Cluster Analysis showed that the Aoulouz population formed a distinct group, highlighting its unique characteristics. Significant differences were also observed in fruit, seed, and almond diversity parameters.

Conclusion: The study confirms the high diversity of argan populations in Morocco's natural distribution areas. These findings are crucial for developing integrated in situ and ex situ conservation strategies for the argan species. The research outputs will support the economic viability, ecological integrity, and long-term sustainability of this valuable and long-degraded species.

Keywords: Fruit seed traits, eco-region, population, variation, endemic tree, morphological characteristics.

HIGHLIGHTS

Argan tree populations in Morocco show high diversity despite climate change threats.
Study examined 520 samples from 13 populations across coastal and inland habitats.
Aoulouz population stood out with unique morphological traits and high variability.
Findings support effective in situ and ex situ conservation of argan genetic diversity.

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INTRODUCTION

Morocco forest areas cover nine million hectares of natural area, accounting for 12% of the national territory (Laaribya et al., 2017). The argan tree [*Argania spinosa* (L.) Skeels], is a relict species known since the time of the Phoenicians. Native to Morocco, it is considered the most remarkable species in North Africa due to its botanical and ecological importance and its importance for local rural communities. These communities, particularly Berber women, rely on the tree for their livelihood and well-being. The production of argan oil from the tree's fruit provides a crucial source of income, empowering women through cooperatives and improving their economic independence. Additionally, the argan forest plays a vital role in combating desertification by preventing soil erosion and helping to maintain the local ecosystem. The tree also serves as a source of animal feed and has deep cultural significance, representing a symbol of heritage and traditional knowledge passed down through generations (Timzioura et al., 2025; Hallouch et al., 2025). It is believed that during the Quaternary glaciations, argan trees disappeared from most of North Africa, surviving only in southwestern Morocco (Boujnikh and Humbert, 2010). The argan tree is a plant species that can live in environments with many different climatic characteristics. Thanks to its deep root system, it is extremely drought-resistant and can live for 150 years, sometimes more than 200 years. Therefore, in the desert Souss Valley, the argan tree is often the dominant and most resilient species. The species is located in a climatic zone that combines the Atlantic Ocean, high mountains and sea-level desert. It can grow at altitudes up to 1500 meters (Santoro et al., 2023).

The argan tree endemic to Morocco, is a slow-growing species adapted to semi-arid regions (Díaz-Barradas et al., 2010). However, its population has faced significant decline, with its distribution area halving in the 20th century due to overgrazing and wood harvesting (De Waroux and Lambin, 2012). This decline is accelerated by climate change, threatening the species with irreversible desertification. Because of the difficulties in the tree's natural reproduction and the failure of many artificial propagation efforts (Santoro et al., 2023), it is crucial to establish a broad genetic base for breeding programs and conservation (Ait Aabd et al., 2012). Recent studies have focused on evaluating the genetic diversity of argan trees using morphological, chemical, and biochemical characteristics to support conservation efforts (Khayi et al., 2018; Ayan et al., 2023). Therefore, effective conservation and restoration of degraded forests depend on understanding and monitoring genetic diversity within and among populations (Jian et al., 2006). This approach is essential to ensure the long-term success of afforestation investments.

Knowing the variation in fruit quality traits among populations may facilitate using the species in the appropriate location. In this study, it was aimed to reveal the differences and similarities among argan populations by making morphological characteristics on fruits, seeds and almonds belonging to argan populations obtained from different ecological regions of Morocco, which is located in the north of the African continent, which can be characterized as arid or semi-arid.

MATERIALS AND METHOD

Material

Seeds were sourced from south-western Morocco and sampled to represent the inland and coastal regions of the country. The region has a semi-arid to arid Mediterranean climate with rainfall ranging from 100 to 300 mm on average and altitudes ranging from 20 to 1132 m. samples were obtained from different habitat zones, representing both coastal and inland ecosystems. This study was conducted on 13 argan populations, the details of which are provided in Table 1. Their geographical distribution is shown in Figure 1 and Figure 2.

Table 1: Geographical and habitat characteristics of the sampled argan tree populations.

Population number	Population name	Altitude (m)	Latitude	Longitude	Climate
1	Aoujdad-Aziar	200	-9.69458	30.5563	Semi-arid
2	Argana	780	-9.12385	30.7847	Semi-arid
3	Tamanar	227	-9.80856	30.7423	Semi-arid
4	Aoulouz	736	-8.15603	30.6849	Arid
5	Admine	90	-9.36146	30.3330	Semi-arid
6	Anzi	400	-9.35903	29.6615	Arid
7	Ain Asmama	1480	-9.25822	30.7527	Subhumid
8	Lakhsass	900	-9.75488	29.3627	Arid
9	Arghen	520	-8.60863	30.5033	Semi-arid
10	Sidi Ifni	300	-10.1655	29.3802	Arid
11	Ait Baha	560	-9.15263	30.0745	Arid
12	Taznakht	1244	-9.49133	30.6691	Semi-arid
13	Tasgaou Drar	525	-9.58931	30.7565	Semi-arid

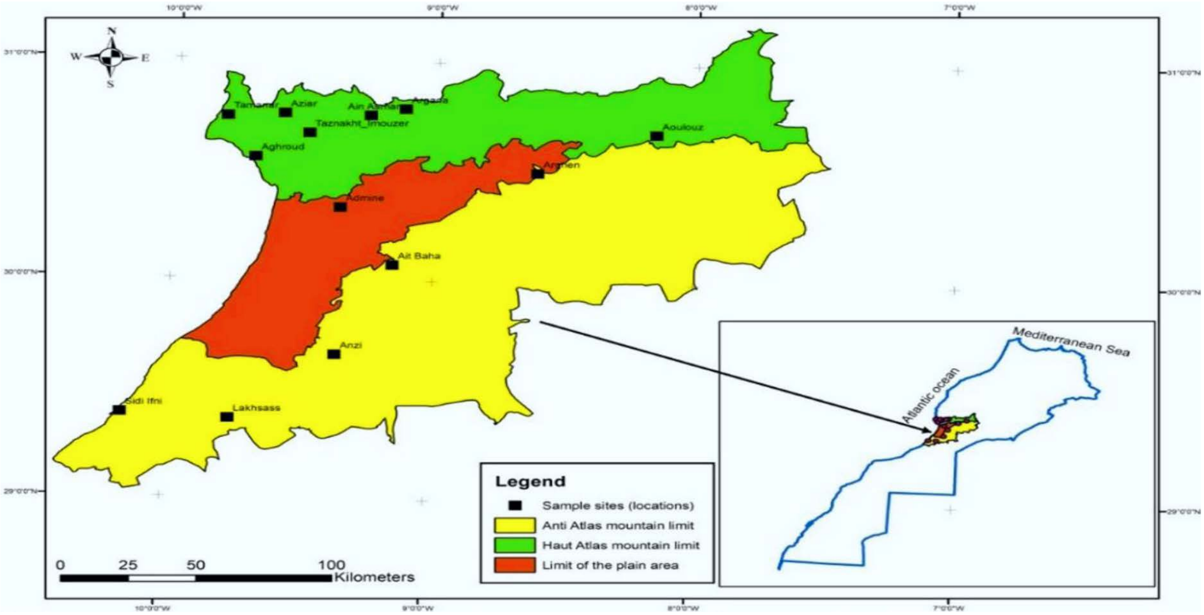

Figure 1: Locations of 13 different populations in the investigation area (southwestern Morocco).

Figure 2: Argania spinosa fruits of 13 different populations used in the study.

A mortar mixture consisting of 60% mineral soil, 5% fine sand, 20% humus and 15% burnt barn manure was used for seedlings grown in polyethylene containers.

Experimental design

When the fruits were ripe, the seeds were collected in May-June, the standard harvest period. Within the scope of the study, 520 samples were carried out on 40 fruits in each population in 13 different populations.

The morphological characters such as Fruit Length (FL) (mm), Fruit Thickness (FT) (mm), Fruit Width (FWi) (mm), Fruit Weight (FW) (g), Fruit Coat Thickness (FCT) (mm), Fruit Coat Weight (FCW) (mm), Seed Length (SL) (mm), Seed Thickness (ST) (mm), Seed Width (SWi) (mm), Seed Weight (SW) (g), Seed Coat Thickness (SCT) (mm), Seed Coat Weight (SCW) (mm), Almond Length (AL) (mm), Almond Thickness (AT) (mm), Almond Width (AWi) (mm) and Almond Weight (AW) (g) measured on Seeds, Almonds and Fruits (Table 2, Figure 3).

Table 2: Formulas used in the calculation of morphological variables.

Calculated morphological variable	Formula	References
Fruit Size (FSi)	$FSi = \frac{FL + FWi}{2}$	(Semiz, 2016)
Seed Size (SSi)	$SSi = \frac{SL + SWi}{2}$	(Semiz, 2016)
Almond Size (ASi)	$ASi = \frac{AL + AWi}{2}$	(Semiz, 2016)
Fruit Shape (FS)	$FS = \frac{FL}{FWi}$	(Kara et al., 2013)
Seed Shape (SS)	$SS = \frac{SL}{SWi}$	(Kara et al., 2013)
Almond Shape (AS)	$AS = \frac{AL}{AWi}$	(Kara et al., 2013)
Fruit Flatness Index (FFI)	$FFI = \frac{FWi}{FT}$	(Kara et al., 2013)
Seed Flatness Index (SFI)	$SFI = \frac{SWi}{ST}$	(Kara et al., 2013)
Almond Flatness Index (AFI)	$AFI = \frac{AWi}{AT}$	(Kara et al., 2013)
Fruit Shape Index (FSI)	$FSI = \frac{FL}{\left(\frac{(FWi + FT)}{2}\right)}$	(Semiz, 2016)
Seed Shape Index (SSI)	$SSI = \frac{SL}{\left(\frac{(SWi + ST)}{2}\right)}$	(Semiz, 2016)
Almond Shape Index (ASI)	$ASI = \frac{AL}{\left(\frac{(AWi + AT)}{2}\right)}$	(Semiz, 2016)
Fruit Size Index (FSiI)	$FSI = \sqrt[3]{FL * FWi * FT}$	(Ixtaina et al., 2008)
Seed Size Index (SSiI)	$SSiI = \sqrt[3]{SL * SWi * ST}$	(Ixtaina et al., 2008)
Almond Size Index (ASiI)	$ASiI = \sqrt[3]{AL * AWi * AT}$	(Ixtaina et al., 2008)
Kernel Ratio (KR)	$KR = \frac{AW}{FW} * 100$	(Macit and Işık, 2023)

Fruit Size (FSi), Seed Size (SSi), Almond Size (ASi), Fruit Shape (FS), Seed Shape (SS), Almond Shape (AS), Fruit Flatness Index (FFI, Seed Flatness Index (SFI), Almond Flatness Index (AFI) Fruit Shape Index (FSI), Seed Shape Index (SSI), Almond Shape Index (ASI), Fruit Size Index (FSiI), Seed Size Index (SSiI), Almond Size Index (ASiI) and Kernel Ratio (KR).

A digital caliper sensitive to 0.01 mm and a precision balance sensitive to 0.01 gram were used for measurements (Pérez-Sánchez and Morales-Corts, 2021). The morphological measurement variables were used to calculate using the formulas given in Table 2. These measurements; Fruit Size (FSi), Seed Size (SSi), Almond Size (ASi), Fruit Shape (FS), Seed Shape (SS), Almond Shape (AS), Fruit Flatness Index (FFI), Seed Flatness Index (SFI), Almond Flatness Index (AFI), Fruit Shape Index (FSI), Seed Shape Index (SSI), Almond Shape Index (ASI), Fruit Size Index (FSiI), Seed Size Index (SSiI), Almond Size Index (ASiI), and Kernel Ratio (KR) (Pérez-Sánchez and Morales-Corts, 2021; Li et al., 2022).

Statistical Evaluations

Data from 520 samples of 40 Argan fruits from 13 populations were evaluated. The normality of the morphological variables measured and calculated for Argan fruit, seed, and almond was checked using the Kolmogorov-Smirnov test. Morphological variables that did not show normal distribution were approximated to normal distribution by logarithmic and square root transformations. The homogeneity of the variables was determined using Bartlett's test. Analysis of variance and post-hoc tests were applied to data showing normal distribution to reveal differences between populations. Tamhane T2 analysis was performed using the 'PMCMRplus' package to determine differences between populations and homogeneous groups. The Kruskal–Wallis test, a non-parametric test, was used for variables that did not show a normal distribution. The 'dunn.test' package was used for multiple comparison tests for the Kruskal–Wallis test. All of these statistical analyses were performed using R software, version 4.3.2 (R Core Team, 2019), while cluster analysis was performed using IBM SPSS Statistics, version 23.0.

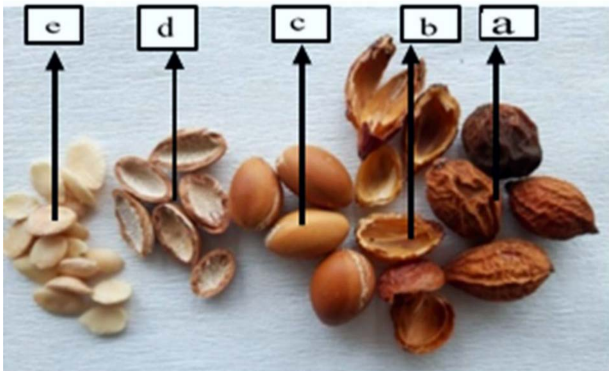

Figure 3: Argan fruit (a) - fruit coat (b) - seed (c) - seed coat (d) - almond (e).

RESULTS

As a result of the variance analysis, *Argania spinosa* species showed a statistically significant difference at the significance level of p = 0.001 for all measured variables. Since the variances did not provide homogeneity, the differences in the 32 measured and calculated dependent variables were determined by Tamhane T2 post hoc tests.

In terms of fruit length and fruit weight, the Anzi population had the lowest values, while the Aoulouz population had the highest values. Fruit thickness was lowest in Arghen and highest in Taznakht populations. The population with the highest fruit width, fruit coat thickness and fruit coat weight was determined as Lakhsass. The population with the lowest fruit width was Aoujdad-Aziar, the lowest fruit coat thickness was Argana and the lowest fruit coat weight was Tasgaou Drar (Table 3).

Regarding seed characteristics of argan populations, the Tasgaou Drar population had the lowest seed thickness, seed width, and seed coat thickness, while the Taznakht population had the highest. Regarding seed length, seed weight, and seed coat weight, the Anzi population had the lowest values, while the Aoulouz population had the highest values (Table 4).

While Aoulouz was the tallest population in almond length, it was the lowest in almond thickness evaluation. The Anzi population had the shortest almond length and showed homogeneity with the other populations regarding almond weight. Almond width was the highest in Sidi Ifni population and it was homogeneous with Ait Baha and Argana in terms of almond weight (Table 5).

The Anzi population showed homogeneity with the Aoujdad Aziar population in terms of almond size and the Tasgaou Drar population in fruit weight. Aoujdad Aziar population showed homogeneity with the Aoulouz population in terms of almond shape index. Aoulouz showed homogeneity with Ain Asmama and Argana in terms of seed weights. Argana population had one of the highest values in terms of Almond size and showed homogeneity with Ait Baha, Sidi Ifni. Cluster analysis of 13 argan populations for 32 morphological variables resulted in 3 large clusters.

Table 3 Multiple test results of fruits.

Populations	FL (mm)	FT (mm)	FWi (mm)	FW (g)	FCT (mm)	FCW (mm)
	Mean±St.Dev	Mean±St.Dev	Mean±St.Dev	Mean±St.Dev	Mean±St.Dev	Mean±St.Dev
Admine	$28.22^{c.d.e.f}$±1.16	$18.25^{b.c.d}$±2.09	$18.30^{b.c.d}$±2.71	$4.13^{c.d}$±1.09	$1.95^{d.e}$±1.34	$1.93^{b.c.d}$±0.68
Ain Asmama	$30.27^{e.f.g}$±1.16	$19.47^{c.d}$±2.92	$19.31^{c.d.e}$±2.66	$4.36^{c.d.e}$±0.76	$1.97^{d.e}$±1.46	$1.66^{a.b.c}$±0.39
Ait Baha	$31.19^{f.g}$±1.2	$17.70^{b.c}$±1.92	$19.72^{d.e}$±2.28	$4.54^{c.d.e}$±1.35	$1.52^{a.b.c.d}$±1.55	$1.96^{b.c.d}$±0.85
Anzi	23.1^{a}±1.16	$18.06^{b.c}$±1.84	$17.44^{a.b.c}$±2.04	3.03^{s}±0.94	$1.79^{c.d.e}$±1.38	1.44^{a}±0.55
Aoujdad Aziar	$24.05^{a.b}$±1.19	16.60^{b}±1.32	17.05^{a}±1.43	$3.37^{a.b}$±0.65	$1.36^{a.b}$±1.25	$1.54^{a.b}$±0.48
Aoulouz	38.09^{h}±1.25	$18.32^{b.c.d}$±2.95	$17.92^{a.b.c.d}$±2.85	5.12^{e}±1.31	$1.82^{d.e}$±1.20	2.06^{d}±0.52
Argana	$33.12^{h.g}$±1.19	$18.20^{b.c.d}$±1.92	$18.41^{b.c.d}$±1.65	$4.82^{d.e}$±0.99	1.32^{a}±1.26	$1.85^{a.b.c.d}$±0.61
Arghen	$26.31^{b.c.d}$±1.19	16.39^{a}±1.80	$17.30^{a.b}$±1.88	$3.74^{a.b.c}$±1.04	$1.55^{a.b.c.d}$±1.30	1.45^{a}±0.41
Lakhsass	$30.88^{e.f.g}$±1.08	$19.26^{c.d}$±2.32	20.34^{e}±1.99	$4.59^{d.e}$±0.90	2.16^{e}±1.28	2.11^{d}±0.48
Sidi Ifni	$28.22^{d.e}$±1.07	16.91^{b}±1.49	$17.96^{b.c}$±1.61	$4.25^{c.d.e}$±0.85	$1.42^{a.b}$±1.22	$1.93^{b.c.d}$±0.39
Tamanar	$25.79^{b.c}$±1.13	$17.68^{b.c}$±1.77	$18.31^{b.c.d}$±2.11	$3.86^{b.c}$±0.82	$1.46^{a.b.c}$±1.40	$1.55^{a.b}$±0.44
Tasgaou Drar	$25.03^{a.b.c}$±1.19	$16.55^{a.b}$±2.69	$17.14^{a.b}$±2.30	3.07^{a}±0.95	$1.73^{b.c.d.e}$±1.48	1.39^{a}±0.57
Taznakht	$31.19^{g.f}$±1.14	19.81^{d}±1.84	$19.02^{b.c.d.e}$±2.65	$4.12^{c.d}$±0.84	$1.57^{a.b.c.d.e}$±1.67	$1.73^{a.b.c.d}$±0.51
F value and Sig. level	36.317^{***}	11.237^{***}	8.603^{***}	17.331^{***}	9.045^{***}	8.516^{***}

*** Significant at the 0.001 level, there is a significant difference between the groups shown with different letters.

The Admine, Ain Asmama, Ait Baha, Argana, Lakhsass, Sidi Ifni, Taznakht populations formed a single group. A similar situation was observed in Anzi, Aoujdad Aziar, Arghen, Tamanar, Tasgaou Drar populations. On the other hand, the Aoulouz population differed from the 12 populations and formed a group on its own. The results of the cluster analysis support the results of the variance analysis. It was found that the clusters formed by the populations did not depend on geographical origin (Figure 4).

Anzi had the lowest fruit, seed and almond size while Aoulouz had the highest values. Regarding fruit, seed and almond shape, Anzi was the highest population while Aoulouz was the lowest. Aoujdad Azar has the lowest values regarding fruit, seed and almond shape index and fruit, seed and almond size. The Lakhsass population has the highest values in fruit shape index, Taznakht has the highest values in seed shape index and Sidi Ifni has the highest values in terms of almond shape index. Ait Baha population has the highest values in terms of fruit and seed size and Aoulouz almond size. Anzi and Taznakht had the lowest values in terms of fruit flatness index. Arghen showed homogeneity with Lakhsass and Sidi Ifni regarding Kernel Ratio and had the highest value. Kruskal Wallis Test, one of the nonparametric tests, was used for the seed flatness index, which does not show normal distribution, and significant differences were found among the populations as a result. While Aoujdad Aziar showed the lowest seed flatness index, the Argana population showed the highest seed flatness index value (Table 6).

Table 4 Multiple test results of seeds.

Populations	SL (mm)	ST (mm)	SWi (mm)	SW (g)	SCT (mm)	SCW (mm)
	Mean±St.Dev	Mean±St.Dev	Mean±St.Dev	Mean±St.Dev	Mean±St.Dev	Mean±St.Dev
Admine	21.54$^{c.d}$±1.14	13.20$^{a.b}$±1.13	12.90$^{a.b}$±1.67	2.16$^{b.c}$±0.62	2.45$^{b.c}$±0.50	1.90$^{b.c}$±0.53
Ain Asmama	23.81$^{e.f}$±1.14	13.74$^{a.b}$±1.13	13.90$^{a.b}$±2.30	3.02$^{d.e}$±0.74	2.68^{d}±0.33	2.77$^{e.f}$±0.72
Ait Baha	22.87$^{d.e.f}$±1.16	13.46$^{a.b}$±1.15	13.91$^{a.b}$±1.58	2.56$^{c.d.e}$±0.78	2.40$^{b.c}$±0.48	2.20$^{c.d}$±0.70
Anzi	16.61^{a}±1.14	12.94$^{a.b}$±1.17	13.11$^{a.b}$±2.18	1.65^{a}±0.63	2.59$^{b.c.d}$±0.76	1.39^{a}±0.54
Aoujdad Aziar	18.17$^{a.b}$±1.12	13.20$^{a.b}$±1.12	13.06$^{a.b}$±1.61	1.82$^{a.b}$±0.46	2.50$^{b.c}$±0.45	1.59$^{a.b}$±0.41
Aoulouz	31.82^{g}±1.17	14.01$^{a.b}$±1.20	13.13$^{a.b}$±2.32	3.04$^{d.e}$±0.94	2.66^{d}±.044	2.78$^{e.f}$±0.84
Argana	25.53^{f}±1.12	15.03$^{a.b}$±1.09	14.02$^{a.b}$±1.40	2.96$^{c.d}$±0.62	3.04^{e}±.051	2.73$^{d.e.f}$±0.65
Arghen	21.12$^{c.d}$±1.13	13.33$^{a.b}$±1.15	13.83$^{a.b}$±1.81	2.34$^{c.d}$±0.92	2.72$^{d.e}$±0.71	2.03$^{b.c}$±0.83
Lakhsass	21.54^{d}±1.09	14.59$^{a.b}$±1.08	13.90$^{a.b}$±1.29	2.49^{c}±0.56	3.05^{e}±0.55	2.22$^{c.d.e}$±0.51
Sidi Ifni	22.20$^{d.e}$±1.08	14.01$^{a.b}$±1.11	13.56$^{a.b}$±1.60	2.31^{c}±0.61	2.57$^{b.c.d}$±0.46	1.94$^{b.c}$±0.50
Tamanar	19.49$^{b.c}$±1.13	13.60$^{a.b}$±1.12	13.31$^{a.b}$±1.49	2.27^{c}±0.57	2.90$^{d.e}$±0.59	2.03$^{b.c}$±0.52
Tasgaou Drar	17.99$^{a.b}$±1.14	12.43^{a}±1.15	12.50^{a}±2.28	1.72$^{a.b}$±0.66	2.19$^{a.b}$±0.47	1.50$^{a.b}$±0.63
Taznakht	22.87$^{d.e.f}$±1.11	16.61^{b}±1.25	14.03$^{a.b}$±1.67	2.65$^{c.d.e}$±0.68	3.07^{e}±0.51	2.35$^{c.d.e.f}$±0.65
F value and Sig. level	71.234***	12.141***	3.055***	18.641***	10.661***	21.603***

*** Significant at the 0.001 level, there is a significant difference between the groups shown with different letters.

Table 5 Multiple test results for almonds.

Populations	AL (mm)	AT (mm)	AWi (mm)	AW (g)
	Mean±St.Dev	Mean±St.Dev	Mean±St.Dev	Mean±St.Dev
Admine	16.58$^{d.e}$±2.13	2.87$^{a.b.c.d}$±0.61	8.09$^{a.b.c}$±1.03	0.21$^{b.c.d}$±0.05
Ain Asmama	18.03$^{e.f}$±2.12	2.63$^{a.b.c}$±0.55	8.63$^{c.d.e}$±0.96	0.23$^{c.d.e}$±0.05
Ait Baha	17.82$^{e.f}$±2.28	3.04$^{a.b.c.d}$±0.69	8.97$^{d.e.f}$±1.13	0.27^{e}±0.06
Anzi	12.60$^{a.b}$±1.93	3.32$^{a.b.c.d}$±0.69	7.96$^{.ab.c}$±1.08	0.18$^{a.b}$±0.06
Aoujdad Aziar	13.83$^{b.c.d}$±1.58	2.97 $^{a.b.c.d}$±0.65	7.85$^{a.b}$±0.85	0.17^{a}±0.04
Aoulouz	22.73^{f}±3.93	2.33$^{a.b}$±0.99	8.34$^{b.c.d}$±2.01	0.24$^{c.d.e}$±0.09
Argana	19.26$^{e.f}$±2.04	2.81$^{a.b.c.d}$±0.68	8.99$^{d.e.f}$±0.84	0.27^{e}±0.05
Arghen	16.07$^{d.e}$±3.02	2.94$^{a.b.c.d}$±0.65	9.16$^{e.f}$±1.91	0.25$^{d.e}$±0.07
Lakhsass	15.47$^{d.e}$±1.60	3.41$^{a.b.c.d}$±0.54	8.69$^{c.d.e}$±0.96	0.24$^{d.e}$±0.05
Sidi Ifni	17.99$^{e.f}$±1.70	2.76$^{a.b.c.d}$±0.44	9.53^{f}±0.98	0.27^{e}±0.06
Tamanar	15.22$^{d.e}$±1.92	2.87$^{a.b.c.d}$±0.64	8.50$^{b.c.d}$±0.97	0.20$^{a.b.c.d}$±0.07
Tasgaou Drar	14.53$^{d.e}$±2.08	3.41$^{a.b.c.d}$±0.71	7.39^{a}±1.23	0.19$^{a.b.c}$±0.06
Taznakht	17.98$^{e.f}$±3.01	2.68$^{a.b.c}$±0.40	9.39$^{e.f}$±1.20	0.24$^{d.e}$±0.05
F value and Sig. level	50.205***	9.436***	11.000***	13.189***

*** Significant at the 0.001 level, there is a significant difference between the groups shown with different letters.

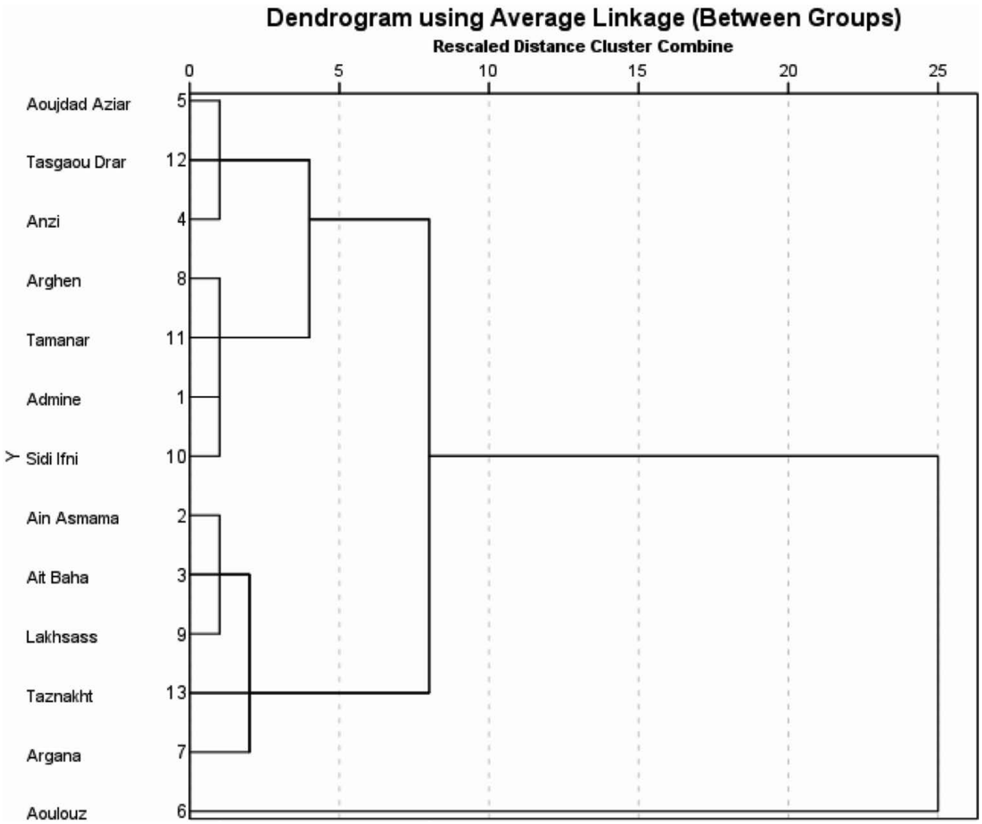

Figure 4: Dendrogram from cluster analysis illustrating three distinct argan population clusters based on a specified cutoff point.

When the fruit color status of the populations was examined, it was determined that Ait Baha, Argen, Tamanar populations were dark brown, Admine, Anzi, Aoujdad Aziar, Aoulouz, Lakhsass, Şıdı Ifnı and Taznakht populations were light brown and Ain Asmama, Argana and Tasgou Drar populations showed mixed color combination. In addition, the population with the highest number of double and triple almonds among the populations was Anzi, while the lowest was Ain Asmama population. While the rate of double almonds in Anzi population was 40%, the rate of triple almonds was 5%. At least one almond was found in each seed.

DISCUSSION

Argan plantations, which are highly resistant to water stress in arid and semi-arid areas of the region, prevent desertification. Argan trees are significant in the fight against erosion for soil stabilization, and their fruits also provide the development of wildlife (Bezzalla et al., 2017, Charrouf and Guillaume, 2011). In this context, it is useful to determine the morphological characteristics of the species' populations. The findings showed that there is morphological variability among argan tree populations. These differences in morphological characteristics may be due to climate, soil type, and ecological differences (Haloui et al., 2017). Argan trees exhibit significant genetic, morphological, and biochemical diversity even within a small, isolated area (Louati et al., 2019). This shows the vital importance of argan tree conservation efforts within its main distribution area in Morocco and encompassing these valuable and vulnerable populations in other regions. Furthermore, studies supporting morphological observations at the molecular level have increased in recent years. In this context, the study by Pakhrou et al. (2017), which analyzed the genetic diversity and population structure of Argania spinosa using genetic markers such as IRAP and ISSR, is critical. This paper demonstrates a high level of genetic diversity among different populations, and that the distribution of this diversity forms distinct clusters reflecting the phenotypic variation observed in morphological traits. This finding, in agreement with the results of your study, confirms the existence of a genetic basis underlying morphological differences. The results of this study provide strong evidence that genetically unique and highly diverse populations should be prioritized for future conservation strategies for the species. The book chapter "Advances in Plant Breeding Strategies: Nut and Beverage Crops," written by Ait Aabd et al. (2019), comprehensively examines the argan tree's genetic diversity and breeding potential. This chapter highlights the vital role of genetic differences among populations in the species' ability to adapt to changing climatic conditions. It supports the need for selection and breeding efforts based on morphological traits. The findings of your study, in line

Table 6 Multiple test results for fruit/seed/almond size, shape, shape index, size index, flatness index and internal yield ratio.

Populations / Multiple test results	Admine	Ain Asmama	Ait Baha	Anzi	Aoujdad Aziar	Aoulouz	Argana	Arghen	Lakhsass	Sidi Ifni	Tamanar	Tasgaou Drar	Taznakht	One-way ANOVA
	Mean ± St. Dev	Mean ± St. Dev	Mean ± St. Dev	Mean ± St. Dev	Mean ± St. Dev	Mean ± St. Dev	Mean ± St. Dev	Mean ± St. Dev	Mean ± St. Dev	Mean ± St. Dev	Mean ± St. Dev	Mean ± St. Dev	Mean ± St. Dev	
FSi	23.44$^{d.e}$ ±2.25	24.92$^{e.f}$ ±2.84	25.68$^{e.f}$ ±3.43	20.38^{a} ±2.43	20.67$^{a.b}$ ±1.93	28.38^{g} ±3.32	25.96^{f} ±2.69	21.95$^{a.b.c.d}$ ±2.94	25.71^{f} ±1.55	23.07$^{c.d}$ ±1.41	22.18$^{b.c.d}$ ±2.05	21.32$^{a.b.c}$ ±2.75	25.25$^{e.f}$ ±2.33	F=36.854***
SSi	17.31$^{c.d}$ ±1.51	18.99$^{e.f}$ ±1.90	18.54$^{d.e.f}$ ±2.31	14.91^{a} ±1.99	15.71$^{a.b}$ ±1.52	22.71^{g} ±2.37	19.80^{f} ±1.52	17.55$^{c.d.e}$ ±2.07	17.72$^{c.d.e}$ ±1.40	17.88$^{d.e}$ ±1.44	16.52$^{b.c}$ ±1.63	15.25$^{a.b}$ ±1.77	18.55$^{d.e.f}$ ±1.63	F=53.276***
ASi	12.33$^{c.d}$ ±1.17	13.33$^{d.e.f}$ ±1.21	13.40$^{e.f}$ ±1.59	10.28^{a} ±1.40	10.84^{a} ±0.98	15.54^{g} ±2.11	14.13^{f} ±1.12	12.62$^{c.d.e}$ ±2.30	12.09^{c} ±1.16	13.76$^{e.f}$ ±1.26	11.86$^{b.c}$ ±.123	10.96$^{a.b}$ ±1.32	13.69$^{e.f}$ ±1.42	F=42.076***
FS	0.66$^{c.d}$ ±0.14	0.64$^{b.c.d}$ ±0.12	0.64$^{b.c.d}$ ±0.10	0.76^{e} ±0.10	0.72$^{d.e}$ ±0.11	0.49^{a} ±0.16	0.57$^{a.b.c}$ ±0.12	0.67$^{c.d}$ ±0.11	0.66$^{c.d}$ ±0.09	0.64$^{b.c.d}$ ±0.06	0.71$^{d.e}$ ±0.10	0.69$^{c.d.e}$ ±0.13	0.62$^{a.b.c}$ ±0.12	F=14.476***
SS	0.61$^{b.c.d}$ ±0.12	0.59$^{b.c}$ ±0.12	0.61$^{b.c.d}$ ±0.08	0.79^{f} ±0.11	0.72$^{e.f}$ ±0.10	0.42^{a} ±0.13	0.56^{b} ±0.09	0.66$^{c.d.e}$ ±0.08	0.65$^{c.d}$ ±0.06	0.61$^{b.c.d}$ ±0.07	0.70$^{d.e}$ ±0.10	0.70$^{d.e.f}$ ±0.13	0.62$^{b.c.d}$ ±0.10	F=31.421***
AS	0.50$^{b.c.d}$ ±0.10	0.48$^{b.c}$ ±0.07	0.51$^{b.c.d}$ ±0.05	0.64^{f} ±0.07	0.57^{e} ±0.07	0.38^{a} ±0.13	0.47^{b} ±0.07	0.57^{e} ±0.09	0.56$^{d.e}$ ±0.05	0.53$^{c.d.e}$ ±0.04	0.56$^{d.e}$ ±0.07	0.52$^{b.c.d.e}$ ±0.10	0.54$^{c.d.e}$ ±0.11	F=23.049***
FSI	18.28$^{b.c.d.e.f.g}$ ±2.19	19.39$^{d.e.f.g}$ ±2.34	18.71$^{c.d.e.f.g}$ ±1.89	17.75$^{a.b.c.d.e}$ ±1.84	16.83^{a} ±1.26	18.12$^{b.c.d.e.f}$ ±2.75	18.30$^{b.c.d.e.f.g}$ ±1.44	16.85$^{a.b}$ ±1.76	19.80^{f} ±1.96	17.43$^{a.b.c.d}$ ±1.52	17.99$^{b.c.d.e}$ ±1.64	16.86$^{a.b.c}$ ±2.23	19.42$^{f.g}$ ±1.85	F=10.723***
SSI	13.08^{a} ±1.59	13.86$^{a.b.c}$ ±1.68	13.75$^{a.b.c}$ ±1.58	13.08$^{a.b}$ ±2.00	13.18$^{a.b}$ ±1.48	13.66$^{a.b.c}$ ±2.41	14.58$^{c.d}$ ±1.28	13.66$^{a.b.c}$ ±1.68	14.28$^{b.c.d}$ ±1.19	13.79$^{a.b.c}$ ±1.44	13.51$^{a.b}$ ±1.39	12.52^{a} ±1.93	15.51^{d} ±2.24	F=7.788***
ASI	5.48^{a} ±0.54	5.63$^{a.b}$ ±0.58	6.01$^{b.c}$ ±0.67	5.64$^{a.b}$ ±0.65	5.40^{a} ±0.46	5.34^{a} ±1.27	5.90$^{b.c}$ ±0.38	6.05$^{b.c}$ ±1.11	6.05$^{b.c}$ ±0.52	6.14^{c} ±0.59	5.68$^{a.b.c}$ ±0.68	5.41^{a} ±0.70	6.04$^{b.c}$ ±0.63	F=6.690***
FSiI	21.09$^{b.c}$ ±1.83	22.46$^{c.d}$ ±2.41	22.19$^{c.d}$ ±2.37	19.40$^{a.b}$ ±2.04	18.96^{a} ±1.37	23.15^{d} ±2.41	22.28$^{c.d}$ ±1.66	19.53$^{a.b}$ ±1.93	22.96$^{a.b}$ ±1.61	20.44$^{b.c}$ ±1.40	20.30$^{b.c}$ ±1.54	19.25$^{a.b}$ ±2.39	22.70^{d} ±1.91	F=25.525***
SSiI	15.42$^{b.c.d.e}$ ±1.38	16.58$^{e.f.g}$ ±1.50	16.32$^{d.e.f.g}$ ±1.88	14.69$^{a.b.c}$ ±1.96	14.17$^{a.b}$ ±1.40	18.02^{i} ±1.91	17.54$^{h.i}$ ±1.25	15.79$^{c.d.e.f}$ ±1.76	16.34$^{e.f.g}$ ±1.25	16.14$^{d.e.f}$ ±1.40	15.29$^{a.b.c.d}$ ±1.37	14.08^{a} ±1.73	17.51$^{g.h}$ ±1.67	F=25.023***
ASiI	7.25$^{a.b.c.d}$ ±3.20	7.41$^{b.c.d.e}$ ±3.30	7.84^{e} ±3.53	6.93$^{a.b}$ ±3.35	6.82^{a} ±2.89	7.58$^{b.c.d.e}$ ±4.52	7.80^{e} ±3.09	7.61$^{b.c.d.e}$ ±3.92	7.68$^{d.e}$ ±2.83	7.80^{e} ±3.25	7.19$^{a.b.c.d}$ ±3.51	7.13$^{a.b.c}$ ±3.38	7.65$^{c.d.e}$ ±3.12	F=7.096***
FFI	1.00$^{a.b.c.d}$ ±0.11	1.00$^{a.b.c.d}$ ±0.15	1.12^{e} ±0.11	0.97$^{a.b}$ ±0.07	1.03$^{b.c.d}$ ±0.07	0.98$^{a.b.c}$ ±0.11	1.02$^{a.b.c.d}$ ±0.10	1.06$^{d.e}$ ±0.07	1.06$^{d.e}$ ±0.07	1.06$^{d.e}$ ±0.07	1.04$^{b.c.d.e}$ ±0.11	1.05$^{b.c.d.e}$ ±0.13	0.97$^{a.b}$ ±0.14	F=6.990***
AFI	0.36$^{c.d.e}$ ±0.10	0.31^{b} ±0.07	0.34$^{b.c.d}$ ±0.09	0.42$^{e.f}$ ±0.10	0.39$^{c.d.e.f}$ ±0.11	0.28$^{a.b}$ ±0.12	0.32$^{b.c}$ ±0.09	0.33$^{b.c}$ ±0.08	0.40$^{d.e.f}$ ±0.08	0.30^{b} ±0.05	0.34$^{b.c.d}$ ±0.07	0.47^{f} ±0.12	0.29$^{a.b}$ ±0.06	F=16.846***
KR	0.05$^{a.b}$ ±0.001	0.05$^{a.b}$ ±0.001	0.06$^{b.c}$ ±0.002	0.06$^{b.c}$ ±0.002	0.05$^{a.b}$ ±0.001	0.04^{a} ±0.002	0.06$^{b.c}$ ±0.001	0.07^{c} ±0.002	0.09^{c} ±0.001	0.07^{c} ±0.001	0.05$^{a.b}$ ±0.002	0.06$^{b.c}$ ±0.002	0.06$^{b.c}$ ±0.001	F=6.695***
Variations	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Kruskal Wallis Test
SFI	1.92	1.54	1.37	1.81	1.32	1.56	2.13	1.39	1.52	1.64	1.66	1.92	1.54	F=99.646***

*** Significant at the 0.001 level, there is a significant difference between the groups shown with different letters.

with this publication, demonstrate that morphological differences provide a valuable genetic pool for future breeding programs. In particular, marked differences in flowering and fruiting cycles have been observed among populations in different regions of Algeria. The early-maturing, high-yielding, and phenol-flavonoid-rich fruits of the Tindouf region suggest that this population is genetically uniquely adapted to the challenging environmental conditions. Such phenotypic variation directly reflects the genetic diversity within the species (Mokeddem et al., 2025). Morphological traits and productivity within the argan tree, further confirming the species' extensive genetic diversity. This diversity, detected using methods such as analysis of variance and the Shannon-Weaver index, reveals a high degree of heterogeneity within and among the sampled populations. It is particularly noteworthy that the Had Dra and Biougra provenances exhibit superior traits compared to the others, while cluster analysis does not correlate morphological similarities with geographical origin. Pakhrou et al. (2017) using genetic markers, which indicate that genetic variation can be independent of geographical location. This result suggests that gene flow and intra-population adaptation are more dominant than environmental factors in the evolutionary history of the argan tree. Consequently, this high degree of genotypic variation offers critical potential for selection and breeding programs. Identifying genotypes with superior phenotypes, regardless of their geographical location, provides a solid scientific basis for developing strategies to increase argan cultivation's sustainability and strengthen the species' resilience to changing climatic conditions (Ait Aabd et al., 2021). Another study used the MaxEnt model to identify potential areas for argan tree plantations, providing a critical roadmap for sustainable argan cultivation and afforestation efforts. The results indicate that Algeria's northwestern, eastern, and central coasts are highly suitable for argan tree planting. At the same time, more arid regions such as deserts and steppes are less appropriate. These findings shed light on the key environmental factors that determine the morphological and genetic diversity of the argan tree. Specifically, bioclimatic conditions, such as minimum temperature between 2.5 and 6.5°C and annual rainfall between 160 and 1.400 mm, were decisive for suitability. These data highlight the adaptation of populations to different ecological niches and provide scientific support for the regions that should be preferred to maximize the success of large-scale plantation projects (Djebbouri et al., 2024). In another study, the analysis of morphological variability revealed five distinct groups, supporting the continued genetic diversity within the plantation and its valuable resource for breeding programs. Finally, the high oil yield from seeds (38.27% mechanical, 59.27% Soxhlet) highlights the tree's adaptability and potential to provide an economically sustainable resource even in challenging regions. These findings demonstrate the argan tree's promising potential in combating climate change and afforestation projects in the arid areas (Ould Safi et al., 2023). Another recent study highlights the critical role of ex-situ collections of argan trees established outside their natural habitats, particularly on the Iberian Peninsula, in terms of genetic diversity and the species' future. The study's most striking finding is that a 10-year Iberian collection highly represents the genetic diversity of wild populations. This representativeness suggests that these collections could serve not only for commercial purposes but also as complementary conservation tools that could mitigate the pressures of climate change on the species. MaxEnt modeling results indicate that argan's natural distribution area is projected to shrink significantly and shift northward between 2050 and 2080, highlighting the urgent need to identify climatic refuges and new planting areas. Therefore, such ex-situ collections provide a vital starting point for the domestication, breeding, and cultivation of argan across a wide environmental range, contributing to the long-term sustainability of the species (Djebbouri et. al, 2024). Analysis of variance across 32 measured and calculated variables showed statistically significant differences among populations, supported by both parametric and non-parametric tests, as well as cluster analysis. Among the populations, Aoulouz consistently exhibited superior values in most size-related traits, such as fruit length, fruit weight, seed length, and almond length, positioning it as a population with robust morphological features. Conversely, the Anzi population presented the lowest measurements for many traits, including fruit, seed, and almond size, while interestingly displaying the highest values for shape indices, suggesting a different growth pattern emphasizing elongation or narrowness rather than volume. Populations such as Lakhsass, Taznakht, and Sidi Ifni stood out in specific morphological aspects: Lakhsass for fruit width and coat characteristics, Taznakht for seed shape index, and Sidi Ifni for almond width and shape. The Argana and Ait Baha populations also demonstrated high values in almond and seed size, respectively, showing potential for selective breeding or conservation programs. The presence of unique traits such as high rates of double and triple almonds in Anzi, and the variability in fruit color across populations, adds further evidence of the wide intraspecific diversity within A. spinosa. Buernor et al. (2021) pointed out that there is a high level of phenotypic diversity among a total of 255 argan trees distributed throughout the argan zone), and specific qualitative and quantitative traits, particularly related to leaf shape, fruit shape and seed characteristics. Recent studies reveal significant variations in morphological, ecophysiological, and biochemical parameters that directly impact the physiological state of trees. While some populations, such as Tioughza, exhibit drought resistance through superior leaf area and water-holding capacity, others, such as Ezzaouite, have been observed to be more vulnerable under this stress. This suggests that the intraspecific diversity of the argan tree reflects the adaptability of different ecotypes to changing environmental conditions. The findings highlight that despite the argan tree's natural resilience, climate change poses a serious threat to the species' health and population structure (Afi et al., 2024). These highlighted factors can serve as key descriptors for the identification and monitoring of this diversity for the purposes of conservation, selection and development of arganiculture.

Seeds differences can be considered an important factor in seed germination (Souza and Fagundes 2014). In a study conducted by Nouaim et al. (2002) three different plant propagation methods were evaluated: seed, cuttings and micropropagation. In the experiment, which consisted of various seed collection methods, they observed that germination occurred easily when young (less than 12 months old) and heavy seeds (weighing more than 3 g) were used. Thin-shelled seeds germinated better than thick-shelled seeds.

Metougui et al. (2017) examined 30 morphological traits in 122 argan trees. By analyzing the traits, they found that growth traits (leaf and shoot size) were positively correlated with fruit traits. They also identified five homogeneous groups by cluster analysis based on Euclidean lengths. The cluster analysis grouped populations into three major clusters, showing that morphological similarities were not strictly related to geographic origin, highlighting the influence of other environmental or genetic factors.

In addition, the size, shape, flatness index and shape index of the seeds also give an idea about the size of the seed and since the increase in seed size affects the water uptake of the seed, it is stated that the water absorption capacity is high especially in tiny seeds (Dolan 1984). By examining the effect of seed weight on water uptake and germination rates, the research reveals that the lightest seeds from class W1 have the highest germination rate (84.4%). However, heavier seed classes such as W2 and W3 have been shown to yield significantly higher seedling yields overall (99.2% and 97.2%) due to their ability to produce multiple seedlings from a single seed. This finding offers a critical implication for nursery practices: while initial germination is essential, using heavier, multi-seeded seeds is most effective in mass production. Furthermore, the fact that seedling growth and development are directly proportional to seed weight demonstrates that the initially selected seed material directly influences the plant's future development. Therefore, this study presents a scientifically optimized method for argan tree propagation, playing a vital role in the success of large-scale argan cultivation and conservation projects (Azizi et al., 2022). As the shell of argan seeds thickens, the water uptake of the seed slows down and the germination time is prolonged (Berka et al., 2019). In this study, the seed size of the Tasgaou Drar population was smaller than the other populations, followed by the Aoujdad Aziar population. Considering the production situation of Argan seedlings in nurseries, it would be useful to use Tasgaou Drar, Aoujdad Aziar, Taznakht, and Anzi populations (Fowler and Bianchetti 2000). Studies conducted on Argana populations show that small spherical seeds have a strong correlation with germination (Berka et al., 2019). In this study, the Ait Baha population had the most significant values regarding almond size, while it showed homogeneity with Ait Baha and Argana regarding almond weight. In terms of having double or triple almonds, the Anti-Atlas Mountains region was found to be higher than the populations in the High Atlas Mountains line. Increasing agroforestry planting success will benefit the development of the region. In addition, the region, which has an arid and semi-arid climate, will also stabilize the soils against erosion and desertification (Bezzalla et al., 2017). The suitability of the argan tree for integration into different agro-forestry models forms the basis for developing comprehensive and applicable strategies for the conservation and future development of the species (Chakhchar et al., 2022). In the study conducted by Fouzia and Abderrahim (2001), the Ait Baha population was found to be higher than the Argana population in terms of morphological characteristics.

CONCLUSIONS

The comprehensive morphological analysis of 13 Argania spinosa populations, from different geographical locations in the High Atlas Mountains, Anti Atlas Mountains, and the plains between the two mountain ranges, revealed significant variations across fruit, seed, and almond traits, confirming the presence of considerable genetic and phenotypic diversity. Overall, the study emphasizes the importance of conserving diverse argan populations due to their distinct morphological traits. This diversity could be invaluable for future breeding programs, sustainable argan cultivation, and in situ and ex situ conservation strategies under changing climatic and environmental conditions.

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AUTHORSHIP CONTRIBUTION

Project Idea: SA, SL

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Processing: SA, SL, HQ, AA

Analysis: GA, ENYÇ, BMY

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DATA AVAILABILITY

The datasets supporting the conclusions are included in the article.

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