

## Agromorphological and biochemical diversity of sea buckthorn in Northern Kazakhstan for breeding and conservation

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**Abstract.** Mukan GS, Shadmanova LS, Yeszhanova AS, Kanapin CB, Achatov KZ, Razhanov MR, Sankaibayeva AG, Baimaganbetova MM, Sitpayeva GT. 2026. Agromorphological and biochemical diversity of sea buckthorn in Northern Kazakhstan for breeding and conservation. *Biodiversitas* 27 (1): d270126. <https://doi.org/10.13057/biodiv/d270126>. Sea buckthorn (*Hippophae rhamnoides*), a versatile, dioecious shrub native to Eurasia, exhibits significant ecological and nutritional potential, yet remains underexploited in Kazakhstan despite widespread global utilization. This study evaluated the agromorphological and biochemical diversity of 11 selected forms (as proxies for potential genetic units) from five natural cenopopulations in the North Kazakhstan and Kostanay regions during 2023-2024 to identify elite forms suitable for breeding and commercial production. Field and laboratory assessments analyzed dendrometric, agromorphological, and biochemical traits. Dendrometric measurements revealed variations in bush height (2-4 m) and fruit cluster length (5.55-38.23 cm). Agromorphological fruit traits showed diversity in weight (24.36-48.47 g per 100 berries) and fruiting degree (2-5 points). Biochemical analyses indicated ranges in soluble solids (7.9-12.8%), sugars (1.2-7.5 g/100 g), polyphenols (401-1860 mg GAE/100 g), vitamin C (9.68-105.6 mg/100 g), and antioxidant activity (FRAP: 1.33-10.22  $\mu$ M FeSO<sub>4</sub>/g; DPPH: 18-78%). Cluster analysis identified the KT form as distinct, with superior antioxidant capacity. These findings highlight putative phenotypic divergence in underexplored northern populations, offering valuable resources for developing high-yielding, disease-resistant varieties adapted to harsh climates. The results support strategic breeding programs and advocate for the targeted conservation of unique forms (e.g., KT) to enhance agricultural and ecological resilience in the region.

**Keywords:** Antioxidant traits, breeding resources, cenopopulation, *Hippophae rhamnoides*, phenotypic diversity

### INTRODUCTION

Sea buckthorn (*Hippophae rhamnoides* L.), a dioecious shrub or small tree of the *Elaeagnaceae* family, typically grows to 0.5-3.5 m, occasionally reaching 10 m. This Euro-Asian species is distributed across East and West Asia, as well as Eastern, Central, and Northern Europe, and parts of North America, including Canada (Pop et al. 2014; Li et al. 2020). In Kazakhstan, natural populations thrive in Almaty, Taldykorgan, and East Kazakhstan, primarily in river valleys, floodplains, and erosion-prone northern slopes of the Northern Tien Shan and Zhongar Alatau (Dzhangaliev et al. 2001; Vdovina 2011). The species' ecological polymorphism, driven by climatic factors such as light, humidity, temperature, and ultraviolet radiation, enables its adaptation to diverse environments, from mountainous to coastal zones (Sabir et al. 2005; Li et al. 2020). This plasticity results in significant variation in growth, crown structure, and fruit ripening, making sea buckthorn valuable for reclamation, afforestation, and erosion control (Singh et al. 2003; Ficzek et al. 2019). Its nitrogen-fixing ability and robust root system enhance soil fertility and stability, supporting its use in restoring disturbed landscapes, such as ash dumps and quarries (Bachurina et al. 2020; Korchagin

et al. 2022). In Kazakhstan's Kostanay region, sea buckthorn forms dense thickets in quarries and along roads, demonstrating high winter hardiness and suitability for breeding programs. Beyond its ecological benefits, sea buckthorn fruits are rich in bioactive compounds that support immunity, cardiovascular health, and cancer prevention (Sahin et al. 2002; Li et al. 2021; Chen et al. 2023). These properties underpin its use in functional foods and pharmaceuticals. In northern Kazakhstan, where harsh climates limit local fruit production, wild sea buckthorn serves as a vital source of vitamin-rich fresh produce. Globally, interest in the sustainable exploitation of wild fruit species has increased, emphasizing minimal ecosystem impact (Kaur et al. 2025; Zheng et al. 2025).

Recent international studies, such as Yu et al. 2022 on genomic diversity in Eurasian populations and (Li et al. 2020) on integrated morpho-molecular approaches in China, have improved the understanding of *H. rhamnoides*' biodiversity. Almerikova et al. (2024) used DNA barcoding of ITS sequences to differentiate natural and introduced populations in Kazakhstan, revealing genetic polymorphisms and phylogenetic relationships that inform conservation strategies. Melnikova et al. (2025) employed whole-genome sequencing to assess genetic diversity in Russian varieties,

focusing on fruit traits such as weight and flavor, providing insights into breeding potential. Nybom et al. (2023) combined data on systematics, reproductive biology, and biochemistry, highlighting bioactive compounds and breeding for yield and stress tolerance. These studies emphasize the species' genetic diversity, ecological resilience, and medicinal value, supporting targeted breeding and conservation across its Eurasian range.

Despite its potential, research on sea buckthorn in northern Kazakhstan remains limited, with previous studies focusing on southern regions like Almaty and East Kazakhstan for chemical composition and breeding (Kubczak et al. 2022; Vdovina et al. 2024). Agromorphological and biochemical traits of northern populations, particularly in North Kazakhstan and Kostanay, are underexplored, hindering locally adapted varieties and limiting contributions to agricultural resilience and biodiversity conservation in harsh environments (Gauhar et al. 2025).

This study addressed this gap by evaluating 11 naturally occurring sea buckthorn forms in these regions to identify high-yielding, resilient varieties for breeding. The research objectives included assessing agromorphological traits, analyzing biochemical and antioxidant properties, and comparing these characteristics across forms to test the hypothesis that environmental gradients (e.g., altitude) drive phenotypic divergence in key breeding traits. Based on established selection criteria (Korekar et al. 2014; Pop et al. 2014), the findings aimed to support the development of new varieties, enhancing the utilization of this understudied species in Kazakhstan. By providing comprehensive data on local populations, this study contributed to global knowledge of *H. rhamnoides* and informed sustainable breeding strategies for harsh environments. While this study is primarily phenotypic, future integration with molecular markers (e.g., SSR or SNP) is recommended to validate genetic diversity and distinguish plasticity from putative genetic divergence.

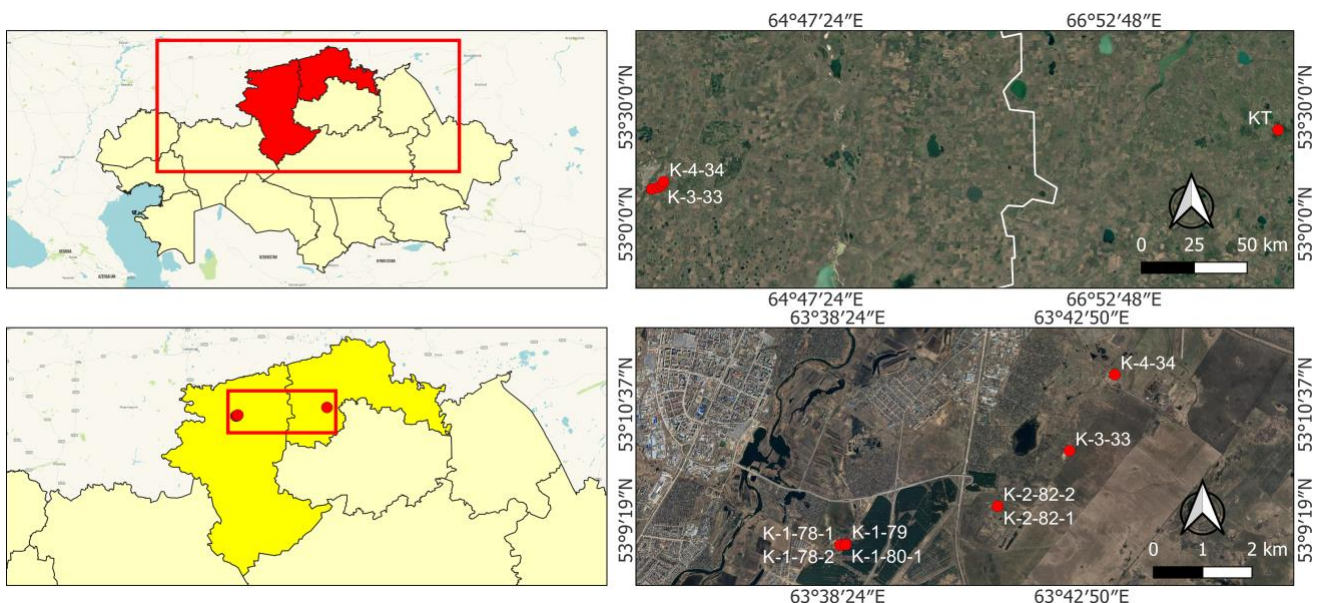
## MATERIALS AND METHODS

### Study area

The research was carried out in 2023-2024 in two administrative regions of northern Kazakhstan: Akmola (State National Natural Park “SNNP “Kokshetau”) and Kostanay (Prigorodnoye Forestry) (Figure 1, Table 1).

SNNP “Kokshetau”, located in the Zerendy District (Akmola Region) and Ayirtau District (North Kazakhstan Region). The park features diverse landscapes, including mountains, freshwater lakes, and forests (pine, birch, and mixed deciduous-coniferous) (Dukenbaeva et al. 2016). The climate is sharply continental, with January temperatures ranging from  $-35^{\circ}\text{C}$  to  $-5^{\circ}\text{C}$  and July temperatures from  $+3^{\circ}\text{C}$  to  $+27^{\circ}\text{C}$ . Annual precipitation varies from 250-310 mm on the plains to 440 mm in the mountainous areas. Spring is short (late April to May), with frequent frosts, while summers are hot and dry, with temperatures occasionally reaching  $38-40^{\circ}\text{C}$ . Most precipitation occurs in early autumn.

Prigorodnoye Forestry, Kostanay Region, is situated at the confluence of the Urals, Western Siberia, and Central Kazakhstan, contributing to diverse natural conditions. The region encompasses forest-steppe in the north, steppe in the center, and semi-deserts in the south. The climate is sharply continental, with January temperatures from  $-18^{\circ}\text{C}$  to  $-8^{\circ}\text{C}$  and July temperatures from  $+19^{\circ}\text{C}$  to  $+25^{\circ}\text{C}$ . Annual precipitation decreases from 390 mm in the north to 159 mm in the south, creating a pronounced aridity gradient. A total of five natural cenopopulations of *H. rhamnoides* representing contrasting ecological conditions (mountain-forest zone at 290 m a.s.l. vs. forest-steppe quarries at 147-207 m a.s.l.) were selected (Figure 1, Table 1). Altitude, soil (loamy vs. sandy), and climate likely shape trait variation, with higher-altitude forms showing stronger antioxidant responses under greater stress.



**Figure 1.** Map showing the distribution of five studied *Hippophae rhamnoides* cenopopulations in Northern Kazakhstan and Qostanay, Kazakhstan

**Table 1.** Geographical locations of *Hippophae rhamnoides* in Northern Kazakhstan

Forms	Forestry	Coordinates		Altitude (m)
		North	East	
KT	Syrymbet	53°24'252	068°01'760	290
K-1-32	Prigorodnoye	53°09'0622	063°38'5524	147
K-1-78-1	Prigorodnoye	53°09'0510	063°38'4453	148
K-1-78-2	Prigorodnoye	53°09'0510	063°38'4453	148
K-1-79	Prigorodnoye	53°09'0635	063°38'5519	155
K-1-80-1	Prigorodnoye	53°09'0559	063°38'5450	157
K-1-80-2	Prigorodnoye	53°09'0559	063°38'5450	157
K-2-82-1	Prigorodnoye	53°09'4832	063°41'3120	207
K-2-82-2	Prigorodnoye	53°09'4832	063°41'3120	207
K-3-33	Prigorodnoye	53°10'1005	063°42'6198	190
K-4-34	Prigorodnoye	53°10'9484	063°43'4440	196

### Plant material

Sea buckthorn (*H. rhamnoides*) was selected for its ecological potential in restoring degraded lands, improving microclimate, promoting soil formation, and supporting soil biota (Korchagin et al. 2022). Its rapid spread is facilitated by root shoots and seed dispersal by birds, forming dense thickets (up to 240,000 plants/ha). One form (KT) was sampled from SNNP “Kokshetau” (Syrymbet Forestry, 290 m altitude), and 10 forms (K-1-32, K-1-78-1, K-1-78-2, K-1-79, K-1-80-1, K-1-80-2, K-2-82-1, K-2-82-2, K-3-33, K-4-34) were sampled from Prigorodnoye Forestry (147–207 m altitude). Geographical coordinates and altitudes are presented in Table 1. Forms were selected as balanced representatives of phenotypic variation within cenopopulations, serving as proxies for population-level diversity; however, they do not represent confirmed genetic units without molecular validation, limiting inferences to phenotypic patterns.

Most forms in Prigorodnoye were located at lower altitudes (147–207 m) compared to the KT form (290 m), enabling comparative analysis of environmental influences on growth. Figure 1 shows the location map of the five studied cenopopulations. The map encompasses eco-geographical variability, with populations selected to represent gradients in altitude (147–290 m), soil types (sandy in the lowlands to loamy in the highlands), and moisture regimes (arid steppe to moderate forest-steppe). Within each cenopopulation, five permanent plots of 10 × 10 m (100 m<sup>2</sup>) were established using stratified random sampling (stratification by microrelief and shrub density). Berries for biochemical analyses were collected from the same marked bushes (3–5 technical replicates per form).

Description of morphological characters was carried out according to the method of V.T. Kondrashov (Kondrashov 1977). All agromorphological measurements were performed on 10 marked female bushes performing at full technological maturity (August–September). Bush height and crown diameters were measured with a telescopic measuring pole (±1 cm); trunk diameter at 10 cm above soil level with a digital caliper (±0.1 mm); 100-berry weight from 3 independent samples of 100 fully colored berries per bush; fruit cluster length-average of 20 clusters per bush; thorniness and fruiting degree scored on a 0–5 scale

on 5 branches per bush. The 0–5 scoring system for thorniness (0: absent, 5: very high) and fruiting degree (0: none, 5: abundant) was adopted for its practicality in field assessments and prior use in similar studies, though its semi-quantitative nature may introduce subjectivity, as discussed in limitations. Ripening date was recorded when ≥90% of berries reached typical color and softness.

### Ecological-phytocenotic and floristic analysis

Each population was characterized by location, area, elevation, community type, shrub age, height, stem diameter, yield, and associated plant species. Plot coordinates and elevation were recorded using a GPS navigator (Garmin eTrex 10). Geobotanical surveys followed established methods (Lavrenko et al. 1972; Beydeman 1974). Shrub age was determined using a borer (Koykov 1980). Yield was calculated by multiplying the average yield of representative bushes by the number of bushes per 100 m<sup>2</sup>, scaled to 1 ha. Plant nomenclature followed POWO (powo.science.kew.org).

### Sample preparation and extraction

To determine total phenolic content (TPC) and total antioxidant activity (TAA) using the DPPH and FRAP methods, berry samples (100 g per bush) were collected, immediately frozen in liquid nitrogen, and stored at -80°C until analysis. Before extraction, frozen berries (10 g) were homogenized in liquid nitrogen. Extraction was performed using 96% (v/v) ethanol. The extract was evaporated to dryness at 40°C in a water bath, and the resulting dry residue was redissolved and used for analysis. All spectrophotometric measurements were performed in triplicate using 96-well round-bottom microplates on a Thermo Scientific Multiskan FC plate reader (Vantaa, Finland). Total phenolic content was determined using the Folin-Ciocalteu method with gallic acid as a calibration standard (detection at 690 nm).

Fresh fruit (fresh weight, FW) was used to determine the content of total sugars, titratable acidity, pectin substances, total vitamin C, catechins, and leucoanthocyanidins. At the same time, antioxidant activity (FRAP, DPPH) and total phenolic content were determined in dry extracts (dry weight, DW). The use of dry extract ensures a standardized sample weight, eliminates variations associated with fruit moisture content, and allows for more accurate assessment of antioxidant levels.

### Biochemical composition analysis

Soluble solids content (SSC)-digital refractometer Hanna (Germany), %, ATC. Total sugars-Bertrand method (Ermakov 1987). Titratable acidity - titration with 0.1 M NaOH to pH 8.1, results as g malic acid/100 g FW. Pectin fractions-carbazole colorimetric method (Zhang et al. 2019). Catechins-vanillin-HCl method; leucoanthocyanidins- butanol-HCl method (Hagerman et al. 2000). Total phenolic content (TPC) Folin-Ciocalteu method, results expressed as mg gallic acid equivalents (GAE)/100 g FW (calibration curve 0–200 µg/mL gallic acid, R<sup>2</sup> = 0.999). Vitamin C-Tillman's titration with 2,6-dichlorophenolindophenol. FRAP and DPPH - exactly as described in Benzie and Strain (1996) and Reis et al. (2012) with ascorbic acid standard.

### Total phenolic content assay

TPC was quantified using the Folin-Ciocalteu method (Hagerman et al. 2000) with modifications. Ethanol extract aliquots (40  $\mu$ L) were mixed with 210  $\mu$ L of 10% sodium carbonate solution, incubated at 38°C for 10 min, followed by the addition of 50  $\mu$ L of Folin-Ciocalteu reagent (diluted 1:6 with ethanol). After 15 min at room temperature, absorbance was measured at 690 nm. TPC was calculated as gallic acid equivalents (mg/g dry extract) using a calibration curve (0.005-0.1 mg/mL).

### DPPH antioxidant assay

The free radical scavenging activity was assessed using the DPPH method (Reis et al. 2012) with modifications. Sample extracts (20  $\mu$ L, diluted 1-0.025) were combined with 300  $\mu$ L of DPPH solution in three microplate wells, with control wells containing 20  $\mu$ L of solvent and 300  $\mu$ L of DPPH. After 30 min at room temperature, absorbance was measured at 517 nm. Ascorbic acid served as the standard.

### FRAP antioxidant assay

The ferric-reducing antioxidant power was evaluated using the FRAP method (Benzie and Strain 1996) with adaptations. The FRAP reagent was prepared by mixing 300 mM acetic acid buffer (pH 3.6), 20 mM FeCl<sub>3</sub>, and 10 mM TPTZ (10:1:1, v/v/v) in 40 mM HCl, warmed at 37°C for 5 min. Sample extracts (35  $\mu$ L) were mixed with 265  $\mu$ L of FRAP reagent, and absorbance was measured at 620 nm after 4 min at 37°C. A 0.8 mM FeSO<sub>4</sub> solution (1:5, v/v) was used as a positive control. FRAP values were expressed as  $\mu$ M FeSO<sub>4</sub>/g dry extract.

### Quality control

Recovery of gallic acid 96.4-102.1%, ascorbic acid 98.7-101.3%; intra-day RSD  $\leq$ 4.2%, inter-day RSD  $\leq$ 6.8%. Blank and positive controls were included in every microplate.

### Statistical analysis

All measurements were performed in 3-10 biological replicates per form. Data are presented as mean  $\pm$  standard error (SE). The normality of data distribution was assessed using the Shapiro-Wilk test, while homogeneity of variances was evaluated with Levene's test. Since both assumptions were met for all traits, parametric methods were applied. Differences among the studied forms were analyzed using one-way analysis of variance (ANOVA) in JASP version 0.18.3, with the significance level set at  $p < 0.05$ . Post-hoc pairwise differences between forms were tested using Fisher's LSD; however, small mean separations should be interpreted cautiously as they may lack biological relevance. Hierarchical cluster analysis in XLStat 2024 (Ward's method, Euclidean distance) generated a dendrogram to visualize relationships among forms based on combined agromorphological and biochemical traits.

Principal component analysis (PCA) was also carried out in XLStat 2024 to reveal patterns of diversity and to determine which traits contributed most to the separation of forms. Variance components were estimated using a random-effects model in JASP 0.18.3. Broad-sense heritability ( $h^2$ )

for key quantitative traits (e.g., fruit weight, total soluble solids, antioxidant activity, etc.) was calculated as  $h^2 = \sigma^2_G / (\sigma^2_G + \sigma^2_E)$ , where  $\sigma^2_G$  is the genotypic variance and  $\sigma^2_E$  is the environmental variance. These estimates assume no genotype-environment interactions and are preliminary, derived from observational phenotypic data; they do not imply narrow-sense genetic parameters without controlled genetic designs such as progeny testing.

Raw data and detailed accession passport data are deposited in the repository of the Institute of Botany and Phytointroduction (Almaty, Kazakhstan) and are available from the corresponding author on reasonable request.

## RESULTS AND DISCUSSION

### Dendrometric variations

Sea buckthorn occupies a small area (0.15 ha) in the SNNP "Kokshetau". The population is rare, with low productivity due to the steppe landscape and continental climate, resulting in stunted bushes (height 2-3 m). In the Kostanay Region, sea buckthorn grows in excavations 1.5-40 m deep, formed during sand mining in the 1980s, supporting dense thickets (500-7000 trunks/ha, with the highest density in young stands). The surface root system with numerous scions forms clumps and impenetrable thickets.

Dendrometric parameters of 11 sea buckthorn forms vary considerably (Table 2). Form K-4-34 has the highest mean height (4.0 m), which is significantly different from all other forms. Forms K-3-33 and K-1-79 have an average height of 3.0 m. Most forms (KT, K-1-32, K-1-78-1, K-1-78-2, K-1-80-1, K-1-80-2, K-2-82-1, K-2-82-2) have an average height of 2.5 m, with no significant differences among them. Trunk diameter ranges from 2 to 14 cm. Habitus types include rounded (3 forms), cone-shaped (1 form), oval (2 forms), spreading (2 forms), and umbrella-shaped (3 forms). Four forms lack thorns (KT, K-1-78-1, K-1-79, and K-3-33), six exhibit medium thorn presence (K-1-32, K-1-78-2, K-1-80-1, K-2-82-1, K-2-82-2, and K-4-34), and one has few thorns (K-1-80-2). The mean fruit cluster length (Figure 2) ranges from 5.55 cm (K-4-34) to 38.23 cm (K-2-82-1), with significant differences among forms ( $F = 56.199$ ,  $p < 0.001$ ). Forms K-2-82-1 and K-2-82-2 have the longest cluster lengths, significantly differing from the others, while K-1-78-1 (16.02 cm) occupies an intermediate position. As shown in Table 2, these dendrometric variations highlight statistically supported patterns in growth and structure across forms.

In Kokshetau SNNP, the population is rare and low-growing, whereas in the Kostanay region, it is dense and productive (Table 3). As shown in Table 3, environmental differences in altitude, soil, and climate contribute to observed variations in population characteristics.

### Ecological-phytocenotic and floristic analysis of sea buckthorn cenopopulations

This study examined the ecological-phytocenotic and floristic characteristics of five sea buckthorn (*H. rhamnoides*) cenopopulations in northern Kazakhstan, focusing on their

roles in ecosystem restoration, species diversity, and productivity. The populations, located in Kokshetau State National Natural Park (SNNP) and the Kostanay region’s Prigorodnoye area, were analyzed for their floristic structure, succession dynamics, and environmental contributions to disturbed landscapes.

*Cenopopulation characteristics and distribution*

The Kokshetau SNNP cenopopulation occupies a compact 0.15 ha area at 290 m above sea level, characterized as a *H. rhamnoides*-grass-*Fragaria viridis* community with an average shrub age of 18 years. This population exhibits moderate productivity (3 points). It supports a diverse herbaceous layer with both forest and steppe species, alongside a tree tier including *Betula pendula*, *Sorbus aucuparia*, and *Malus baccata* (Table 3). In contrast, the cenopopulations in the Kostanay region, located in a disrupted former quarry, demonstrate active natural vegetation restoration. These populations vary in area (5-30 ha), altitude (147-207 m), and age (7.5-32 years), with community types ranging from *Elaeagnus angustifolia*-*H. rhamnoides*-herbaceous communities to mixed herbaceous formations of *H. rhamnoides* and *Salix fragilis*. The tree-shrub layer includes species such as *Pinus sylvestris*, *Ulmus pumila*, *Acer negundo*, and *Lonicera tatarica*. In contrast, the herbaceous layer is dominated by species like *Euphorbia virgata*, *Achillea millefolium*, and *Koeleria cristata* (Table 4).

*Succession dynamics and species diversity*

The cenopopulations exhibit distinct successional patterns reflective of classical ecological succession. Cenopopulation 1, covering the largest area (30 ha), exhibits the highest tree-shrub diversity (7 species), indicative of active succession in a disturbed landscape. The youngest cenopopulation (2, 7.5 years) displays the greatest herbaceous diversity (23 species), suggesting intensive species establishment in early successional stages. Conversely, the oldest cenopopulation (4, 32 years) exhibits the lowest herbaceous diversity (15 species), reflecting the formation of a stable, competitive community dominated by fewer species. These patterns align with ecological theory, where early stages are characterized by high species turnover, and mature stages favor competitive dominance (Connell and Slatyer 1977).

*Productivity and resource allocation*

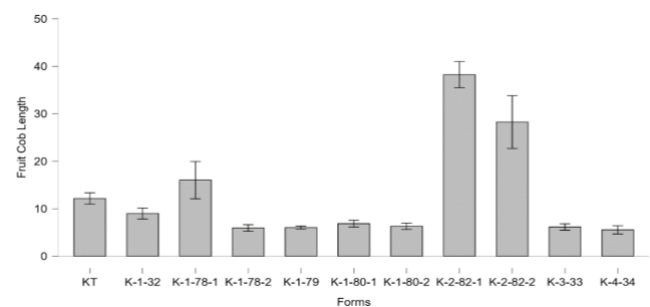
Productivity varies across cenopopulations, with younger populations (1 and 2) achieving higher yields (5 points) compared to older populations (3 and 4, 3-4 points), despite

the latter having larger shrub sizes. This suggests a shift in resource allocation: younger communities prioritize reproductive output for dispersal and establishment, while mature communities allocate resources toward vegetative growth and spatial competition. The high productivity in younger cenopopulations highlights sea buckthorn’s role in facilitating rapid ecosystem recovery in disturbed areas.

**Table 2.** Dendrometric parameters of model *Hippophae rhamnoides* bushes in the Kokshetau and Kostanay Regions

Forms	Height (m)	Stem diameter (cm)	Habitus	Thorns	Fruit cluster length (cm)
KT	2.5±0.08 <sup>c</sup>	4.0±0.09 <sup>b</sup>	Round	No	12.15±0.96 <sup>d</sup>
K-1-32	2.5±0.12 <sup>c</sup>	6.5±0.63 <sup>c</sup>	Cone	Medium	8.98±0.92 <sup>e</sup>
K-1-78-1	2.0±0.18 <sup>d</sup>	6.0±0.27 <sup>c</sup>	Oval	No	16.02±3.10 <sup>c</sup>
K-1-78-2	2.0±0.31 <sup>d</sup>	6.0±0.69 <sup>c</sup>	Round	Medium	5.9±0.56 <sup>f</sup>
K-1-79	3.0±0.19 <sup>b</sup>	6.0±0.63 <sup>c</sup>	Oval	No	6.03±0.25 <sup>f</sup>
K-1-80-1	2.5±0.14 <sup>c</sup>	4.5±0.54 <sup>b</sup>	Spreading	Medium	6.80±0.57 <sup>f</sup>
K-1-80-2	2.5±0.07 <sup>c</sup>	4.0±0.42 <sup>b</sup>	Spreading	Few	6.29±0.54 <sup>f</sup>
K-2-82-1	2.5±0.04 <sup>e</sup>	6.0±0.79 <sup>c</sup>	Umbrella	Medium	38.23±2.22 <sup>a</sup>
K-2-82-2	2.5±0.21 <sup>c</sup>	2.0±0.27 <sup>a</sup>	Umbrella	Medium	28.23±4.47 <sup>b</sup>
K-3-33	3.0±0.26 <sup>b</sup>	9.0±0.32 <sup>d</sup>	Round	No	6.14±0.54 <sup>f</sup>
K-4-34	4.0±0.30 <sup>a</sup>	14±0.66 <sup>e</sup>	Umbrella	Medium	5.55±0.70 <sup>f</sup>

Note: Values are mean ± SE (n = 3-10); different letters within column - p<0.05 (Fisher’s LSD)



**Figure 2.** Fruit cluster length of *Hippophae rhamnoides* in Kokshetau and Kostanay Regions (illustrating significant variation in cluster length, which supports patterns in productivity across forms)

**Table 3.** Environmental characteristics of studied cenopopulations in Northern Kazakhstan

Cenopopulation	Altitude (m)	Characteristic of soil	Annual precipitation (mm)	Mean January t (°C)	Mean July t
Kokshetau SNNP	290	Soils of forest and steppe zones with forest vegetation, coniferous forests; alluvial soils near rivers and reservoirs	420-440	-18 ... -14	+18 ... +20
Kostanay, Prigorodnoye	147-207	Chernozems with different mechanical composition (medium loamy, sandy loam), chestnut soils are often carbonate, solonchek, and alluvial in river floodplains and ravines	300-350	-17 ... -15	+19 ... +22

**Table 4.** Floristic composition of sea buckthorn cenopopulations (demonstrating species diversity and community structure across sites, contributing to understanding succession dynamics)

Cenopopulation	Floristic composition
Kokshetau SNNP	21 species (3 woody: <i>Betula pendula</i> Roth, <i>Sorbus aucuparia</i> L., <i>Malus baccata</i> (L.) Borkh.; 18 herbaceous: <i>Fragaria viridis</i> (Duchesne) Weston, <i>Fragaria vesca</i> L.), <i>Euphorbia virgata</i> Waldst. ex Kit., <i>Plantago urvillei</i> Opiz; <i>Vicia cracca</i> L., <i>Urtica urens</i> L., <i>Bromopsis inermis</i> (Leyss.) Holub, <i>Melica nutans</i> L., <i>Calamagrostis neglecta</i> G.Gaertn., B.Mey. & Scherb., <i>Agrostis gigantea</i> Roth, <i>Elytrigia repens</i> (L.) Nevski, <i>Achillea millefolium</i> L., <i>Artemisia sericea</i> (Besser) Weber, <i>Stellaria graminea</i> L., <i>Convolvulus arvensis</i> L., <i>A. sericea</i> , <i>Ranunculus polyanthemus</i> L., <i>Koeleria cristata</i> Kar. & Kir.
Cenopopulation 1 (Kostanay, Prigorodnoye)	27 species (7 tree-shrub: <i>Pinus sylvestris</i> L., <i>Ulmus pumila</i> L., <i>Acer negundo</i> L., <i>Betula pendula</i> Roth, <i>Elaeagnus angustifolia</i> L., <i>Salix × fragilis</i> L., <i>Lonicera tatarica</i> L.; 20 herbaceous: <i>Euphorbia virgata</i> Waldst. ex Kit., <i>Achillea millefolium</i> L., <i>Polygonum aviculare</i> L., <i>Veronica incana</i> L., <i>Koeleria cristata</i> (L.) Pers., <i>Artemisia dracunculoides</i> L., <i>Artemisia sericea</i> Weber ex Stechm., <i>Plantago media</i> L., <i>Vicia sepium</i> L., <i>Vicia cracca</i> L., <i>Medicago falcata</i> L., <i>Lathyrus pratensis</i> L., <i>Cirsium setosum</i> (Willd.) Bes., <i>Phleum phleoides</i> (L.) H.Karst., <i>Poa angustifolia</i> L., <i>Agropyron pectinatum</i> (M.Bieb.) Beauv., <i>Calamagrostis epigeios</i> (L.) Roth, <i>Melilotus officinalis</i> (L.) Lam., <i>Potentilla humifusa</i> Willd. ex Schltdl., <i>Helictotrichon desertorum</i> (Less.) Nevs.
Cenopopulation 2 (Kostanay, Prigorodnoye)	27 species (4 woody: <i>Pinus sylvestris</i> L., <i>Betula pendula</i> Roth, <i>Hippophae rhamnoides</i> L., <i>Salix × fragilis</i> L.; 23 herbaceous: <i>Euphorbia virgata</i> Waldst. ex Kit., <i>Achillea millefolium</i> L., <i>Koeleria cristata</i> (L.) Pers., <i>Artemisia dracunculoides</i> L., <i>Artemisia sericea</i> Weber ex Stechm., <i>Carex polyphylla</i> Kar. & Kir., <i>Dianthus versicolor</i> Fisch. ex Link, <i>Astragalus onobrychis</i> L., <i>Onobrychis arenaria</i> (Kit.) DC., <i>Onobrychis vicifolia</i> Scop., <i>Plantago media</i> L., <i>Vicia sepium</i> L.; <i>Vicia cracca</i> L., <i>Medicago falcata</i> L., <i>Lathyrus pratensis</i> L., <i>Cirsium setosum</i> (Willd.) Bes., <i>Phleum phleoides</i> (L.) H.Karst., <i>Poa angustifolia</i> L., <i>Agropyron pectinatum</i> (M.Bieb.) Beauv., <i>Agropyron kazachstanicum</i> (Tzvelev) Peschkova, <i>Calamagrostis epigeios</i> (L.) Roth, <i>Plantago media</i> L., <i>Veronica incana</i> L.
Cenopopulation 3 (Kostanay, Prigorodnoye)	23 species (3 woody-shrub: <i>Elaeagnus angustifolia</i> L., <i>Lonicera tatarica</i> L., <i>Salix × fragilis</i> L.; 20 herbaceous: <i>Achillea millefolium</i> L., <i>Koeleria cristata</i> (L.) Pers., <i>Artemisia dracunculoides</i> L., <i>Artemisia sericea</i> Weber ex Stechm., <i>Polygonum aviculare</i> L., <i>Dianthus versicolor</i> Fisch. ex Link, <i>Astragalus onobrychis</i> L., <i>Sedum telephium</i> L.; <i>Vicia sepium</i> L.; <i>Vicia cracca</i> L.; <i>Medicago falcata</i> L.; <i>Lathyrus pratensis</i> L.; <i>Cirsium setosum</i> (Willd.) Bes., <i>Phleum phleoides</i> (L.) H. Karst., <i>Poa angustifolia</i> L., <i>Agropyron pectinatum</i> (M. Bieb.) Beauv., <i>Agropyron kazachstanicum</i> (Tzvelev) Peschkova, <i>Calamagrostis epigeios</i> (L.) Roth, <i>Plantago media</i> L., <i>Trifolium repens</i> L.
Cenopopulation 4 (Kostanay, Prigorodnoye)	19 species (4 tree-shrub: <i>Pinus sylvestris</i> L., <i>Betula pendula</i> Roth., <i>Lonicera tatarica</i> L., <i>Salix × fragilis</i> L.; 15 herbaceous: <i>Euphorbia virgata</i> Waldst. ex Kit., <i>Achillea millefolium</i> L., <i>Koeleria cristata</i> (L.) Pers., <i>Artemisia dracunculoides</i> L., <i>Artemisia sericea</i> Weber ex Stechm., <i>Carex polyphylla</i> Kar. & Kir., <i>Plantago media</i> L., <i>Vicia sepium</i> L., <i>Vicia cracca</i> L., <i>Medicago falcata</i> L., <i>Cirsium setosum</i> (Willd.) Bes., <i>Phleum phleoides</i> (L.) H. Karst., <i>Poa angustifolia</i> L., <i>Agropyron pectinatum</i> (M. Bieb.) Beauv., <i>Agropyron kazachstanicum</i> (Tzvelev) Peschkova.

#### Environmental impact and ecosystem development

Sea buckthorn's nitrogen-fixing capability enhances soil fertility, fostering diverse plant communities and accelerating succession in degraded landscapes. The Kostanay cenopopulations, particularly in Prigorodnoye, illustrate this through clump distribution and the integration of species such as *P. sylvestris* and *S. fragilis*, which contribute to structural complexity. The presence of both forest and steppe species in the herbaceous layer underscores sea buckthorn's ability to bridge ecological niches, promoting biodiversity and ecosystem resilience.

The analysis of sea buckthorn cenopopulations demonstrates their critical role in restoring disturbed landscapes in northern Kazakhstan. Variations in species diversity, productivity, and successional dynamics reflect the interplay of ecological conditions and community age. Younger cenopopulations exhibit high diversity and productivity, while older ones form stable, less diverse communities. These findings underscore sea buckthorn's ecological significance in facilitating succession and enhancing ecosystem development, with implications for conservation and restoration strategies.

#### Agromorphological fruit traits

Sea buckthorn is characterized by high polymorphism, which is expressed in the diversity of morphological and agronomic traits among its forms and varieties (Figure 3).

This diversity is essential for selecting high-yielding, large-fruited varieties with resistance to diseases and pests, as well as those adapted to diverse conditions. In this study, 11 sea buckthorn forms were evaluated based on the following economically valuable traits: weight of 100 berries, shape, color, fruit taste, fruiting degree, ripening time, and resistance to pests and diseases (Table 5).

The weight of 100 berries ranged from 24.36 g (K-1-78-1, K-4-34) to 48.47 g (K-1-32), showing a twofold difference among the forms. According to ANOVA results, a significant difference in weight was observed among the forms ( $p < 0.001$ ). Tukey's HSD post-hoc tests identified six shape groups where differences are not significant within groups, but are statistically significant between groups. Table 4, using uppercase letters, illustrates these groups and indicates which shapes differ in weight (i.e., the composition of the different groups).



**Figure 3.** Morphological appearance of selected *Hippophae rhamnoides* forms: A. KT, B. K-1-32, C. K-1-78-1, D. K-1-78-2, E. K-1-79, F. K-1-80-1, G. K-1-80-2, H. K-2-82-1, I. K-2-82-2, J. K-3-33, K. K-4-34 (highlighting diversity in shape and size, which contributes to patterns in agronomic traits)

**Table 5.** Average agro-morphological traits of the 11 *Hippophae rhamnoides* forms (summarizing key fruit traits, contributing to identification of variation patterns)

Forms	100-berry weight (g)	Shape	Skin color	Taste	Degree of fruiting, points	Ripening time	Pest and disease damage
KT	29.84±0.63 <sup>b</sup>	Round	Dark orange	Sour with bitterness	2	3 decade of September	No
K-1-32	48.47±0.38 <sup>f</sup>	Round	Light orange	Sweet-sour buttery	5	3 decade of September	Yes
K-1-78-1	24.36±0.13 <sup>a</sup>	Ovoid	Orange-raspberry	Sweet-sour with tartness	5	2 decade of September	No
K-1-78-2	24.63±0.19 <sup>a</sup>	Oval	Bright yellow	Sweet-sour with tartness	5	2 decade of September	No
K-1-79	46.71±0.18 <sup>e</sup>	Round	Orange	Sweet with bitterness	3	3 decade of September	Yes
K-1-80-1	34.31±0.09 <sup>d</sup>	Elongated	Dark yellow	Sweet	5	2 decade of September	Yes
K-1-80-2	34.36±0.25 <sup>d</sup>	Barrel	Light orange	Sweet	5	2 decade of September	Yes
K-2-82-1	33.54±0.34 <sup>e</sup>	Oblong	Orange	Fresh	5	1 decade of October	Yes
K-2-82-2	33.71±0.18 <sup>e</sup>	Round	Dark orange	Tart	5	1 decade of October	No
K-3-33	34.45±0.13 <sup>d</sup>	Round	Dark orange	Tart	4	3 decade of September	Yes
K-4-34	24.36±0.25 <sup>a</sup>	Round	Red	Sweet with tartness	4	3 decade of September	Yes

Note: Values are mean ± SE (n = 3-10); different letters within column - p<0.05 (Fisher's LSD)

The rounded shape predominates (KT, K-1-32, K-1-79, K-2-82-2, K-3-33, K-4-34), while ovoid (K-1-78-1), oval (K-1-78-2), elongated (K-1-80-1), barrel-shaped (K-1-80-2), and oblong (K-2-82-1) shapes also occur. Coloration varies as follows: dark orange (KT, K-2-82-2, K-3-33), light orange (K-1-32, K-1-80-2), orange-raspberry (K-1-78-1), bright yellow (K-1-78-2), dark yellow (K-1-80-1), and red (K-4-34).

Fruit flavor profiles are diverse: sour with bitterness (KT), sweet-sour and buttery (K-1-32), sweet-sour with

tartness (K-1-78-1, K-1-78-2), sweet (K-1-80-1), sweet with bitterness (K-1-79), tart (K-1-80-2, K-2-82-2, K-3-33), fresh (K-2-82-1), and sweet with tartness (K-4-34).

Most forms (K-1-32, K-1-78-1, K-1-78-2, K-1-80-1, K-1-80-2, K-2-82-1, K-2-82-2) exhibit a high fruiting degree (5 points). Forms K-1-79, K-3-33, and K-4-34 showed 3-4 points, while KT showed only 2 points, which may be due to the age of the plant or growing conditions.

The forms mature at varying times: second decade of September (K-1-78-1, K-1-78-2, K-1-80-1, K-1-80-2),

third decade of September (KT, K-1-32, K-1-79, K-3-33, K-4-34), and first decade of October (K-2-82-1, K-2-82-2). Forms KT, K-1-78-1, K-1-78-2, K-1-79, and K-2-82-2 showed no signs of pest or disease damage. Forms K-1-32, K-1-80-1, K-1-80-2, K-2-82-1, K-3-33, and K-4-34 were affected by buckthorn aphids (*Capitophorus elaeagni*) and sooty molds (*Capnodium* spp., *Cladosporium* spp.), particularly in late September.

### Biochemical composition

Biochemical analysis (Table 6) revealed significant differences in soluble solids content (SSC: 7.9-12.8%), total sugars (TS: 1.2-7.5 g/100 g), titratable acidity (TA: 1.02-2.5 g/100 g), and pectin content (water-insoluble pectin, WIP: 0.11-0.83%; water-soluble pectin, WSP: 0.08-0.9%). The TS/TA ratio, a measure of flavor balance, ranged from 0.56 (KT) to 4.26 (K-1-80-1). Form K-1-80-1 displayed the highest sweetness (TS: 7.5 g/100 g, TS/TA: 4.26), while KT and K-3-33 were notably sour (TA: 2.12% and 2.03%, respectively). WIP/WSP ratios ranged from 0.33 (K-1-78-1) to 8.62 (K-2-82-2), reflecting diverse textural properties, with K-2-82-2 being the firmest and K-1-78-1 the softest. As shown in Table 6, these biochemical variations indicate patterns in flavor and texture across forms.

### Antioxidant activity and correlations

Antioxidant analysis (Table 7) demonstrated a broad range in total phenolic content (TPC: 401-1860 mg GAE/100 g), catechins (21.02-61.2 mg/100 g), leucoanthocyanidins (LAC: 13.6-100.8 mg/100 g), and vitamin C (9.68-105.6 mg/100 g). Form KT exhibited the highest TPC (1860 mg GAE/100 g), followed by K-2-82-2 (1267 mg GAE/100 g). Antioxidant capacity, assessed by FRAP (1.33-10.22  $\mu$ M FeSO<sub>4</sub>/g) and DPPH (18-78%), peaked in KT (FRAP: 10.22, DPPH: 78%). Forms K-1-78-1 and K-1-78-2 stood out for their high vitamin C (105.6 mg/100 g) and LAC (100.8 mg/100 g), respectively. As shown in Table 7, these antioxidant variations reveal patterns in bioactive content across forms.

Pearson correlation matrix analysis (Figure 4) identified strong positive correlations among sugar-related parameters (TS and TS/TA:  $r = 0.978$ ; SSC and TS:  $r = 0.529$ ) and antioxidant measures (FRAP and DPPH:  $r = 0.849$ ; TPC and FRAP:  $r = 0.821$ ; TPC and DPPH:  $r = 0.744$ ). Negative correlations were noted between sugar and antioxidant parameters (SSC and FRAP:  $r = -0.559$ ). A significant positive correlation was observed between WSP and vitamin C ( $r = 0.777$ ). As shown in Figure 4, these correlations reveal patterns in biochemical relationships, supporting trait associations.

**Table 6.** Biochemical characterization of the 11 *Hippophae rhamnoides* forms

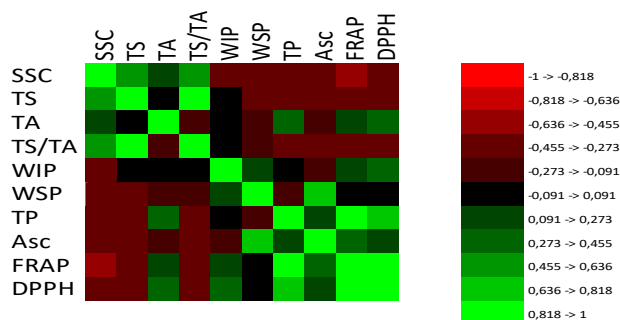
Forms	SSC %	Total Sugars g/100 g FW	Titratable Acidity g/100 g FW	TS/TA index	WIP g/100 g FW	WSP g/100 g FW	WIP/WSP ratio
KT	8.4±0.15 <sup>b</sup>	1.2±0.2 <sup>a</sup>	2.12±0.01 <sup>a</sup>	0.56	0.52±0.12 <sup>ab</sup>	0.51±0.39 <sup>a</sup>	1.02
K-1-32	9.7±0.2 <sup>c</sup>	1.2±0.2 <sup>a</sup>	1.84±0.01 <sup>b</sup>	0.65	0.14±0.01 <sup>a</sup>	0.19±0.1 <sup>b</sup>	0.73
K-1-78-1	8.5±0.05 <sup>b</sup>	1.2±0.2 <sup>a</sup>	1.02±0.01 <sup>c</sup>	1.18	0.3±0.05 <sup>ab</sup>	0.9±0.11 <sup>c</sup>	0.33
K-1-78-2	11.9±0.1 <sup>d</sup>	1.2±0.2 <sup>a</sup>	1.6±0.05 <sup>d</sup>	0.75	0.11±0.03 <sup>a</sup>	0.14±0.05 <sup>b</sup>	0.78
K-1-79	10.6±0.3 <sup>c</sup>	1.8±0.5 <sup>b</sup>	2.5±0.05 <sup>e</sup>	0.72	0.27±0.12 <sup>ab</sup>	0.20±0.15 <sup>b</sup>	1.35
K-1-80-1	12.8±0.6 <sup>e</sup>	7.5±0.5 <sup>d</sup>	1.76±0.01 <sup>b</sup>	4.26	0.25±0.15 <sup>ab</sup>	0.17±0.02 <sup>b</sup>	1.47
K-1-80-2	8.9±0.4 <sup>b</sup>	1.2±0.2 <sup>a</sup>	1.6±0.05 <sup>d</sup>	0.75	0.22±0.07 <sup>ab</sup>	0.08±0.01 <sup>d</sup>	2.75
K-2-82-1	10.3±0.3 <sup>c</sup>	1.2±0.2 <sup>a</sup>	1.63±0.01 <sup>d</sup>	0.73	0.41±0.08 <sup>ab</sup>	0.45±0.25 <sup>a</sup>	0.91
K-2-82-2	10.4±0.3 <sup>c</sup>	3.0±0.3 <sup>c</sup>	1.4±0.00 <sup>f</sup>	2.14	0.69±0.15 <sup>bc</sup>	0.08±0.02 <sup>d</sup>	8.62
K-3-33	10.3±1.2 <sup>c</sup>	1.2±0.3 <sup>a</sup>	2.03±0.01 <sup>a</sup>	0.59	0.83±0.07 <sup>c</sup>	0.55±0.25 <sup>a</sup>	1.50
K-4-34	7.9±0.15 <sup>a</sup>	3.0±0.4 <sup>c</sup>	1.6±0.05 <sup>d</sup>	1.87	0.83±0.07 <sup>c</sup>	0.25±0.04 <sup>b</sup>	3.32

Note: Values are mean ± SE (n = 3-10); different letters within column -  $p < 0.05$  (Fisher's LSD)

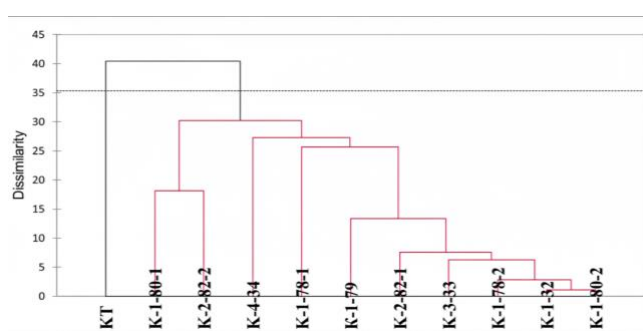
**Table 7.** Polyphenols and antioxidant activity of *Hippophae rhamnoides* fruits of eleven different forms (highlighting diversity in phenolic and antioxidant measures, contributing to identification of elite forms)

Forms	Total phenolic content mg GAE/100 g DW	Catechin mg/100g FW	LAC mg/100g FW	Total vitamin C mg/100 g	FRAP $\mu$ M ferrous/100 g DW	DPPH, %
KT	1860±20 <sup>g</sup>	43.48±0.26 <sup>a</sup>	30.24±1.67 <sup>bc</sup>	91.34±0.02 <sup>i</sup>	10.22±1.02 <sup>e</sup>	78±1.58 <sup>a</sup>
K-1-32	1090±10 <sup>d</sup>	36.4±0.40 <sup>b</sup>	54.0±1.83 <sup>e</sup>	70.4±0.5 <sup>g</sup>	2.87±0.33 <sup>b</sup>	47±2.51 <sup>b</sup>
K-1-78-1	424±15 <sup>a</sup>	61.2±0.34 <sup>c</sup>	37.4±2.0 <sup>d</sup>	105.6±1.1 <sup>j</sup>	1.33±0.18 <sup>a</sup>	18±2.00 <sup>c</sup>
K-1-78-2	834±15 <sup>c</sup>	49.82±0.04 <sup>d</sup>	100.8±9.2 <sup>h</sup>	25.52±1.15 <sup>e</sup>	2.77±0.22 <sup>b</sup>	46±4.0 <sup>b</sup>
K-1-79	1070±10 <sup>d</sup>	23.61±0.13 <sup>e</sup>	13.6±0.95 <sup>a</sup>	9.85±0.15 <sup>a</sup>	2.55±0.55 <sup>b</sup>	35±5.0 <sup>cd</sup>
K-1-80-1	513±4 <sup>b</sup>	21.02±0.0 <sup>f</sup>	25.9±3.3 <sup>b</sup>	22.8±0.2 <sup>d</sup>	0.86±0.06 <sup>a</sup>	24±4.5 <sup>cd</sup>
K-1-80-2	1216±8 <sup>e</sup>	36.72±0.22 <sup>b</sup>	34.6±2.9 <sup>cd</sup>	9.68±0.05 <sup>a</sup>	4.08±0.2 <sup>c</sup>	32±4.5 <sup>cd</sup>
K-2-82-1	1261±11 <sup>f</sup>	37.7±0.85 <sup>b</sup>	89.3±8.8 <sup>g</sup>	84.48±0.08 <sup>h</sup>	4.08±1.06 <sup>c</sup>	50±5.5 <sup>b</sup>
K-2-82-2	1267±13 <sup>f</sup>	34.84±1.06 <sup>g</sup>	71.3±2.7 <sup>f</sup>	16.72±0.14 <sup>b</sup>	2.5±0.4 <sup>b</sup>	42±2.5 <sup>bc</sup>
K-3-33	401±4 <sup>a</sup>	26.06±0.08 <sup>h</sup>	74.8±4.6 <sup>f</sup>	33.4±0.1 <sup>f</sup>	1.00±0.15 <sup>a</sup>	42±6.5 <sup>bc</sup>
K-4-34	845±5 <sup>c</sup>	60.76±0.22 <sup>c</sup>	71.3±1.8 <sup>f</sup>	19.36±0.04 <sup>c</sup>	5.4±0.50 <sup>d</sup>	50±6.0 <sup>b</sup>

Note: Values are mean ± SE (n = 3-10); different letters within column -  $p < 0.05$  (Fisher's LSD)



**Figure 4.** Correlation matrix of biochemical and antioxidant properties of selected sea buckthorn forms (illustrating positive and negative trait relationships, contributing to understanding diversity drivers)



**Figure 5.** Agglomerative Hierarchical Clustering (AHC) of sea buckthorn forms (two clusters) (visualizing form relationships based on traits, supporting divergence patterns)

### Cluster and PCA outcomes

Agglomerative hierarchical clustering (AHC, Figure 5) categorized the forms into two clusters: Cluster 1 (KT alone, at an altitude of 290 m, with high FRAP and DPPH) and Cluster 2 (the remaining 10 forms, at altitudes of 147–207 m, with lower antioxidant activity). PCA confirmed these patterns, with PC1 explaining 45% of variance driven by antioxidant traits. As shown in Figure 5, the clustering highlights distinct groups, contributing to the identification of unique forms like KT.

### Discussion

This study revealed substantial agromorphological and biochemical diversity among 11 sea buckthorn forms in northern Kazakhstan, with key variations in height, fruit weight, sugars, and antioxidant capacity, aligning with the objectives of identifying resilient forms for breeding.

Sea buckthorn exhibits significant morphological variability, making it a valuable subject for selection. In Kokshetau SNNP, the population is rare and low-growing, whereas in the Kostanay region, it is dense and productive. This phenotypic variation may reflect genetic divergence or environmental plasticity; molecular confirmation is needed to distinguish these effects.

The biochemical diversity of the 11 sea buckthorn forms underscores their suitability for various applications. The high TS/TA ratio of K-1-80-1 (4.26) and its elevated

sugar content (7.5 g/100 g) make it ideal for fresh consumption, consistent with findings from European cultivars exhibiting similar sweetness profiles (e.g., TS/TA up to 4.5 in Czech cultivars; Rop et al. 2014). In contrast, the sour profiles of KT (TA: 2.12%) and K-3-33 (TA: 2.03%) indicate suitability for processing into juices or jams, aligning with preferences in the Chinese sea buckthorn processing industry (Ma et al. 2020).

Texturally, the high WIP/WSP ratio in K-2-82-2 (8.62) indicates firmness suitable for storage, while the low ratio in K-1-78-1 (0.33) suggests immediate consumption, supporting findings on pectin-driven texture in Indian sea buckthorn genotypes (Sharma et al. 2022).

The antioxidant profiles of the studied forms, particularly KT's high TPC (1860 mg GAE/100 g) and antioxidant capacity (FRAP: 10.22, DPPH: 78%), exceed those of wild sea buckthorn (247 mg GAE/100 g; Saeidi et al. 2016) and match or surpass cultivated varieties from Romania (1012–1866 mg GAE/100 g; Criste et al. 2020) and China (800–1500 mg GAE/100 g; Ma et al. 2020). The elevated vitamin C content in K-1-78-1 (105.6 mg/100 g) is comparable to that of high-yielding European genotypes (28–201 mg/100 g; Yao et al. 1992) but surpasses some Turkish genotypes (19–34 mg/100 g; Sezen et al. 2015). Correlations between TPC and antioxidant capacity may suggest contributions from catechins and vitamin C, aligning with studies on Indian sea buckthorn (Sharma et al. 2022). The strong correlation between WSP and vitamin C ( $r = 0.777$ ) justifies further investigation into pectin's role in stabilizing antioxidants, a novel finding not extensively reported. While altitude differences suggest environmental influence on traits like antioxidant capacity in KT, formal disentangling of genotype-environment interactions requires further study.

The agro-morphological and biochemical traits of specific forms present clear breeding opportunities. The large fruit size of Form K-1-32 (100-berry weight: 48.47 g) positions it as a prime candidate for developing large-fruited varieties, a priority in European breeding programs (Rop et al. 2014). Spikeless forms (KT, K-1-78-1, K-1-79, K-3-33) enable efficient harvesting, addressing labor challenges identified in Chinese sea buckthorn cultivation (Ma et al. 2020). High-yielding forms (e.g., K-1-80-1, K-2-82-2), with a fruiting degree of 5 points, offer economic value, while KT's exceptional antioxidant profile supports its application in functional food development, consistent with global trends toward health-focused sea buckthorn products (Criste et al. 2020). The distinct clustering of KT, influenced by its high-altitude adaptation (290 m), may suggest that environmental factors influence antioxidant accumulation, a consideration for breeding to enhance bioactive content.

In India, the 100-berry mass ranged from 11.53 to 18.87 g (Yadav et al. 2006), and in China from 18.5 to 20.5 g (Rongsen 1993), both lower than the studied forms (24.36–48.47 g). This highlights the significant potential of these forms for breeding large-fruited varieties. The studied sea buckthorn forms exhibit substantial diversity in morphological and agronomic traits, creating opportunities for breeding. Form K-1-32 (48.47 g, 5 points) is promising for developing

large-fruited and highly productive varieties. Forms with early ripening (K-1-78-1, K-1-78-2) and pest resistance (KT, K-1-79) should be prioritized for developing resistant varieties. Further research into the genetic basis of resistance and trait correlations, including molecular validation, is recommended.

The significant variability among the 11 forms highlights the rich genetic diversity of sea buckthorn in northern Kazakhstan, especially in technogenic and natural habitats. Forms like KT, adapted to higher altitudes, and others flourishing in disturbed landscapes exhibit resilience to environmental stress, a trait essential for conservation amid habitat degradation (Sharma et al. 2022). While phenotypic variation is observed, it may reflect underlying genetic divergence, warranting molecular studies (e.g., ISSR or SNP) for confirmation. The present study is based exclusively on phenotypic and biochemical data. Although molecular markers were beyond the scope of this work, recent DNA-barcoding (Almerekova et al. 2024) and whole-genome data (Melnikova et al. 2025) on Kazakh and Russian *H. rhamnoides* confirm high genetic polymorphism in the species, supporting the assumption that the observed phenotypic variation has a significant genetic component.

Preserving this diversity is crucial, as cenopopulation differences reveal unique adaptations that may be lost in disturbed habitats. Strategies for ex situ conservation, such as seed banks, and in situ protection of diverse cenopopulations are recommended to preserve this genetic resource, supporting sustainable breeding and ecological restoration efforts in Kazakhstan. Particularly, the KT form's unique antioxidant profile warrants targeted conservation of high-altitude populations like KT to maintain elite traits.

This study relied on phenotypic assessments from a single year (2023-2024), potentially overlooking multi-year environmental variations. The focus on northern populations limits generalizability to southern Kazakhstan, and environmental heterogeneity across sites may confound genotypic effects. Future work should incorporate longitudinal data and molecular markers to validate findings.

The present study provides the first statistically robust, replicated phenotypic and biochemical characterization of sea buckthorn genetic resources from northern Kazakhstan. Combined with recently published molecular evidence, our results identify elite genotypes with immediate breeding value and justify targeted in situ conservation of the high-altitude KT population.

In conclusion, this study highlights the significant agromorphological and biochemical diversity of sea buckthorn (*H. rhamnoides*) in northern Kazakhstan, emphasizing its adaptability to diverse ecological conditions, including technogenic landscapes. The findings demonstrate substantial variation in dendrometric traits, fruit morphology, and antioxidant profiles. Notably, K-1-32 exhibits large fruit size and high yield potential, while KT stands out for its exceptional antioxidant capacity, likely linked to its high-altitude origin (290 m a.s.l.), forming a distinct cluster in principal component analysis. These traits make K-1-32 and KT valuable for targeted breeding-K-1-32 for productivity and KT for functional bioactive compounds. Preserving this genetic diversity is essential for maintaining

Kazakhstan's biodiversity and for breeding resilient varieties suited to climate-stressed environments. The results also fill critical regional knowledge gaps, supporting global efforts in sustainable use and conservation of *H. rhamnoides*. Future research should focus on genetic studies to support the species' introduction and unlock its full economic and ecological potential.

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