

Comparative analysis of soil properties in habitats of *Ajania fastigiata* (C. Winkl.) Poljakov in the Ile Alatau Region, Kazakhstan

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Abstract

This study evaluates the physicochemical properties of soils supporting natural populations of *Ajania fastigiata* (C. Winkl.) Poljakov in the Ile Alatau region of Kazakhstan. Soil analyses revealed clear differences among populations in moisture regime, nutrient availability, carbonate accumulation, exchangeable bases, and soluble salts. In all profiles, soils were weakly alkaline, with pH ranging from 7.71 to 8.12, and were predominantly characterized by a light loamy texture. The highest surface soil moisture was recorded in Population 3 (14.53%), whereas the lowest value in the deeper horizon was observed in Population 1 (6.13%). Population 3 was distinguished by elevated humus content (7.54%), available phosphorus (86 mg/kg), available potassium (490 mg/kg), and carbonate content (6.86%), indicating more favorable edaphic conditions. In contrast, Population 2 showed the highest surface nitrogen content (100.8 mg/kg) and relatively higher bicarbonate and total soluble salt contents (0.046-0.074%). Population 1 was characterized by the lowest salinity level, with total soluble salts decreasing from 0.049% to 0.018% along the soil profile. In all soils, Ca²⁺ dominated the exchange complex, while Na⁺ remained low. These findings demonstrate that local edaphic differences play a key role in shaping the ecological conditions of *Ajania fastigiata* populations in the Ile Alatau.

Keywords: *Ajania fastigiata*; soil properties; nutrient availability; soil moisture; carbonate accumulation; salinity

Introduction

The study of medicinal plants growing in natural ecosystems is of considerable scientific interest due to

their ecological adaptations and valuable biologically active compounds (Han et al., 2022; Jenis et al., 2025). Many plant species inhabiting arid and mountainous

regions possess unique biochemical compositions that allow them to survive under stressful environmental conditions such as limited soil moisture, high solar radiation, and nutrient deficiency (Han et al., 2022). These adaptations often lead to the accumulation of biologically active secondary metabolites with significant pharmacological potential (Mamurova et al., 2025). The genus *Ajania* (*Asteraceae*) includes several perennial herbaceous species distributed mainly in Central Asia, Siberia, Mongolia, and northern China (Amertayeva et al., 2024). Representatives of this genus are known for their ecological plasticity and ability to grow in mountainous and steppe landscapes characterized by diverse soil conditions. Some species of *Ajania* have attracted increasing scientific attention due to their phytochemical composition and potential medicinal properties, including antioxidant, antimicrobial, and anti-inflammatory activities (Taldybay et al., 2024). One of the important representatives of this genus is *Ajania fastigiata* (C.Winkl.) Poljakov (Fig.1), a perennial medicinal plant widely distributed in mountainous regions of Kazakhstan and adjacent territories of Central Asia (Amertayeva et al., 2023). This species is adapted to rocky slopes, mountain valleys, and arid steppe habitats, where environmental conditions are strongly influenced by soil properties such as moisture content, granulometric composition, nutrient availability, and salinity. These edaphic factors play a crucial role in determining the distribution, growth, and productivity of plant populations (Amertayeva et al., 2025). In mountainous ecosystems, soils often demonstrate significant spatial heterogeneity caused by differences in relief, parent material, and climatic conditions. Therefore, detailed investigation of soil parameters associated with natural plant populations provides important insights into their ecological requirements and



Figure 1. *Ajania fastigiata* (C.Winkl.) Poljakov in its natural habitat in the Ile Alatau region, Kazakhstan

adaptive strategies (Ileuberlina et al., 2026). Despite the growing interest in medicinal plants of the genus *Ajania*, information on the soil conditions and ecological characteristics of *Ajania fastigiata* populations remains limited. Most existing studies have focused primarily on phytochemical composition and pharmacological activity, whereas environmental factors influencing the distribution of this species have been insufficiently studied (Taldybay et al., 2024). In particular, the relationship between physicochemical soil properties and natural habitats of *A. fastigiata* populations in the Ile Alatau region has not been comprehensively investigated (Mamurova et al., 2025). The Ile Alatau mountain system is characterized by complex ecological gradients and diverse soil types (Fig. 2), which create favorable conditions for the formation of unique plant communities (Sadyrova et al., 2025). Therefore, the aim of this study was to investigate the morphological structure and physicochemical properties of soils supporting natural populations of *Ajania fastigiata* (C.Winkl.) Poljakov in the Ile Alatau region of Kazakhstan. Particular attention was given to soil moisture, humus content, nutrient availability (N, P, K), granulometric composition, and salinity, which are key factors determining ecological conditions of plant habitats.

Materials and Methods

Study area

The study was conducted in September 2024 in the Ile Alatau mountain region located in southeastern Kazakhstan (Fig. 2). Field investigations were carried out in three natural populations of *Ajania fastigiata* (C.Winkl.) Poljakov located in different mountain gorges: the Vysokaya Shchel gorge (Population 1), Ushkonyr gorge (Population 2), and Saty gorge (Population 3). The locations of the study sites are presented in Table 1. These territories belong to the northern slopes of the Trans-Ili Alatau, where soil types and vegetation cover vary depending on altitudinal zonality, forming diverse ecological conditions for plant communities (Sitpayeva et al., 2020). In The taxonomic identity of *Ajania fastigiata* (C.Winkl.) Poljakov (Figure 1) was verified using the Flora of Kazakhstan (1956-1966) and the Illustrated Plant Identification Guide of Kazakhstan (1969). Following the taxonomic verification, soil sampling was carried out in the natural habitats of the species.

Population	Location	Geographic coordinates	Altitude (m a.s.l.)
Population 1	Vysokaya Shchel gorge (Ile Alatau)	43°14'48.14" N, 77°00'21.17" E	1436
Population 2	Ushkonyr gorge (Ile Alatau)	43°57'41" N, 77°01'16" E	1300
Population 3	Saty gorge, Kegen district	43.0609796° N, 78.30461082° E	1475

Table 1

Locations and elevations of studied populations in the in the Ile Alatau region, Kazakhstan.

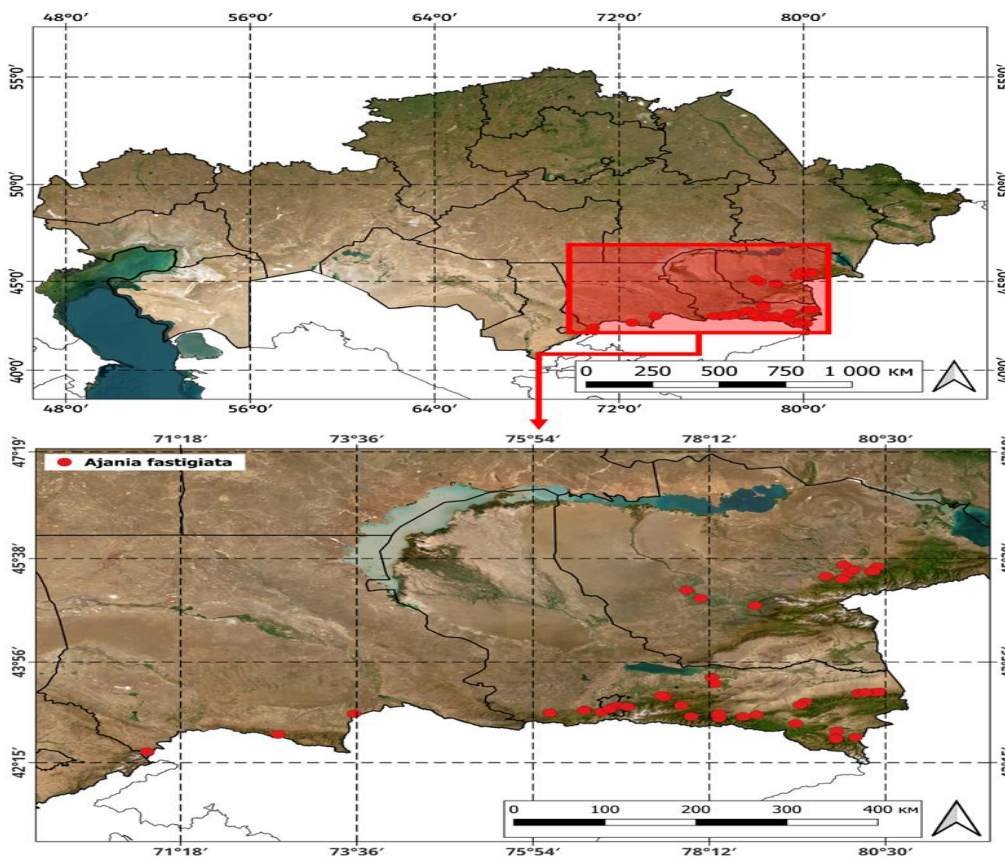


Figure 2

Distribution of *Ajania fastigiata* (C.Winkl.) Poljakov in Kazakhstan and location of the study area

Relief

The study area is located on the northern slopes of the Trans-Ili Alatau mountain range in southeastern Kazakhstan. The region is characterized by a complex mountainous relief formed as a result of long-term tectonic and geomorphological processes (Narama et al., 2010). The terrain includes mountain ridges, steep and gentle slopes, intermountain valleys, and narrow gorges. Altitudinal gradients have a strong influence on the spatial distribution of soils and vegetation in the region (Körner, 2007). The studied populations of *Ajania fastigiata* are located in mountain gorges and on slopes differing in elevation and microrelief conditions. The Vysokaya Shchel gorge is characterized by moderately steep slopes and a rocky substrate. The Ushkonyr

gorge represents a mountain valley with heterogeneous terrain and the presence of stony and gravelly deposits (Sitpayeva et al., 2020; Salimbayeva et.al., 2026). The Saty gorge is distinguished by more pronounced mountain slopes and relatively complex microrelief. Variations in slope inclination, exposure, and elevation create different ecological conditions for plant growth. These relief features play an important role in soil formation processes and the spatial distribution of plant communities within the study area (Jenny, 1941; Körner, 2007).

Climatic Conditions

The climate of the Ile Alatau mountain region is continental and strongly influenced by altitudinal gradients and complex mountain relief. The Trans-Ili

Alatau is characterized by a high-altitude continental climate formed under the influence of its geographical position in the center of Eurasia and the barrier effect of mountain ranges (Issaldayeva et al., 2023). Climatic conditions vary considerably with elevation, leading to the formation of distinct vertical climatic zones within the mountain system. Summers are relatively warm, whereas winters are cold, which is typical for mountainous regions of southeastern Kazakhstan. In the foothill zones of the Ile Alatau, the average air temperature in January is about -8°C , while in July it reaches approximately $+23^{\circ}\text{C}$ (Reyer et al., 2017). At higher elevations, temperatures decrease significantly and the growing season becomes much shorter. Annual precipitation also varies with altitude and generally increases in the mountain belt. In the foothills, the annual precipitation is about 560 mm, while in higher mountain zones it may reach 800-1300 mm, mainly in the form of snow (Deng and Chen, 2017). Seasonal precipitation patterns and temperature fluctuations significantly affect soil moisture regimes and vegetation development. Altitudinal climatic differentiation plays a key role in determining soil formation processes and the spatial distribution of plant communities in mountain ecosystems. As elevation increases, climatic conditions become cooler and more humid, which influences ecological niches and the distribution of plant species in the Trans-Ili Alatau region (Iskaliyeva et al., 2025).

Field survey and laboratory methods

Field investigations were carried out in September 2024 in the Ile Alatau mountain system (southeastern Kazakhstan) within three natural populations of *Ajania fastigiata*. Soil profiles were excavated in representative habitats of the species using the key transect method commonly applied in geobotanical and soil investigations. The geographic coordinates and altitude of each sampling site were recorded using GPS (Garmin eTrex 22x). Morphological descriptions of soil profiles were conducted in situ according to classical pedological approaches (Rozanov, 2004; Korolyuk, 2012). Each soil profile was characterized by genetic horizons with determination of horizon depth, color, structure, compaction, texture, carbonate effervescence, and abundance of plant roots. Representative soil samples were collected from each genetic horizon and transported to the laboratory for physicochemical analyses. All laboratory investigations were performed at the Kazakh Research Institute of Soil Science and Agrochemistry named after U.U. Usmanov (Almaty, Kazakhstan). Soil moisture content was determined

using the gravimetric method. Fresh soil samples were weighed in aluminum containers using analytical balances (MBS-300N, Germany), dried in a laboratory drying oven (VENTICELL 111, MMM Group, Germany) at 105°C for 5 hours, cooled in a desiccator, and weighed again. The soil moisture content was calculated as a percentage of dry mass. For conversion of field-moist soil samples to oven-dry equivalents, a moisture correction coefficient was calculated using the following formula:

$$K = \frac{100 + a}{100} \quad [1]$$

Where K - moisture correction coefficient, a - soil moisture content (%). This coefficient was used to standardize analytical results to oven-dry soil mass for accurate comparison of physicochemical indicators.

Soil reaction (pH) was measured potentiometrically in a 1:2.5 soil-water suspension using a laboratory pH meter (pH-150M, Russia) according to GOST 26423-85. Carbonate content (CO_2) was determined volumetrically by the acid neutralization method following GOST 26425-85.

Organic matter (humus) content was determined by the Tyurin titrimetric method according to GOST 23740-79. The granulometric composition of soils was determined by the Kachinsky pipette method according to GOST 12536-2014. The content of available macronutrients (nitrogen, phosphorus, and potassium) was determined following standard soil chemical procedures (Arinushkina, 1977; Alexandrova, 1986). Available phosphorus was measured spectrophotometrically using a UV-Vis spectrophotometer (UNICO, USA), potassium content was determined by flame photometry (PFP-7, Jenway, UK), and nitrogen content was determined by titrimetric methods according to GOST 26205-91. Exchangeable bases and water-soluble salts, including anions (CO_3^{2-} , HCO_3^- , Cl^- , SO_4^{2-}) and cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+), were determined using classical titrimetric methods according to GOST 26425-85. The combination of field morphological analysis and laboratory physicochemical measurements made it possible to characterize the soil formation conditions and edaphic factors influencing the distribution of *Ajania fastigiata* populations in the Ile Alatau region.

Statistical analysis

Statistical analysis of the obtained data was performed using standard methods for calculating mean values

and their associated errors. Data processing was carried out using IBM SPSS Statistics 28.0 (IBM Corp., 2024). The results are presented as mean values ± standard deviation (SD).

Results and Discussion

Morphological Description of Soil

Population 1 – Vysokaya Shchel Gorge, Ile Alatau 43°14'48.14" N, 77°00'21.17" E, elevation: 1,436 m a.s.l. Soil type: Mountain grey-brown soil. The study site is located within the Ile Alatau mountain system, which forms part of the Northern Tien Shan,

and is characterized by complex mountainous relief and altitudinal zonation of soils and vegetation. Soil-forming materials in the region include limestone sands, and weathering products of rocks, while deluvial and colluvial deposits are widely distributed along mountain slopes (Balkybek et al., 2025). These conditions strongly influence soil formation processes in the study area. The presence of carbonate accumulations in the B₂ and C horizons, increasing carbonate effervescence with depth, medium to light loamy texture, and low salinity indicates that the soil can be classified as a Calcaric Cambisol (Loamic) according to the World Reference Base for Soil Resources (WRB, 2022).



Horizon	Depth (cm)	Thickness (cm)	Description
A	0-7	7	Grey-brown, dry, loose, medium loamy, nutty-granular structure, rich in plant roots, weak effervescence, clear transition to the next horizon.
B ₁	7-20	13	Light grey-brown, dry, medium loamy, nutty-fine granular structure, roots present, weak effervescence, gradual transition to the next horizon.
B ₂	20-40	20	Light grey-brown, dry, light loamy, fine granular-dusty structure, main roots present, carbonate compounds observed, strong effervescence, clear transition to the next horizon.
C	40-100	60	Light grey, dry, slightly compacted, sandy texture, powdery-dusty structure, carbonate compounds present, very strong effervescence.

Population 2 – Ushkonyr Gorge, Ile Alatau (43°57'41" N, 77°01'16" E, elevation: 1,300 m a.s.l.)

Soil type: Dark-brown carbonate soil. The second population is located in the Ushkonyr



Horizon	Depth (cm)	Thickness (cm)	Description
A	0-7	7	Dark-brown, moist, slightly compacted, light loamy, nutty-granular structure, rich in plant roots, weak effervescence, gradual transition to the next horizon.
AB	7-24	17	Light-brown, dry, compacted, light loamy, powdery-fine granular structure, inclusions of stones, numerous lateral roots, weak effervescence, gradual transition to the next horizon.
B	24-54	30	Light-brown, dry, dense, powdery-fine granular structure, sandy loam, inclusions of large stones, presence of main roots, carbonate accumulations, strong effervescence, gradual transition to the next horizon.
C ₁	54-95	41	Light gray-brown, dry, compacted, sandy, powdery-dusty structure, gravelly-stony, carbonate accumulations, very strong effervescence..

Gorge of the Ile Alatau, part of the Northern Tien Shan, characterized by mountainous terrain and active slope processes. Soil formation occurs under mountain-steppe conditions on colluvial and deluvial deposits derived from carbonate-bearing rocks and weathering products of sandstones and limestones (Balkybek et al., 2025). The studied soil profile consists of A–AB–B–C horizons and is characterized by loamy to sandy loam texture, increasing compaction with depth, the presence of gravel and rock fragments throughout the profile, and carbonate accumulations in the subsurface horizons with increasing effervescence downward. Weak horizon differentiation indicates an early stage of soil development. According to the World Reference Base for Soil Resources (WRB, 2022), the soil can be classified as a Calcaric Cambisol (Loamic).

Population 3 – Saty Gorge, Kegen District (43.0609 796° N, 78.30461082° E., elevation: 1,475 m a.s.l.).

Soil type: Mountain brown soil.

The third study site is located in the Saty Gorge of the Kegen district within the Ile Alatau mountain system of the Northern Tien Sha (Turgara et.al., 2025). The area is characterized by mountainous terrain and active slope processes. Soil formation occurs on colluvial and deluvial deposits derived from weathering products of carbonate rocks. The soil profile consists of A–AB–B–C horizons and is characterized by loam to sandy loam texture, the presence of gravel and rock fragments throughout the profile, and carbonate accumulations with increasing effervescence with depth. Weak horizon differentiation is observed, with a weakly developed cambic horizon. According to the World Reference Base for Soil Resources (WRB, 2022), the soil can be classified as a Calcaric Cambisol (Loamic).



Horizon	Depth (cm)	Thickness (cm)	Description
A	0-6	6	Dark brown in color, slightly compacted, moist, medium loam texture, rich in plant roots, loose cloddy–powdery structure, no carbonate effervescence, clear transition to the next horizon.
AB	6-20	14	Brownish-grey in color, moist, medium loam texture, granular–prismatic structure, colloidal coatings often observed on the edges of structural aggregates, rich in plant roots, stony–gravelly, with carbonate accumulations, strong effervescence, gradual transition to the next horizon.
B	20-50	30	Light brown, moist, compacted, light loam texture, stony–gravelly, with carbonate accumulations, strong effervescence, clear transition to the next horizon.
C	50-65	15	Light gray-brown, moist, sandy texture, powdery–dusty structure, stony–gravelly, with carbonate accumulations, very strong effervescence.

Physical properties of soils

The physical properties of soils were evaluated based on soil moisture content, which is an important indicator determining the soil water regime and influencing plant growth, biological activity, and nutrient mobility in soil (Gou et.al., 2021). In all studied soil profiles, moisture content gradually decreased with depth. In Population 1 (Vysokaya Shchel Gorge), soil moisture ranged from 10.53% in the upper horizon to 6.13% in deeper layers (Fig. 3). In Population 2 (Ushkonyr Gorge), moisture values varied from 12.22% to 6.64% throughout the soil profile. The highest moi-

sture content was recorded in Population 3 (Saty Gorge), where it ranged from 14.53% in the surface horizon to 7.38% in deeper layers. The higher moisture values observed in Population 3 may be related to local geomorphological conditions, including slope position and the accumulation of fine soil particles that improve water retention capacity (Mamurova et.al., 2025). In contrast, the lower moisture content in deeper horizons reflects increased soil compaction and reduced water infiltration (Tleuberlina et.al., 2026; Turgara et.al., 2025).

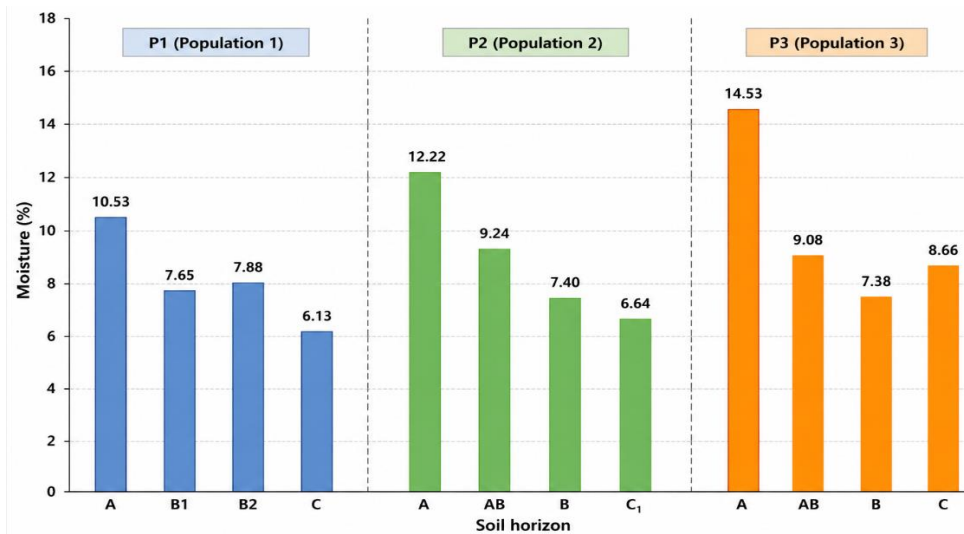


Figure 3. Soil moisture content (%) across genetic soil horizons in the studied populations

Granulometric composition of soils

The granulometric composition of soils plays a key role in soil formation processes and strongly influences their structural and physical properties. Particle-size distribution determines the movement, transformation, and accumulation of substances in soil and controls important physical characteristics such as porosity, water-holding capacity, permeability, structure, and soil air and thermal regimes (Hengl et.al., 2017). In the soil profile of Population 1, the dominant fraction was coarse silt (0.05–0.01 mm), accounting for approximately 40–52%. This was followed by fine sand (about 16–23%), medium silt (15–27%), coarse sand (8–16%), fine silt (9–22%), and clay particles (2–9%). The decreasing order of fractions (%) was: coarse silt > fine sand > medium silt > coarse sand > fine silt > clay (Fig. 4). According to particle-size classification, the soil of Population 1 corresponds to a light loam texture class

(Minasny et.al., 2016). In Population 2, the granulometric composition of the soil profile was characterized by the predominance of silt fractions, with coarse silt reaching up to approximately 51%. Fine sand ranged from about 27–41%, while fine silt, medium silt, and clay fractions remained relatively low. The decreasing order of fractions (%) was: coarse silt > fine sand > fine silt > medium silt > clay. Based on the granulometric composition, the soil of Population 2 also belongs to the light loam (loam) texture class (USDA, 2022). In the soil profile of Population 3, fine sand was the dominant fraction, accounting for approximately 25–36%, followed by coarse silt (about 30–35%), coarse sand (10–19%), fine silt (6–14%), medium silt (7–13%), and clay particles (3–9%). The decreasing order of fractions (%) was: fine sand > coarse silt > coarse sand > fine silt > medium silt > clay (Fig. 4). According to granulometric classification, the soil of Population 3 is

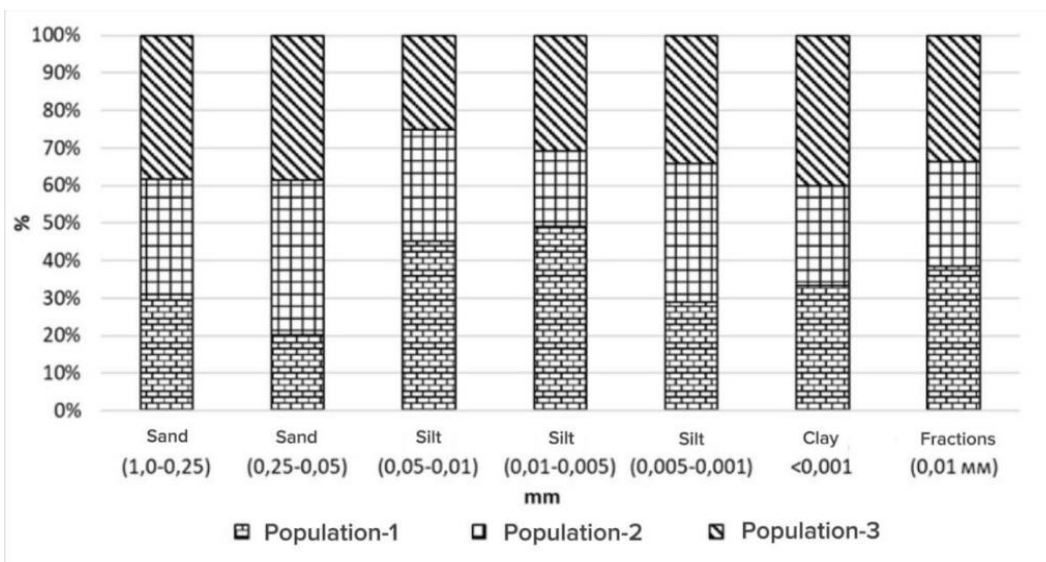


Figure 4 Granulometric composition of soils

also characterized as light loam, with a tendency toward sandy loam (USDA, 2022). The soils of the studied populations are characterized by light loamy texture with a considerable proportion of sand and silt fractions, which contributes to moderate water retention capacity and relatively good aeration conditions typical for mountain soils formed on deluvial and colluvial deposits.

Chemical properties of soils

The content of humus, carbonate compounds (CO₂), and soil reaction (pH) are important indicators that determine the chemical state of soils and significantly influence soil fertility and nutrient availability (Waksman,1937). In Population 1 (Vysokaya Shchel Gorge, Ile Alatau), the humus content within the 0-100 cm soil profile ranges from 0.62% to 7.36%, with the highest values recorded in the upper horizons and decreasing gradually with depth. Soil reaction is weakly alkaline,

with pH values between 7.71 and 8.01. The carbonate (CO₂) content varies from 0.48% to 4.15%, indicating the presence of carbonate accumulations within the soil profile (Fig. 5). In Population 2 (Ushkonyr Gorge, Ile Alatau), the humus content ranges from 0.64% to 6.48% within the 0-95 cm soil layer. Soil reaction remains weakly alkaline, with pH values ranging from 7.86 to 8.02. The carbonate (CO₂) content varies between 0.86% and 4.38%, reflecting carbonate enrichment in the soil horizons. In Population 3 (Saty Gorge, Kegen District), the soils show relatively higher organic matter accumulation compared with the other studied sites. The humus content ranges from 1.15% to 7.54% within the 0-65 cm soil profile. Soil reaction is also weakly alkaline, with pH values between 7.85 and 8.12. The content of available nutrient forms is an important indicator of soil fertility and determines the availability of essential elements for plant growth (Mamurova et.al.,2025).

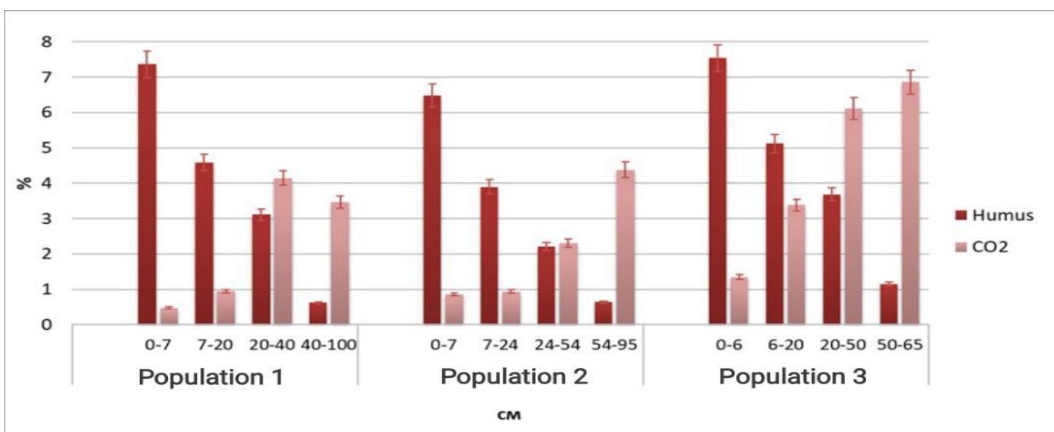


Figure 5
Humus and CO₂ indicators in the soil, %

In Population 1, the content of available nitrogen (N) ranges from 22.4 to 89.6 mg/kg, available phosphorus (P) from 16 to 48 mg/kg, and available potassium (K).

from 110 to 450 mg/kg (Fig. 6). Higher concentrations are observed in the upper soil horizons. In Population 2, the content of available nitrogen ranges from 22.4 to

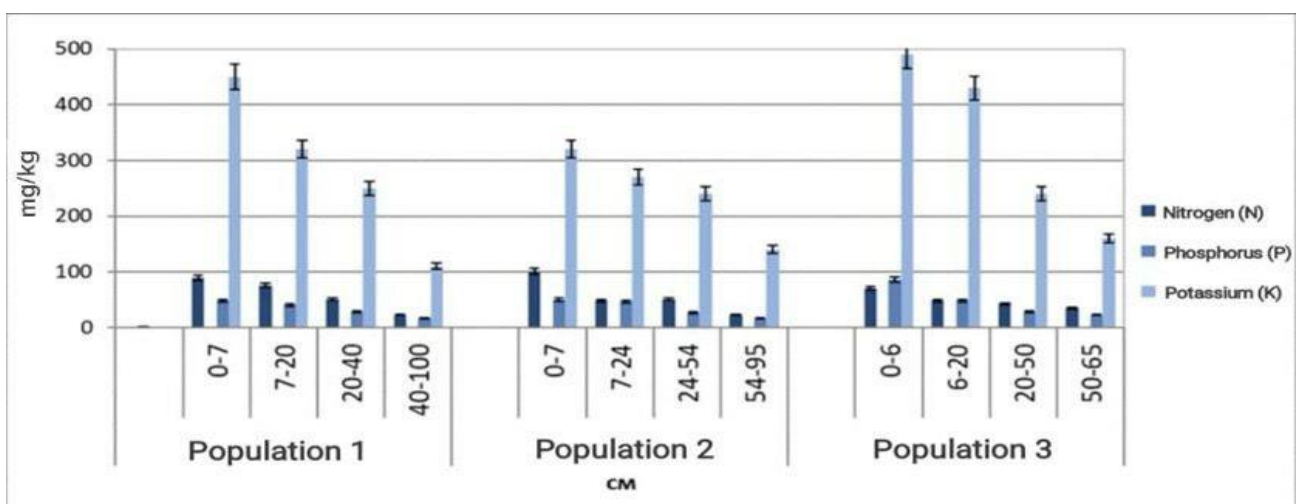


Figure 6. Indicators of mobile nitrogen, phosphorus, potassium in the soil, mg/ kg

100.8 mg/kg, available phosphorus from 16 to 50 mg/kg, and available potassium from 140 to 320 mg/kg within the soil profile (Roy et.al., 2006). In Population 3, relatively higher nutrient concentrations are observed compared with the other sites. Available nitrogen ranges from 33.6 to 70.0 mg/kg, available phosphorus from 22 to 86 mg/kg, and available potassium from 160 to 490 mg/kg. The obtained results indicate that the studied soils contain sufficient amounts of available macronutrients necessary for plant growth. The higher concentrations of nitrogen, phosphorus, and potassium in the upper horizons reflect the accumulation of organic matter and active biological processes in surface soil layers. Among the studied sites, Population 3 demonstrates relatively higher nutrient availability, suggesting more favorable soil conditions compared with the other populations (Mamurova et.al., 2025). The obtained results suggest that the observed soil characteristics generally provide favorable ecological conditions for the growth and distribution of *Ajania fastigiata* in the Ile Alatau region. In particular, the relatively higher moisture content, humus accumulation, and elevated concentrations of available phosphorus and potassium observed in Population 3 indicate more optimal edaphic conditions for plant development (Wang et al., 2023). The weakly alkaline soil reaction and low salinity levels recorded in

all studied populations are also consistent with the ecological requirements of many mountain-steppe plant species adapted to carbonate-rich soils. However, significant changes in these physicochemical parameters may negatively affect the stability of *Ajania fastigiata* populations. A decrease in soil moisture and organic matter content could reduce nutrient availability and limit plant growth, whereas excessive salinity or carbonate accumulation may negatively influence root functioning and water uptake processes (Gou et al., 2021). Therefore, the balance of soil moisture, nutrient availability, and salinity appears to play an important role in maintaining suitable habitats for this species in mountain ecosystems.

Vertical distribution of exchangeable base compositions (Na⁺, K⁺, Ca²⁺, Mg²⁺)

The composition and vertical distribution of exchangeable bases are key indicators of soil chemical status, reflecting the intensity of pedogenic processes, nutrient availability, and cation exchange dynamics (Wang et.al., 2020). The analysis of exchangeable cations also provides important insight into inter-population differences in soil-forming conditions (Antonangelo et.al., 2024). The vertical distribution of exchangeable bases (Na⁺, K⁺, Ca²⁺, and Mg²⁺) in the soil profiles of the studied populations is presented in Figure 7.

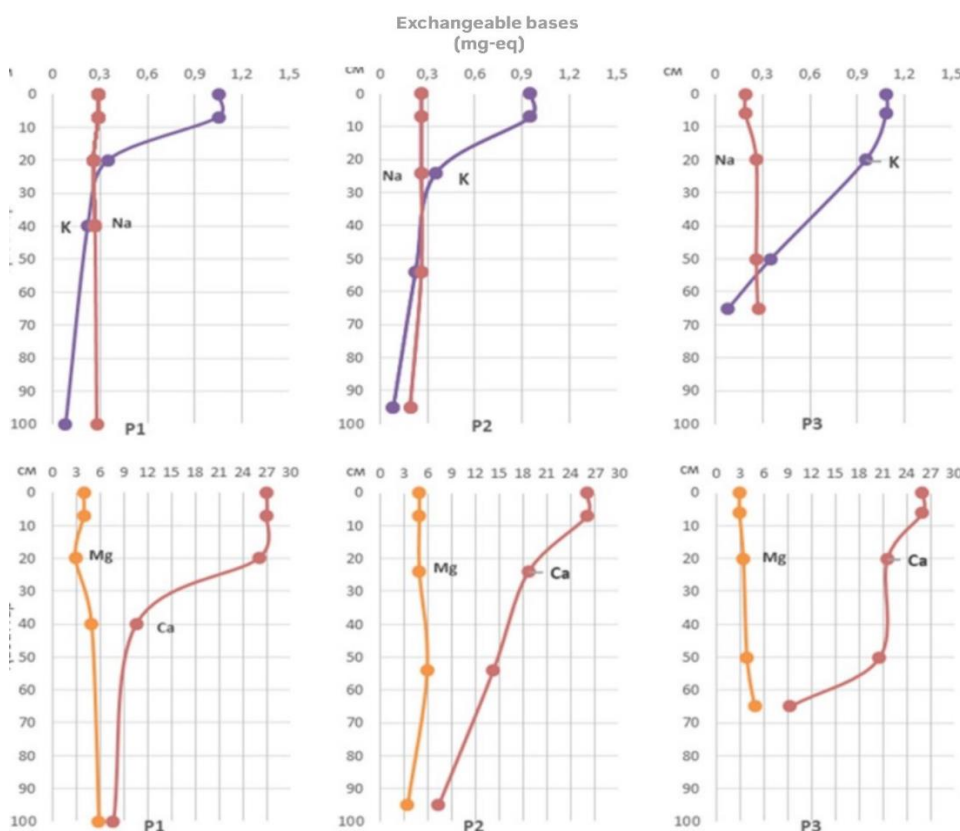


Figure 7
Vertical distribution of exchangeable bases in soil profiles (P1-P3)

In Population 1, calcium (Ca²⁺) clearly dominated the exchange complex, decreasing from 26.95 mg-eq in the upper horizon to 7.66 mg-eq in the deepest layer. Magnesium (Mg²⁺) ranged from 2.94 to 5.80 mg-eq. Sodium (Na⁺) remained low and relatively stable (0.26–0.29 mg-eq), whereas potassium (K⁺) decreased sharply with depth from 1.05 to 0.08 mg-eq. In Population 2, exchangeable calcium also decreased with depth, from 25.97 to 7.33 mg-eq. Magnesium varied from 3.43 to 5.88 mg-eq, with slightly higher values in the middle horizons. Sodium remained low (0.19–0.26 mg-eq), and potassium declined from 0.95 to 0.08 mg-eq. In Population 3, calcium remained high in the upper and middle horizons (25.97–20.58 mg-eq) and decreased to 9.28 mg-eq in the lower layer. Magnesium ranged from 2.94 to 4.90 mg-eq. Sodium was relatively stable (0.19–0.27 mg-eq), while potassium decreased from 1.08 in

the surface layer to 0.08 mg-eq at depth. All soils were characterized by the dominance of Ca²⁺ and Mg²⁺ over Na⁺ and K⁺. Population 1 showed the sharpest decrease in exchangeable bases with depth, Population 2 displayed the most gradual vertical change, and Population 3 retained relatively high Ca²⁺ values in the upper and middle horizons. (Wang et.al., 2023).

Soil salinity and ionic composition

Soil salinity is one of the key degradation processes determining the ecological condition of soils. The analysis of water-soluble salts provides important information on soil geochemical status and salinization intensity (Rengasamy, 2006). The composition of the soil water extract varied across the studied populations and soil depths (Table 2, 3). In Population 1, carbonates (CO₃²⁻) were absent or present only in trace amounts.

Table 2
Anion composition of soil water extract

Depth (cm)	Salts (%)	HCO ₃ ⁻ (mg-eq)	CO ₃ ²⁻ (mg-eq)	Cl ⁻ (mg-eq)	SO ₄ ²⁻ (mg-eq)
P1, 0–7	0.049	0.12	0	0.15	0.46
P1, 7–20	0.039	0.20	0	0.04	0.33
P1, 20–40	0.038	0.28	0.04	0.04	0.22
P1, 40–100	0.018	0.12	0.04	0.04	0.09
P2, 0–7	0.067	0.48	0.08	0	0.47
P2, 7–24	0.074	0.56	0.08	0	0.48
P2, 24–54	0.053	0.56	0	0.04	0.09
P2, 54–95	0.046	0.56	0	0.04	0.01
P3, 0–6	0.060	0.44	0.08	0	0.39
P3, 6–20	0.043	0.48	0	0	0.09
P3, 20–50	0.067	0.48	0.08	0	0.47
P3, 50–65	0.074	0.56	0.08	0	0.48

Table 3
Cation composition of soil water extract

Depth (cm)	Ca ²⁺ (mg-eq)	Mg ²⁺ (mg-eq)	Na ⁺ (mg-eq)	K ⁺ (mg-eq)
P1, 0–7	0.10	0.38	0.10	0.15
P1, 7–20	0.10	0.29	0.16	0.03
P1, 20–40	0.10	0.29	0.14	0.02
P1, 40–100	0.10	0.10	0.04	0.02
P2, 0–7	0.29	0.57	0.10	0
P2, 7–24	0.19	0.57	0.28	0
P2, 24–54	0.19	0.38	0	0.12
P2, 54–95	0.29	0.29	0.04	0
P3, 0–6	0.29	0.38	0.17	0
P3, 6–20	0.29	0.29	0	0
P3, 20–50	0.29	0.57	0.10	0
P3, 50–65	0.19	0.57	0.28	0

The content of bicarbonates (HCO_3^-) ranged from 0.12 to 0.28 mg-eq, chlorides (Cl^-) from 0.04 to 0.15 mg-eq, and sulfates (SO_4^{2-}) from 0.09 to 0.46 mg-eq. The total salt content decreased with depth from 0.049% to 0.018%, indicating weak accumulation of soluble salts in the upper horizons (Qadir and Schubert, 2002). In Population 2, the ionic composition was characterized by higher bicarbonate content (0.48–0.56 mg-eq) and relatively high sulfate concentrations (up to 0.48 mg-eq). The total salt content ranged from 0.046% to 0.074%, indicating a higher degree of salinity compared to Population 1. In Population 3, the ionic composition was similar to Population 2, with bicarbonates ranging from 0.44 to 0.56 mg-eq and sulfates up to 0.48 mg-eq. The total salt content varied between 0.043% and 0.074%, suggesting moderate accumulation of soluble salts. Population 2 and Population 3 are characterized by higher bicarbonate and magnesium contents, whereas Population 1 shows lower ionic concentrations and a clear decrease in salinity with depth. In all cases, the total salt content remains below 0.1%, indicating non-saline or weakly saline soils, reflecting natural geochemical conditions rather than anthropogenic salinization (Shrivastava and Kumar, 2015). The observed differences in soil moisture, granulometric composition, and salinity are closely interrelated and reflect the specific environmental conditions of each population. The predominance of silt fractions in Populations 1 and 2 contributes to higher water retention capacity, which explains the relatively higher moisture content in the upper soil horizons. In contrast, the increased proportion of sand fractions in Population 3 enhances water infiltration and drainage, resulting in a more dynamic moisture regime. At the same time, soil texture plays a key role in the distribution and accumulation of soluble salts. The finer texture of Populations 1 and 2 promotes the retention of water-soluble ions, whereas the relatively higher sand content in Population 3 facilitates leaching processes and limits excessive salt accumulation. This is consistent with the observed moderate salinity levels and the dominance of sulfate-bicarbonate type salinity in all studied soils. The combined influence of granulometric composition and moisture regime determines the vertical distribution of soluble salts and exchangeable cations, highlighting the importance of soil physical properties in controlling chemical processes in mountain soil systems (Mamurova et al., 2026).

Conclusions

The conducted study revealed significant differences in

the morphological, physicochemical, and granulometric properties of soils across the three studied populations in the Ile Alatau region. All soils are characterized by a light loamy texture, weakly alkaline reaction, and a predominance of calcium and magnesium in the exchange complex. The results showed that soil moisture, granulometric composition, and salinity are closely interrelated. The dominance of silt fractions contributes to higher water retention in Populations 1 and 2, while the increased sand content in Population 3 enhances drainage processes. The soils exhibit a sulfate-bicarbonate type of salinity with generally low to moderate salt accumulation. The vertical distribution of exchangeable bases indicates a clear predominance of Ca^{2+} and Mg^{2+} over Na^+ and K^+ , reflecting favorable soil conditions and limited salinization processes. Differences among populations are associated with variations in texture, moisture regime, and landscape position. The obtained results contribute to a better understanding of soil formation processes and ecological conditions in mountain ecosystems of Southeastern Kazakhstan and may serve as a basis for further studies of plant–soil interactions and sustainable land use.

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