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Phenotypic diversity and breeding potential of the ‘*Kharji*’ apricot landrace (*Prunus armeniaca* L.) for sustainable mountain horticulture in Armenia

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Abstract

Background. The Armenian apricot landrace ‘*Kharji*’ (*Prunus armeniaca* L.) is a valuable genetic resource combining high phenotypic diversity with adaptation to mountainous and arid environments. Despite its agronomic importance, it remains insufficiently studied, limiting its use in breeding programs. In the context of increasing climate variability, the study of adaptive landraces such as ‘*Kharji*’ is essential for conserving biodiversity and developing resilient fruit crops for sustainable mountain horticulture.

Purpose. The aim of this research was to characterize the phenotypic, reproductive, and biochemical diversity of ‘*Kharji*’ and to evaluate its potential for breeding and sustainable mountain horticulture in Armenia.

Materials and methods. Plant material of the ‘*Kharji*’ apricot was collected, and field studies were conducted in various regions of Armenia. Phenotyping was performed

according to UPOV (TG/70/5) descriptors. Pollen fertility and viability were assessed using acetocarmine staining and in vitro germination. Biochemical analysis of fruits included the determination of sugars, organic acids, vitamin C, and antioxidant activity. Statistical analyses were carried out using cluster and multivariate methods (K-means, UPGMA, PCA).

Results. This study presents the first comprehensive characterization of the ‘*Kharji*’ landrace, including seedling morphology, vegetative and reproductive traits, fruit and endocarp characteristics, pollen fertility and viability, and fruit biochemical composition. Seedlings exhibited marked early heterophylly, while mature trees showed high variability in growth habit, leaf and floral traits, with diverse stigma–anther arrangements supporting both self- and cross-pollination under mountain conditions. Pollen fertility ranged from 48.1% to 98.2%, with more than half of the accessions showing very high fertility and viability. Fruit and endocarp traits were highly polymorphic in size, shape, symmetry, surface texture, basal apertures, and keel development. Multivariate analyses identified two main morphotypes – cultivated-type and wild-type, reflecting the semi-wild, transitional nature of the landrace. Comparative analysis suggested a shared Iranian–Caucasian origin with Dagestan populations and regional divergence driven by environmental conditions and cultivation history. Biochemical analyses revealed high metabolic diversity, elevated organic acid content, and strong antioxidant activity, indicating adaptive and nutritionally valuable traits for stress-prone mountain environments.

Conclusion. ‘*Kharji*’ landrace represents a key genetic resource for sustainable mountain horticulture, combining broad phenotypic diversity, high reproductive potential, and adaptive biochemical traits. Its tolerance to climatic stress, late flowering, frost resistance, and stable pollen viability make it particularly valuable for breeding programs aimed at developing resilient cultivars for mountain and arid regions. The results highlight the importance of conserving ‘*Kharji*’ both *in situ* and *ex situ* and provide a scientific basis for its targeted use in breeding and long-term strategies for sustainable development of mountain territories.

Keywords: apricot; ‘*Kharji*’ landrace; phenotypic diversity; breeding potential; fruit biochemical traits; pollen fertility; Armenian cultivars; genetic resource; mountain horticulture

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Фенотипическое разнообразие и селекционный потенциал местных форм абрикоса ‘Харджи’ (*Prunus armeniaca* L.) для устойчивого горного садоводства в Армении

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Аннотация

Обоснование. Аборигенные формы абрикоса ‘Харджи’ (*Prunus armeniaca* L.) представляют собой ценный генетический ресурс, сочетающий высокое фенотипическое разнообразие с адаптацией к горным и аридным условиям Армении. Несмотря на ресурсное значение, данные формы остаются недостаточно изученными, что ограничивает возможности их использования в селекционных программах. В условиях нарастающей климатической изменчивости изучение адаптивных аборигенных форм, таких как ‘Харджи’, имеет особую актуальность для сохранения биоразнообразия и создания устойчивых плодовых культур в системе горного садоводства.

Цель. Целью настоящего исследования является характеристика фенотипического, репродуктивного и биохимического разнообразия абрикоса ‘Харджи’, а также оценка его потенциала для селекции и устойчивого горного садоводства в Армении.

Материалы и методы. Сбор материала абрикоса ‘Харджи’ и полевые исследования проводили в разных регионах Армении. Фенотипирование выполняли по дескрипторам UPOV (TG/70/5). Фертильность и жизнеспособность пыльцы оценивали ацетокарминовым окрашиванием и методом *in vitro* прорастивания. Биохимический анализ плодов включал определение сахаров, органических кислот, витамина С и антиоксидантной активности. Статистическую обработку данных проводили с использованием кластерного и многомерного анализа (K-means, UPGMA, PCA).

Результаты. Впервые проведена комплексная характеристика аборигенно-го абрикоса ‘Харджи’, охватывающая морфологию семян, вегетативные и ге-

неративные органы, признаки плодов и эндокарпия, показатели фертильности и жизнеспособности пыльцы, а также биохимические свойства плодов. У сеянцев выявлена выраженная гетерофилия на ранних этапах онтогенеза. Взрослые деревья характеризовались высокой вариабельностью по габитусу, морфологии листьев и цветков, включая разнообразие взаимного расположения рыльца и тычинок, что обеспечивает как самоопыление, так и перекрёстное опыление в горных условиях. Фертильность пыльцы варьировала от 48.1 до 98.2 %, при этом более половины образцов отличались очень высокими показателями фертильности и жизнеспособности. Плоды и эндокарпии отличались высокой полиморфностью по размерам, форме, симметрии, характеру поверхности, базальным отверстиям и степени развития кия. Многомерный анализ позволил выделить два основных морфотипа – культурного и дикого типов, что подтверждает полудикий и переходный характер аборигенной популяции абрикоса ‘Харджи’. Сравнительный анализ показал общее ирано-кавказское происхождение с популяциями Дагестана при наличии региональной дивергенции, обусловленной природными условиями и историей возделывания. Биохимические исследования выявили высокий уровень метаболического разнообразия, повышенное содержание органических кислот и высокую антиоксидантную активность, указывающие на адаптивную и пищевую ценность форм ‘Харджи’ в стрессовых горных условиях.

Выводы. Абрикос ‘Харджи’ представляет собой ключевой генетический ресурс для устойчивого горного садоводства, сочетающий широкое фенотипическое разнообразие, высокую репродуктивную способность и адаптивные биохимические признаки. Толерантность к климатическим стрессам, позднее цветение, морозоустойчивость и стабильная жизнеспособность пыльцы определяют её высокую ценность для селекционных программ, направленных на создание устойчивых сортов для горных и аридных регионов. Полученные результаты подчёркивают необходимость сохранения разнообразия аборигенных форм ‘Харджи’ в *in situ* и *ex situ* условиях и формируют научную основу для их целенаправленного использования в селекции и долгосрочных стратегиях устойчивого развития горных территорий.

Ключевые слова: абрикос; аборигенные формы ‘Харджи’; фенотипическое разнообразие; селекционный потенциал; биохимические признаки плодов; фертильность пыльцы; армянские сорта; генетический ресурс; горное садоводство

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Introduction

The Caucasus is recognized as one of the primary centers of origin and diversity of wild and cultivated fruit trees [46]. The apricot *Prunus armeniaca* L. is a fruit tree of high ecological and economic significance, widely cultivated throughout the Caucasus and well adapted to mountain and foothill environments. Natural populations of wild apricot are found in Central Asia, primarily in the Tien Shan Mountains, as well as in several regions of northern China [26; 48]. Cultivated apricot has long expanded beyond its native area and is classified into four eco-geographical groups, with Armenian and Dagestan apricots belonging to the Iranian-Caucasian group [29].

Apricot cultivation in Armenia has ancient roots. Archaeobotanical findings from the Garni Temple and the Shengavit settlement demonstrate apricot cultivation since the Early Bronze Age [6; 39]. Up to 50 local varieties have originated through traditional selection [36]. Apricot cultivation in Armenia extends over a wide range of ecological conditions. Apricot trees grow and bear fruit successfully at elevations of about 600–1800 m above sea level, and in some areas up to 2000 m. This range includes foothill and moderately mountainous areas and indicates the good adaptation of apricot to the diverse mountain soil and climatic conditions of Armenia. Wild-growing forms are distributed at elevations of 800–2100 m a.s.l. across forested and rocky habitats and open woodland ecosystems [20; 25; 41].

Over 90% of Armenia's territory is covered by mountains, with altitudes above 1000 m, including extensive areas above 2000 m, and an average elevation of approximately 1830 m [18]. Agriculture, including fruit cultivation, occurs under complex mountainous conditions, with varied slopes, exposures, and microclimates. Orchards are mainly located on foothill and mountain sites (600–1800 m and higher), often on steep slopes, under semi-arid conditions with limited water and a high risk of spring frosts. These factors determine agronomic practices, cultivar choice, and breeding strategies in line with mountain horticulture principles. In the mountainous and foothill landscapes of Armenia, traditional agriculture included a well-developed system of terraced horticulture and farming; terrace irrigation systems had unique solutions adapted to the local landscape [21; 22]. Terracing, as a traditional land-use method characteristic of many Armenian settlements, developed under the influence of the geographical environment with the aim of protecting sloping agricultural lands from erosion and preserving the interconnection between terrace gardens and the landscapes. International research suggests that terraced agricultural systems continue to play an important role in soil conservation and slope stabilization in mountain-

ous landscapes, indicating their potential relevance under contemporary environmental conditions [40]. In this context, the traditional terraced gardens of Armenia may be considered not only as a component of cultural heritage, but also as a potential model for sustainable management of mountain agricultural landscapes.

Local indigenous fruit crop forms shaped by long-term adaptation to extreme highland conditions play a key role in Armenia's mountain horticulture. A substantial proportion of Armenian apricots belongs to local seedling populations well adapted to mountainous and semi-arid environments. Among this germplasm, the semi-wild landrace '*Kharji*' is of particular interest, with more than 100 documented forms [36]. Indigenous apricot landraces such as '*Kharji*' exhibit traits essential for sustainable mountain horticulture, including ecological plasticity, tolerance to abiotic stresses, stable fruiting under adverse conditions, and reduced sensitivity of flowers to short-term frosts, making them valuable resources for climate-resilient breeding.

'*Kharji*' trees occur in old terrace orchards, abandoned plantations, rural farms, and occasionally naturalized habitats across Armenia's major fruit-growing regions (Ararat, Armavir, Aragatsotn, Kotayk, Vayots Dzor, Syunik) and display intermediate characteristics between wild and cultivated apricots [25; 36]. Although comparable semi-wild forms are known from Central Asia (e.g., '*Khasak*'), they differ genetically and morphologically from '*Kharji*' [9; 30]. Originating from ungrafted seedlings, '*Kharji*' exhibits pronounced phenotypic polymorphism, with nearly every tree representing a distinct form. Its intra-population variability includes tolerance to low temperatures, late flowering, stable fruit quality, natural disease resistance, and high productivity. As Armenia's predominant rootstock, '*Kharji*' imparts vigor and environmental resilience to grafted cultivars. While typically small-fruited, its wide ecological amplitude enhances its breeding value, and high-altitude populations (1400–1700 m a.s.l.), particularly in Vayots Dzor, include large-fruited forms that further expand its potential for cultivar development.

Indigenous apricot landraces represent an important source of phenotypic and genetic diversity, showing wide variation in morphological, pomological, and biochemical traits, and are essential for breeding programs focused on fruit quality, productivity, and stress tolerance [11; 15; 19]. The conservation and study of local apricot germplasm are essential for sustainable horticulture in Armenia, especially in mountainous, environmentally constrained regions. Despite its wide distribution and agronomic importance, the '*Kharji*' landrace is insufficiently characterized, with no comprehensive assessment of its pheno-

typic diversity, reproductive traits, or agronomic potential. Addressing this gap is crucial for conservation, breeding, and understanding its relationship with other indigenous *P. armeniaca* forms.

This study aimed to provide an integrated phenotypic and reproductive characterization of the '*Kharji*' landrace, encompassing vegetative, floral, fruit, and endocarp traits, pollen fertility and viability, and fruit biochemical properties, to evaluate its value as a genetic resource for sustainable mountain horticulture and to establish a baseline for future molecular and breeding research.

Material and methods

Study Sites and Sample Collection. Field investigations of the *P. armeniaca* '*Kharji*' landrace were conducted in the Aragatsotn (1900–2000 m a.s.l.), Armavir (900–1000 m), Kotayk (1600–1700 m), and Vayots Dzor (2000–2100 m) provinces, as well as in Jrvezh Forest Park (1250 m) and the fruit plant collection of the Yerevan Botanical Garden (1200 m) [1]. For comparison, local apricot cultivars from the Echmiadzin Agricultural Scientific Center and farm orchards ('*Abutalibi*' ('*Payvast*'), '*Deghnanush*', '*Deghnanush Late Ripening*', '*Gargar*', '*Karmreni*', '*Ordubadi*', '*Sateni*', '*Shlor-Tsiran*') were included. Seedlings for morphological assessment were grown from seeds collected near Voghchaberd village, Kotayk Province (40°06'26.7"N, 44°39'51.9"E, 1238 m a.s.l.). Herbarium (ERE) specimens of the A. Takhtajan Institute of Botany NAS RA, together with material from the authors' field collections were examined. Published descriptions of wild apricot forms from Dagestan were also incorporated for comparative analysis [2–5].

Phenotyping. Morphological characterization followed UPOV descriptors (TG/70/5) [45] and included tree architecture and leaf, flower, fruit, and stone traits. Measurements were performed in triplicate on five trees per replicate. Phenological observations were conducted during 2022–2025. Stone traits and kernel bitterness were assessed following standard protocols [10, 16], and yield and quantitative traits were analyzed using established methods [28; 33]. Detail morphological studies were made with an MBC-9 stereomicroscope.

Floral Morphology, Pollen Fertility and Viability. Pollen fertility and germination were assessed using friable flower buds. Fertility was determined on acetocarmine-stained slides [38] by counting 100 grains per slide in three replicates, distinguishing fertile (uniformly stained) from sterile (unstained or partially stained) grains. Pollen germination was evaluated in 20% sucrose solution [23] after 24 h incubation on slides placed in Petri dishes with moistened filter paper. The proportion of germinated grains and pollen tube lengths were

measured under a PZO Warszawa microscope at $\times 250$ magnification. Stigma position relative to anthers was recorded on at least 30 flowers per tree, and the style-to-stamen length ratio was calculated to assess potential for self- and cross-pollination. Data were processed using Microsoft Excel.

Statistical Analysis. Qualitative and quantitative stone traits were analyzed using K-means clustering, hierarchical clustering (UPGMA), and PCA in Statistica 13.3, R 4.3.3, and PAST 4.17. The optimal number of clusters was determined via the GAP statistic [43] in R [14]. Arithmetic means and percentage gradations were calculated to minimize standard errors, which ranged from 1.0 to 5.7% and remained below the 5% threshold commonly accepted in agronomy; thus, mean values were considered reliable at the 95% confidence level.

Fruit Biochemical Assessment. A comparative study evaluated the biochemical traits of the 'Kharji' landrace and local apricot cultivars ('Degnanush Late-Ripening', 'Gargar', 'Ordubadi', 'Abutalibi' ('Payvast'), 'Degnanush', 'Shlor-Tsiran'). Assessed parameters included fruit pulp ash, organic acids (oxalic, tartaric, malic, citric, succinic), sugars (fructose, glucose, sucrose), vitamin C, and antioxidant capacity. Analyses were performed using high-performance liquid chromatography and standard physicochemical techniques [19; 27; 42; 44]. Antioxidant activity was determined by titration with potassium permanganate in sulfuric acid at room temperature, providing an integrated measure of biologically active compounds [13].

Results and discussion

Tree habit, leaf, flower phenotypic characteristics by UPOV (TG/70/5).

The 'Kharji' apricot landrace shows marked morphological variability. Trees are medium to large (3.5–10 m), upright to spreading (Note 3), with numerous branches (Note 5) and crowns ranging from rounded or pyramidal to irregular; mature trees often form tent-shaped canopies up to 8 m. Bud support is small to medium (Note 1–2), and flower buds mainly develop on one-year-old shoots (Note 3). Leaves are broadly ovate to ovate-rounded, occasionally cordate or truncate at the base, narrowing at the apex; blades are light green, glabrous or slightly pubescent, thin, shiny, with single- or double-serrate margins. Petioles are medium to long (Note 6), medium in thickness (Note 2), with weak to medium anthocyanin coloration (Note 4). The variability in tree habit, crown architecture, and vegetative traits of the 'Kharji' landrace reflects adaptation to heterogeneous mountain environments, characterized by sharp altitudinal gradients, variable exposure, and limited soil resources. Such plasticity in growth form and canopy structure is particularly advantageous in mountainous land-

scapes, where microclimatic conditions can vary substantially over short distances. '*Kharji*' lowers are mostly solitary, rarely paired, nearly sessile, 25–30 mm in diameter, with cylindrical greenish-red hypanthia and five dark red reflexed sepals. Petals are circular to widely obovate, white or slightly pinkish (Note 1, 3), with 2–3 nectaries per flower (Note 2). Stigmas are positioned above or occasionally below the anthers (Note 3). Detailed traits are summarized in Table 1.

Table 1.

Tree, leaf, petiole, flower traits of '*Kharji*' landrace by UPOV, 2021

TG/70/5 code	Trait	Observation	UPOV state (Notes)
1	Tree habit	Upright to spreading	3
2	Number of branches	Many	5
3	Size of bud support	Small to medium	1–2
4	Distribution of flower buds	Predominantly on one-year-old shoots	3
14	Leaf blade color (upper side)	Light to medium green	2
15	Leaf base shape	Obtuse	2
16	Leaf base angle	Right-angled	2
17	Leaf margin incisions	Serrate or biserrate	3–4
20	Petiole length	Medium to long	6
21	Petiole thickness	Medium	2
22	Petiole upper side anthocyanin coloration	Weak to medium	4
30	Petal color	White or slightly pinkish	1
31	Petal shape	Circular to widely obovate	3
34	Number of nectaries per flower	Two or three	2
28	Flower diameter	Small to medium	2
33	Stigma position relative to anthers	above the anthers or sometimes lower	3

Seedling traits. Seedlings of the '*Kharji*' landrace were monitored to characterize early morphological development (Table 2). Seed germination was observed during the third ten-day period of March. Seedlings possessed fleshy, reddish cotyledons that remained underground or only slightly emerged above the soil surface. The leaves alternate, glandular-finely or unevenly serrated, with petioles shorter than half of the blade length. Pronounced heterophylly was recorded from the 1st to the 8th leaf, after which leaves (from the 9th node onward)

became uniform in shape. Venation loop-shaped, with 3–4 pairs of lateral veins oriented obliquely upward at approximately 45°, slightly reddish in coloration. Stipules linear to narrowly triangular and glandular-ciliate. Seedlings light-green, stems cylindrical, up to 2 mm in diameter at the base, green with a reddish tip. The early manifestation of heterophylly and variation in seedling morphology indicates high developmental plasticity of the ‘*Kharji*’ landrace at juvenile stages.

Table 2.

Leaf Morphology and Morphometric Variation in ‘*Kharji*’ Apricot Seedlings

Leaf no.	Leaf blade Shape	Blade Length × Width (mm)	Petiole length (mm)	Notes
1	Lanceolate	4.5 × 2.5	2.0	Glandular-finely or unevenly serrated
2	Elliptical	6 × 5	2.3	Pointed at tip
3-4	Oval	11–17 × 6–10	4-6	Bluntly rounded tip, basely broadly rhombic
5-7	Oval	18–28 × 10–17	5-7	Slightly narrowed at tip
8	Ovate	32 × 24	7	Narrowed at tip
9+	Widely-ovate	48–52 × 30–38	8–10	Distinctly narrowly elongated at tip, obtuse or truncate at the base

Note: Leaf numbers correspond to sequential nodes during early seedling development. Shape terminology follows standard botanical descriptors.

Flower structural features, pollen fertility and viability. Reproductive traits in apricot are strongly influenced by flower structure, particularly the stigma position relative to the anthers, which affects self-fertility [45]. Wild apricots and varieties of the Central Asian and Iranian-Caucasian groups are generally autosterile, whereas European and North American cultivars are often autofertile [12; 16; 29]. Autosterility is associated with a style length exceeding stamen length, as even a 2–3 mm excess limits pollen deposition on the stigma [12]. In ‘*Kharji*’, flowers exhibited substantial variation in style and stamen length (Table 3). Style length ranged from 7.0 to 16.8 mm, stamen length from 5.4 to 11.8 mm, and the number of stamens per flower from 19.7 to 36. The style-to-stamen length ratio varied from 1.06 to 2.05, indicating prevalent herkogamy. Most samples showed a significant style length excess, while nearly equal style and stamen lengths suggested potential self-fertility in some cases. The observed diversity in floral morphology, including variability in stigma–anther relationships and pollen fertility, suggests that the ‘*Kharji*’ landrace maintains flexible reproductive strategies. In mountain territories, where weather condi-

tions during flowering are often unpredictable, such reproductive variability may increase the probability of successful fertilization across years, thereby contributing to population persistence and long-term stability.

Table 3.

Characteristics of *Prunus armeniaca* 'Kharji' landrace flowers by the quantity of stamens and the ratio of the style and stamen lengths

№	Style length, mm	Stamen length, mm	Quantity of stamens	Length ratio between style and stamens
1	7.0 ± 0.44	6.4 ± 0.22	19.7 ± 1.48	1.09
2	12.5 ± 1.09	11.4 ± 1.03	30.0 ± 0.72	1.10
3	12.0 ± 0.75	11.3 ± 0.15	32.8 ± 0.60	1.06
4	16.0	9.50 ± 0.38	32.4 ± 0.40	1.68
5	15.3 ± 0.38	10.3 ± 0.28	30.0 ± 0.50	1.49
6	12.0	8.3 ± 0.23	34.4 ± 0.80	1.45
7	16.8 ± 0.25	11.8 ± 0.18	31.0 ± 1.09	1.42
8	15.5 ± 1.09	8.5 ± 0.36	36.0	1.82
9	11.0	7.5 ± 0	27.0 ± 1.08	1.33
10	11.0	6.3 ± 0.27	29.0 ± 0.72	1.75
11	12.0	6.6 ± 0.30	33.2 ± 0.90	1.82
12	13.0	7.5 ± 0.54	30.0	1.73
13	10.0	5.4 ± 0.60	31.5 ± 3.5	1.85
14	$11.5 \pm 0,36$	$5.6 \pm 0,24$	$26.3 \pm 2,35$	2.05
15	10.0	$6.8 \pm 0,20$	$22.7 \pm 0,78$	1.47

Pollen fertility and pollen grain size were assessed in 24 samples of the 'Kharji' landrace. Considerable variability in pollen fertility was observed among the samples. Fourteen samples (58.3%) exhibited very high fertility (90.9 ± 1.1 to $98.2 \pm 0.7\%$), four samples ranged from 82.0 ± 2.5 to $87.0 \pm 1.5\%$, three samples from 63.3 ± 5.6 to $76.8 \pm 2.9\%$, and the remaining three samples showed only 48.1 ± 1.9 to $59.3 \pm 3.4\%$ fertile pollen grains. In 14 samples, 0.2–5.2% of pollen grains were partially stained, indicating disturbances during microsporogenesis. Pollen grain diameter also varied among the samples, ranging from 42.4 to 55.8 μm . According to Golubinsky [23], such variation may result from environmental factors (temperature, humidity) or physiological conditions (nutrient availability related to flower position) during pollen development. No correlation between pollen fertility and pollen grain size was detected across the 24 samples ($r = -0.10835$). Hambartsumyan et al. [24] reported that pollen of wild apricot forms exhibits higher fertility and viability compared with lo-

cal cultivated varieties, likely reflecting long-term natural selection under environmental conditions. Comparative assessment of several cultivated varieties in Armenia showed consistently high pollen fertility: 'Gargar' $97.2 \pm 0.8\%$, 'Degnanush' $97.6 \pm 0.6\%$, 'Karmreni' $98.6 \pm 0.6\%$, 'Sateni' $89.1 \pm 3.9\%$, and 'Abutalibi' ('Payvast') $93.2 \pm 2.3\%$, while 'Ordubadi' showed reduced fertility ($49.8 \pm 5.9\%$). The non-selected 'Kharji' landrace fell within the high-fertility range of 'Gargar', 'Karmreni', and 'Abutalibi'. Thus, high-fertility forms and, less frequently, low-fertility forms are found in both the 'Kharji' landrace and among cultivated varieties, which is consistent with the findings of Nebish et al. [37]. The presence of highly fertile pollen in a majority of 'Kharji' samples, comparable to or exceeding that of several cultivated varieties, is particularly important for mountain horticulture, where pollination success is frequently constrained by low temperatures and short flowering periods.

The pollen grains of three 'Kharji' landrace samples were evaluated for in vitro germination and pollen tube growth. Two samples with 95.6% and 94.6% fertility germinated at 81.5% and 80.0%, respectively, and had a long pollen tubes (1450–1750 μm). In contrast, one sample with the 48.1%-fertile pollen grains showed low germination (16.0%), and shorter pollen tubes (175–1050 μm). Similar relationships between pollen fertility and germination have been reported in works on apricot and peach [31; 32].

Fruit and endocarp phenotypic characteristics. Analysis of fruit traits revealed substantial phenotypic diversity within the 'Kharji' landrace. Skin color ranged from white and greenish to golden, orange, and red, with variation in pulp firmness and pigmentation. Flesh was typically firm, fibrous, light- to dark-orange, sweet with slight bitterness, while kernel taste varied from sweet to bitter. According to UPOV descriptors (TG/70/5) [45], fruits were predominantly circular (note 4), slightly asymmetric (note 2), with a strong suture (note 4), rounded apex (note 2), and weakly depressed pistil end (note 3). Fruit and stone traits are shown in Figure 1.

The fruit ripening period of the 'Kharji' landrace mainly extends from mid-June to late July, although some clones mature as late as September. Fruits are small, with total weight (fruit plus stone) ranging from 6.89 to 16.84 g, stones from 1.24 to 1.81 g, and pulp from 5.65 to 15.34 g, considerably lower than most cultivated varieties. Such reduced fruit size and pulp mass are typical of apricots adapted to mountain and semi-arid environments, where resource allocation favors survival and reproductive assurance over large fruits. The extended ripening in some clones may provide an adaptive advantage by spreading reproductive risk under variable mountain climatic conditions.

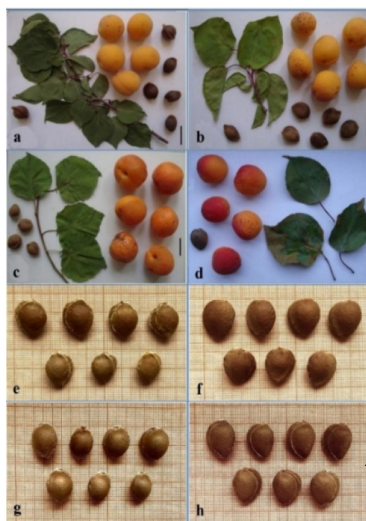


Fig. 1. '*Kharji*' apricot leaves, fruits, stones, collected from Kotayk (a, b, e, f) and Vayots Dzor (c, d, g, h) provinces of Armenia (scale bar 10 mm)

Apricot varieties can be identified by their endocarp characteristics, which, in combination with other morphological traits, can be used to address questions of varietal origin and classification [9]. Given the importance of endocarp traits for apricot identification, the present study focuses on the endocarp characteristics of the Armenian apricot landrace '*Kharji*' (Table 4).

Within the Caucasus region, Dagestan represents another major center of apricot cultivation and diversity, where both cultivated and wild populations persist under arid environmental conditions [7; 8; 34]. At present, cultivated apricot orchards in Dagestan occupy approximately 4470 hectares [17]. Wild populations are primarily distributed along river valleys at elevations of 350–1500 m a.s.l., and in some locations extend up to 1900 m on limestone slopes. In addition, local cultivation practices preserve apricot varieties that are genetically closely related to wild forms [10].

In order to place the endocarp characteristics of the Armenian apricot landrace '*Kharji*' in a broader regional context, Table 4 also presents comparative data on natural apricot populations in Dagestan.

Statistical analyses confirmed data reliability, with relative errors ranging from 1.0% to 5.7%, within acceptable limits for agronomic studies and providing 95% confidence.

Table 4.

Comparative quantitative and qualitative traits of endocarp, leaf, and yield in the Armenian apricot landrace 'Kharji' and wild apricot populations from Dagestan

The traits of the endocarp	Gradation	Statistical significances (Mean or group % for quality traits ± SE or Sp)	
		Armenia	Dagestan
Quantitative			
Yield (n=30)			(n=60) (Anatov, 2024a)
General, kg per tree	Commercial yield	20.9±0.6	59.7±12,14
Leaf (number of samples 88)			(n=120) (Anatov et al., 2018)
Lenght, cm	From min to max (1.1-8.5)	4.8±0.2	5.9±0.05
Width, cm	From min to max (1.0-9.0)	4.1±0.2	5.0±0.05
Surface, cm²	From min to max (1.0-56.5)	15.4±1.0	21.3±0.40
Petiole length, cm	From min to max (1.0 - 4.5)	2.3±0.1	2.7±0.03
Stone (n=101)			(n=90) (Anatov, 2024b)
Lenght, mm	From min to max (10.0-24.0)	19.7±0.2	18.6±0.30
Width, mm	From min to max (10.0-22.0)	15.9±0.2	14.7±0.22
Thickness, mm	From min to max (5.0-14.0)	10.1±0.2	10.1±0.12
Volume, mm³	From min to max (502.1-3012.5)	1661.5±55.4	1492.0±61.0
Qualitative (n=101)			p±Sp (n=328) (Anatov, 2019)
Size, %	Very small	9.9±3.0	36.9±2.7
	Small	52.5±5.0	38.1±2.7
	Medium	34.7±4.7	21.0±2.2
	Large	3.0±1.7	4.0±1.1
Shape, %	Round	36.6±4.8	29.0±2.5
	Ellipsoidal	28.7±4.5	14.0±1.9
	Egg-shaped	33.7±4.7	38.1±2.7
	Oblong	1.0±1.0	11.9±1.8
	Semi-heart-shaped	NA	4.9±1.2
	Teardrop-shaped	NA	2.1±0.8

Symmetry, %	Symmetric	92.1±2.7	45.1±2,8
	Asymmetric	7.9±2.7	54.9±2,8
Base shape, %	Narrowed	43.6±4.9	50.9±2.8
	Wide	56.4±4.9	49.1±2.8
Base hole shape, %	Horizontal	80.2±4.0	36.9±2.7
	Beveled	6.9±2.5	48.8±2.8
	Funnel-shaped	13.9±3.4	14.3±1.9
Top shape, %	Sharp	16.8±3.7	38.1±2.7
	Round with small pointed	80.2±4.0	NA
	Blunt	3.0±1.7	61.9±2.7
Character of the keel, %	Uniform	82.2±3.8	33.5±2.6
	Medium	5.9±2.4	12.2±1.8
	Shifted to the base	9.9±3.0	24.4±2.4
	Shifted to the top	2.0±1.4	29.9±2.5
Keel height, %	Small	4.0±1.9	25.9±2,4
	Medium	74.3±4.4	37.5±2,7
	Large	21.8±4.1	36.6±2,7
Keel shape, %	Sharp	100.0	86.9±1,9
	Blunt	NA	13.1±1.9
Keel surface, %	Smooth	97.0±1.7	NA
	Serrated	3.0±1.7	NA
Side ribs, %	Sulcate	NA	25.9±2.4
	Not developed	9.9±3.0	29.0±2,5
	Poorly developed	21.8±4.1	29.2±2.5
	Highly developed	68.3±4.6	15.9±2.0
Side ribs type, %	Sharp	79.2±4.0	NA
	Blunt	10.9±3.1	NA
	Striated	NA	NA
	Flat	9.9±3.0	NA
Dorsal seam, %	Closed along the entire length	5.0±2.2	19.5±2,2
	Closed in the middle part	3.0±1.7	NA
	Interrupted	33.7±4.7	45.7±2,8
	Open at the base	46.5±5.0	3.0±0,9
	Open at the top	7.9±2.7	25.9±2,4
	Open along the entire length	7.9±2.7	5.8±1,3
Coloring, %	Light brown	85.1±3.5	48.8±2,8
	Dark brown	15.8±3.6	51.2±2,8

Surface, %	Flat	66.3±4.7	13.7±1,9
	Slightly rough	NA	NA
	Very rough	NA	NA
	Slightly wrinkled	12.9±3.3	50.3±2,8
	Heavily wrinkled	NA	33.8±2,6
	Finely pitted-tubercular	19.8±4.0	2.1±0,8
	Coarse pitted-tubercular	NA	NA
Weight, %	Very light (< 1.1g)	NA	23.0±2,3
	Light (1.1 - 2.0 g)	53.5±5.0	71.7±2,5
	Medium (2.1 - 3.0g)	40.6±4.9	5.2±1,2
	Heavy (3.1- 4.0g)	5.9±2.4	0.1±0,5
	Very heavy (> 4g)	NA	NA

Note: NA – not available values

Stones of the 'Kharji' apricot exhibited pronounced intra-landrace variability. Mean dimensions were 19.7 ± 0.2 mm in length, 15.9 ± 0.2 mm in width, 10.1 ± 0.2 mm in thickness, with an average volume of 1661.5 ± 55.4 mm³. Medium-sized stones predominated ($34.7 \pm 4.7\%$), with small ($52.5 \pm 5.0\%$) and very small ($9.9 \pm 3.0\%$) stones also common. Stone shapes were round ($36.6 \pm 4.8\%$) and ovoid ($33.7 \pm 4.7\%$) mainly, followed by ellipsoidal ($28.7 \pm 4.5\%$); oblong stones were rare ($1.0 \pm 1.0\%$). Most stones were symmetrical ($92.1 \pm 2.7\%$), with wide ($56.4 \pm 4.9\%$) or narrow bases ($43.6 \pm 4.9\%$), horizontal basal holes ($80.2 \pm 4.0\%$), and rounded apices with a small point ($80.2 \pm 4.0\%$). All stones had a sharp keel, evenly positioned in $82.2 \pm 3.8\%$, with medium height prevailing ($74.3 \pm 4.4\%$).

Surfaces were mostly flat ($66.3 \pm 4.7\%$), while $19.8 \pm 4.0\%$ were fine pitted-tubercular; dorsal sutures were open at the base ($46.5 \pm 5.0\%$) or interrupted ($33.7 \pm 4.7\%$). Stone color was predominantly light brown ($85.1 \pm 3.5\%$). Weight distribution favored light ($53.5 \pm 5.0\%$) and medium stones ($40.6 \pm 4.9\%$), with heavy stones (3.1–4.0 g) rare ($5.9 \pm 2.4\%$). Qualitative analysis of 82 samples, each with a unique combination of traits, indicated two optimal clusters according to the GAP statistic, visualized by PCA (Figure 2).

The first two PCA axes explained 30.4% of total variance, reflecting high phenotypic diversity. Cluster 1 (70 samples) included two groups: Cl.1.1 (24 samples) with symmetrical, elliptical stones, narrow base, dorsal suture open at the base, medium-height keel, smooth surface, showing affinity to Armenian 'Yerevani' ('Shalakh'); Cl.1.2 (30 samples) with predominantly rounded, medium-sized stones, wide base, and poorly developed or absent lateral ribs. Cluster 2 (12 samples) comprised small, ovoid stones with sharp apex, well-developed

keel, intermittent dorsal suture, slightly wrinkled surface, and a distinctive funnel-shaped basal aperture, indicating a relatively “wild” morphotype. The coexistence of cultivated-like and wild-type stones confirms ‘Kharji’ as a semi-wild landrace, typical of mountain regions where gradual domestication and traditional cultivation maintain high genetic and phenotypic diversity.

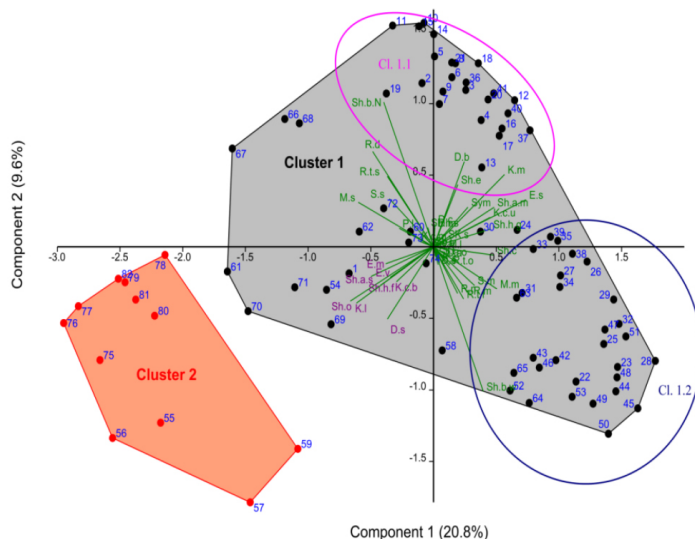


Fig. 2. Principal component analysis (PCA) of qualitative traits of the *Prunus armeniaca* ‘Kharji’ landrace endocarp

Note: S.v – Size Very Small; S.s – Size Small; S.m – Size Medium; S.l – Size Large; Sh.c – Shape Round; Sh.e – Shape Elliptical; Sh.o – Shape ovate; Sh.l – Oblong shape; Sym – Symmetrical (presence of symmetry); Sh.a.s – Acute apex shape; Sh.a.m – Rounded apex shape with a small point; Sh.a.o – Blunt apex shape; Sh.b.N – Narrowly rounded base shape; Sh.b.w – Widely rounded base shape; Sh.h.g – Base opening shape Horizontal; Sh.h.s – Base opening shape Beveled; Sh.h.f – Base opening shape Funnel-shaped; K.s – Small keel height; K.m – Medium keel height; K.l – Large keel height; K.c.u – Uniform keel character; K.c.m – Median keel character; K.c.b – Keel character Shifted toward the base; K.c.a – Keel character Shifted toward the apex; SK.s – Surface of keel Smooth; R.n – Lateral ribs Not developed; R.m – Lateral ribs Weakly developed; R.d – Lateral ribs Strongly developed; R.t.s – Type of lateral ribs Sharp; R.t.o – Type of lateral ribs Obtuse; R.t.f – Type of lateral ribs Smooth; D.c – Dorsal suture Closed along entire length; D.m – Dorsal suture Closed in middle part; D.s – Dorsal suture Interrupted; D.b – Dorsal suture Open at base; D.a – Dorsal suture Open at apex; D.o – Dorsal suture Open along entire length; E.s – Surface Smooth; E.m – Surface Slightly wrinkled; E.v – Surface Strongly wrinkled; P.l – Color of bone Light brown; M.s – Small Mass; M.m – Medium Mass; M.l – Large Mass.

Comparison of the '*Kharji*' landrace with natural apricot populations from Dagestan revealed both shared and region-specific traits (Table 4). Tree productivity was higher in Dagestan (59.7 kg) than in Armenia (20.9 kg). Leaves were larger in Dagestan, but rounded leaf forms were similar in both regions (85%), reflecting their Iranian–Caucasian origin. Stones were slightly larger in Armenia, with fewer very small and small stones (62.9% vs. 75% in Dagestan), while round and ovoid forms predominated in both regions. Symmetrical stones were more frequent in Armenia, whereas symmetry and asymmetry were equally common in Dagestan. Basal apertures differed, with horizontal bases prevailing in Armenia and beveled bases in Dagestan. Overall, these patterns reflect shared origin alongside region-specific influences of cultivation history, population age, and environmental conditions.

Fruit Biochemical Evaluation. From a technological perspective, fruits of the apricot landrace '*Kharji*' are well suited for fresh consumption, processing, canning, and drying. Notably, '*Kharji*' has previously been used in the production of the canned apricot product "Nectar", which incorporates both juice and pulp, and is characterized by a distinct aroma and elevated levels of vitamins [35].

The fruits of the '*Kharji*' landrace were characterized by relatively low mass: the average fruit weight with stone ranged from 6.89 g to 16.84 g, while the stone mass varied from 1.24 g to 1.81 g. The average pulp mass ranged between 5.65 and 15.34 g, which is considerably lower than that of most cultivated varieties.

The comparative biochemical profiling of the landrace '*Kharji*' and local cultivated apricot varieties reveals pronounced metabolic differences that reflect both genetic differentiation and domestication-driven trait selection (Table 5). '*Kharji*' samples demonstrated markedly higher variability across all organic acids. Citric acid ranged from 2.400 to 9.999 mg/ml and malic acid from 1.880 to 10.800 mg/ml, substantially exceeding the values in cultivated varieties, where malic acid remained below 0.022 mg/ml and citric acid did not exceed 0.011 mg/ml.

Tartaric acid levels were also higher and more variable in the unselected '*Kharji*' genotypes (2.340–3.200 mg/ml) compared with the cultivated varieties (0.001–0.004 mg/ml). Succinic acid, absent in all cultivated varieties, appeared only in one '*Kharji*' sample (2.694 mg/ml), indicating the presence of genotype-specific metabolic pathways within non-selected populations. Such unique metabolic signatures may reflect evolutionary diversification in local germplasm, potentially contributing to stress tolerance and ecological fitness in mountain environments. Carbohydrate profiles further underscored the differentiation between landrace form and cultivated varieties. '*Kharji*' showed greater variation in fructose (0.778–1.905% w/v) and glucose (1.186–3.262% w/v), although sucrose content remained moderate

(7.655–14.342% w/v). In contrast, cultivated varieties accumulated substantially higher sucrose concentrations, most notably in ‘*Ordubadi*’ (19.721% w/v) and ‘*Degnanush*’ (11.750% w/v), reflecting selection toward sweeter, more palatable fruits. Only the cultivar ‘*Shlor-Tsiran*’ lacked detectable sucrose.

Table 5.

Fruit Biochemical Traits of the ‘*Kharji*’ Landrace and Local Apricot Cultivars

Apricot samples	Oxalic acid mg/ml	Tartaric acid mg/ml	Malic acid mg/ml	Citric acid mg/ml	Succinic acid mg/ml	Fructose % w/v	Glucose % w/v	Sucrose % w/v	Vitamin C % w/v	Antioxidant activity mg/g
1. ‘ <i>Khardji</i> ’	Nd	2.490	1.880	2.400	Nd	0.778	1.186	7.655	0.0054	2,45
2. ‘ <i>Khardji</i> ’	0.130	3.200	5.997	9.999	Nd	1.689	2.534	8.742	0.0046	8,75
3. ‘ <i>Khardji</i> ’	Nd	Nd	Nd	Nd	Nd	1.905	3.262	14.342	0.0054	3,50
4. ‘ <i>Khardji</i> ’	0.360	2.340	10.800	9.350	2.694	1.799	2.965	11.556	0.0090	17,5
5. ‘ <i>Degnanush Late Ripening</i> ’	Nd	Nd	0.015	0.0004	0.008	0.640	2.085	7.638	0.0022	3,89
6. ‘ <i>Gargar</i> ’	Nd	0.004	0.022	0.002	0.001	1.766	2.966	10.587	0.0125	8,75
7. ‘ <i>Ordubadi</i> ’	Nd	0.003	0.007	0.006	Nd	1.661	2.623	19.721	0.0145	12,92
8. ‘ <i>Abutalibi</i> ’	Nd	0.0014	0.013	0.002	Nd	0.374	1.720	5.952	0.0079	4,375
9. ‘ <i>Degnanush</i> ’	Nd	0.002	0.003	0.006	Nd	0.797	1.526	11.750	0.0052	4,308
10. ‘ <i>Shlor-Tsiran</i> ’	Nd	0.001	0.010	0.011	0.005	1.935	3.368	Nd	0.0182	4,615

Note: Samples 1–2: Kotayk province; 3–4: Vayots Dzor province; 5–10: Armavir province, RA. Nd – not detected.

Vitamin C levels were generally low in ‘*Kharji*’ landrace (0.0046–0.0090% w/v), while cultivated varieties exhibited greater variability and in some cases higher content, with ‘*Shlor-Tsiran*’ showing the maximum value (0.0182% w/v). Antioxidant activity distinguished several landrace genotypes: values ranged from 2.45 to 17.5 mg/g, with the highest activity in the ‘*Kharji*’ sample from Vayots Dzor (village Khndzorut). Cultivated varieties displayed moderate activity (3.89–12.92 mg/g), with ‘*Ordubadi*’ achieving the upper range. Comparable results were obtained in wild apricot populations of Jammu and Kashmir, where wild accessions demonstrated significantly higher phenolic content and antioxidant potential than cultivated varieties [47], reinforcing the general trend observed in ‘*Khardji*’ landrace. Ash content in ‘*Khardji*’ fruits was low (0.039–0.11 g), with the highest value observed in samples from Vayots Dzor (village Zaritap). Cultivated varieties showed consistently higher mineraliza-

tion (0.132–0.26 g), reaching a maximum in '*Abutalibi*' ('*Payvast*') (0.26 g). Cultivated genotypes were markedly more mineral-rich than the more variable, low-ash '*Kharji*' samples. Overall, the dataset highlights that '*Kharji*' landrace apricots retain high metabolic diversity and elevated organic acid and antioxidant levels, whereas cultivated varieties exhibit reduced acidity, increased sugar accumulation, and in some cases enhanced vitamin C content. The elevated levels of organic acids and antioxidant activity detected in '*Kharji*' fruits may be associated with enhanced tolerance to abiotic stress factors prevalent in mountain environments, such as high solar radiation, temperature fluctuations, and water deficit. From a sustainable development perspective, these biochemical traits increase the functional and nutritional value of '*Kharji*' fruits and support their potential use in niche and value-added products from mountain regions.

Terrace Horticulture and *Ex Situ* Collections in the Conservation of the '*Kharji*' Landrace. The last century has seen a major abandonment of traditional horticultural practices, such as terrace gardening, in Armenia and the whole Caucasus. Lowland melioration practices and the larger switch from dry fruit-oriented apricot cultivation to intensive fresh fruit-oriented large-scale apricot horticulture have moved many heirloom apricot varieties and old local landraces to the borders of oblivion and disappearance. The '*Kharji*' landrace, nevertheless, has been still conserved as a valuable rootstock source for grafting and fruit utilization. Recent challenges related to climate change, scarcity of water resources, and the intensification and expansion of agriculture beyond the lowlands have reawakened interest in previous horticultural practices, such as mountain terrace gardening, in combination with modern technology as a perspective approach for sustainable land use and recultivation of once abandoned and widely distributed dry slope areas in the lower and middle mountain belts of Armenia, as well as for the diversification of apricot production. This new reality highly urges the conservation of once-abandoned heirloom varieties and old landraces, such as '*Kharji*', both in situ (natural habitats, traditional and terrace orchards) and ex situ (botanical gardens and gene banks), as such landraces are critical not only for biodiversity preservation but also for maintaining cultural and agricultural heritage in mountain regions. Conservation and sustainable utilization of this germplasm will support resilient horticultural systems adapted to local conditions and contribute to long-term strategies for the sustainable development of mountain agricultural landscapes.

The *ex situ* collection of the '*Kharji*' apricot at the Yerevan Botanical Garden was studied alongside in situ observations from natural populations and traditional orchards. Established progressively since 2013, it comprises plant materi-

al derived from seeds and transplanted seedlings collected across the landrace's natural habitats and traditional cultivation areas. The collection enables long-term monitoring of key agronomic and adaptive traits. Each accession was registered with standard passport descriptors, including collection site, year, geographic coordinates, elevation, and propagation method, ensuring traceability. At the time of evaluation, the collection included fruiting trees as well as individuals at various vegetative stages. The presence of accessions at different developmental stages allows long-term assessment of phenology, reproductive stability, and trait expression under uniform conditions. The living collection also serves as a source of pollen and donor material for cuttings, suitable for grafting and propagation. Complementing the living collection, seeds have been deposited in the Seed Bank of the Department of the Flora of Armenia Genetic Resources Conservation, Institute of Botany, NAS RA with complete passport data. Together, living collections and seed banking offer complementary conservation strategies, ensuring long-term security and accessibility of authentic '*Kharji*' genetic resources for research and horticultural improvement.

Conclusion

This study provides a comprehensive phenotypic characterization of the '*Kharji*' landrace of Armenia, including traits of seedlings, vegetative organs, flowers, fruits, endocarp structure, pollen fertility and viability, and fruit biochemical composition.

'*Kharji*' exhibits high phenotypic variability in vegetative and reproductive traits, indicating intraspecific diversity and adaptability to diverse mountain conditions. Variation in floral structure and pollen characteristics suggests potential for both self- and cross-fertility, enhancing reproductive resilience. Fruit and endocarp morphology revealed two main morphotypes, one resembling cultivated Armenian varieties and another with wild-type features, highlighting the landrace's transitional nature. Comparisons with natural apricot populations of Dagestan suggest a shared Iranian–Caucasian origin, while region-specific differences reflect local adaptation, cultivation history, and population age.

'*Kharji*'s adaptability to high-altitude and dry conditions, combined with late flowering, temperature tolerance, frost and drought resistance, pest and disease resistance, and high pollen viability, make it a promising resource for developing stress-tolerant cultivars with extended fruiting periods and improved quality. Fruits biochemical profiling showed elevated organic acids and antioxidant activity, indicating stress-tolerant and nutritionally valuable traits. Conservation strategies should include ex situ collections in botanical gardens and gene

banks to safeguard genetic resources and ensure accessibility for research and breeding. Terrace orchards in mountainous regions further support conservation by maintaining traditional cultivation practices and favorable growing conditions, enabling the survival and fruit production of 'Kharji' in highland areas.

Future work should include molecular characterization to clarify genetic structure and evolutionary relationships within the *P. armeniaca* complex, expanding geographical sampling to further assess adaptability and resilience. Long term breeding programs incorporating local landraces like 'Kharji' are essential to ensure the conservation and effective use of these valuable genetic resources in the face of global environmental change and for the sustainable development of mountain agricultural systems.

Description of the application of the generative model. While translating the article from Russian to English, we used OpenAI (2023). ChatGPT (March 14 version) [Large language model]. <https://chat.openai.com/chat>) to correct spelling errors and improve the style of the article in English. After using this service, we reviewed and edited the content as necessary and assume full responsibility for the content of the published article.

Conflict of interest information. The authors declare that they do not have conflict of interest.

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