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Ecological and anatomical features of the structure and adaptations of *Sibiraea altaiensis* (L.) Schneid. in the East Kazakhstan context

Sibiraea altaiensis (L.) Schneid. is a characteristic species of high-mountain ecosystems in Eastern Kazakhstan, *Sibiraea altaiensis* experiences intense solar radiation, sharp temperature fluctuations, low humidity, and nutrient-poor soils. This study presents a comprehensive ecological–anatomical analysis of the leaves and stems of *S. altaiensis* from natural populations of the Katon-Karagay National Park. Anatomical parameters were examined using classical microtechnical methods, morphometry, and statistical approaches. The leaf of *S. altaiensis* demonstrates a pronounced combination of xeromorphic and oromorphic traits. The leaf blade has a stable thickness, a well-developed cuticle, and a hypostomatic epidermis. A thickened palisade layer and a moderately variable spongy layer, reflecting adaptation to high insolation and limited moisture, characterize the dorsiventral mesophyll. The vascular bundles are reinforced with sclerenchyma, providing mechanical stability under strong winds. The stem is characterized by well-developed xylem, stable dimensions of vascular elements, and a thick periderm, which performs protective and mechanical functions. Correlation analysis revealed coherence among the main anatomical parameters, including leaf thickness, mesophyll structure, vascular bundle size, and xylem development. The weakly acidic, low-mineral soils of the habitats correspond to the moderate plasticity in mesophyll and conducting tissues. Thus, *S. altaiensis* exhibits a complex of anatomical and morphological adaptations enabling survival under extreme high-mountain conditions of the Kazakh Altai. These findings contribute to a better understanding of the adaptive evolution of Rosaceae taxa in Central Asia and are relevant for further taxonomic and conservation research.

Keywords: *Sibiraea altaiensis*, leaf anatomy, stem anatomy, high-altitude adaptations, ecological-anatomical analysis, East Kazakhstan, Katon-Karagay.

Introduction

Plants growing in the mountainous ecosystems of Central Asia form complex adaptive complexes, allowing them to successfully exist in conditions of extreme and highly variable climate. The Kazakhstan Altai is one of the most biodiverse regions of the country, characterized by high relief contrast, landscape mosaicism, and pronounced climatic zonality. These natural features create a wide range of ecological niches, which contributes to the formation of specific morphological and anatomical adaptations in plants inhabiting various altitudinal levels. The study of such adaptive mechanisms is key to understanding the evolution of high-mountain flora, assessing its resistance to climatic changes, and developing scientifically sound strategies for the conservation of the region's natural heritage [1].

Representatives of the genus *Sibiraea* Maxim. (Rosaceae Juss.) are typical inhabitants of mountainous regions of Eurasia and are characterized by high resistance to unfavorable environmental factors [2]. Special attention is given to *Sibiraea altaiensis* (L.) Schneid., which is widespread in Eastern Kazakhstan, including the territories of the Katon-Karagay State National Nature Park [3, 4]. This region is distinguished by a complex geomorphological structure, pronounced elevation gradients, the presence of glaciers, and intensive exogenous processes that create unique conditions for plant growth. The degree of terrain dissection, slope exposure, types of soil substrates, and moisture regimes determine the variety of ecological stresses experienced by vegetation—from sharp temperature fluctuations to low air humidity, strong winds, short periods of drought, and high solar radiation levels [5].

The conditions of mountain ecosystems impose strict requirements on the anatomical organization of plant leaves and shoots. It is at the anatomical level that key mechanisms of adaptation to moisture deficit,

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excessive insolation, mechanical stress, and low-temperature conditions are manifested. The thickness of the epidermis, the development of the cuticle, the degree of mesophyll differentiation, the density of venation, and the structural features of conducting and mechanical tissues all reflect the adaptive strategies of a species and determine its viability under extreme conditions. Moreover, anatomical traits often possess high diagnostic value and are widely used in the systematics of the Rosaceae family. For the genus *Sibiraea*, such data are particularly important, since morphological differences between closely related species are weakly expressed, whereas anatomical features can serve as additional informative criteria in taxonomic and phylogenetic studies [6].

Despite the ecological significance of *S. altaiensis* and its wide distribution in the mountainous regions of Eastern Kazakhstan, anatomical studies of this species remain limited. Previous descriptions have mainly focused on general morphology and did not address detailed aspects of leaf blade structure in relation to the natural conditions of the region. Meanwhile, current climate change, accompanied by shifts in temperature and moisture regimes, necessitates an in-depth analysis of the adaptive mechanisms of endemic and rare mountain flora species, among which S. *altaiensis* holds an important position [7].

Thus, conducting a comprehensive ecological–anatomical analysis of the leaves of *S. altaiensis* under the conditions of Eastern Kazakhstan is a relevant scientific task, allowing the identification of structural and functional features shaped by the specificity of the environment. The results of this study will help clarify the taxonomic position of the species, reveal its adaptive potential, and enhance our understanding of plant survival strategies in extreme mountain landscapes. In addition, the obtained data have practical value for monitoring natural populations and developing measures to conserve the biological diversity of the Kazakh Altai amid ongoing climatic transformations [8].

Experimental

The material for the study consisted of leaves and stems of *S. altaiensis* collected from natural wild populations in the East Kazakhstan within the Kazakh Altai. The main sampling site was located on the Sarymsakty Ridge (Southern Altai), in the open right-bank valley of the Taldybulak River and on the south-eastern slope of Mount Zhumsak-Asu (coordinates: N 49°06.355', E 086°07.890', elevation 1816 m). The area is characterized by a sharply continental climate with cold winters, short summers, significant daily temperature fluctuations, and high insolation. The soils are well-drained alluvial rocky loam substrates with moderate moisture, determined by precipitation and seasonal snowmelt. The vegetation of the territory belongs to mountain meadow–shrub communities, which correspond to the typical habitats of *S. altaiensis* in Eastern Kazakhstan (Fig. 1).

Figure 1. General view of *S. altaiensis* in its natural habitat (East Kazakhstan)

Leaf and young shoot samples were collected during the period of active growth (June–August). For each plant, 3–5 fully developed leaves from the middle canopy and segments of current-year stems were harvested. For anatomical analysis, the material was immediately fixed in FAA solution (formalin–acetic acid–70 % ethanol, 90:5:5 v/v/v) for 24–48 hours at room temperature, following the classical protocols of Johansen [9] and Sass [10]. After fixation, samples were rinsed with distilled water and stored in 70 % ethanol, in accordance with the recommendations of Berlyn & Miksche [11]. Transverse sections of leaves and stems were prepared using a Leica RM2125 RTS rotary microtome and manual microtomes, with section thickness maintained at 15–30 µm. For the differential identification of tissue complexes, a double staining with Safranin O and Astra Blue (Safranin O + Astra Blue) was applied following the protocols of Ruzin [12] and Kiernan [13]. In this procedure, lignified elements were stained red, whereas cellulose-rich tissues appeared bluish-green. After staining, the specimens were sequentially dehydrated in ethanol of increasing concentrations (70 %, 90 %, 96 %), cleared in xylene, and mounted in Canada balsam. Microscopic observations were performed using a Leica DM500 light microscope at magnifications of ×100–×400. Photo documentation was carried out with a Leica DFC290 HD digital camera using the Leica Application Suite software. Scale calibration was conducted using eyepiece and stage micrometers (100–500 µm). Image processing and morphometric analysis were performed in Image J 1.54f [14], without applying algorithms that distort tissue geometry. Morphometric analysis included measurements of leaf blade thickness, upper and lower epidermis thickness, palisade and spongy mesophyll thickness, main vascular bundle diameter, periderm thickness, phloem and xylem thickness, and the diameter of primary cortex and pith cells. For each parameter, 15–20 measurements were performed, and results were expressed in micrometers as mean ± standard error. Anatomical terminology follows Evert [15] and Kaplan [16]. Key tissue elements were annotated on micrographs, including epidermis, mesophyll, vascular bundles, xylem and phloem elements, cambium, periderm, collenchyma, and parenchyma.

To characterize the soil conditions of *S. altaiensis* habitats, soil (pH) and electrical conductivity (EC) were measured. Soil samples were collected from the upper root-inhabited horizon (0–20 cm) at the sites where the studied plants were growing. Composite samples were air-dried at room temperature, with large fragments of plant debris and stones removed. Soil pH was determined potentiometrically in a 1:2,5 (soil-to-distilled water suspension), following standard soil analytical procedures [17]. Measurements were performed using a portable pH meter with automatic temperature compensation. Prior to measurements, the instrument was calibrated with buffer solutions at pH 4,00, 7,00, and 10,00 according to the international ISO 10390 protocol [18]. pH values were recorded after stabilization of readings, and each analysis was performed in triplicate. Soil solution electrical conductivity (EC) was measured using a conductometric method in a 1:5 (soil-to-distilled water suspension), according to Rhoades et al. [19]. Values were expressed in millisiemens per centimeter (mS/cm), providing an estimate of soil salinity and overall ionic load. Temperature correction was applied automatically at 25 °C. All measurements were repeated at least three times, and mean values ± standard deviations were reported. The obtained pH and EC values were used to correlate the anatomical features of *S. altaiensis* with the soil conditions of its habitats. Soil parameters were interpreted based on the USDA Soil Survey classification [20], allowing assessment of soil acidity and mineralization levels in the context of the species' ecological adaptations.

For the analysis of anatomical traits of *S. altaiensis*, statistical processing of the data was performed, including the assessment of overall variability, testing for normality of distribution, and evaluation of relationships among the measured morphometric characteristics. All measurements were initially screened for outliers and assessed for normality using the [21], test, a standard approach for small biological datasets. When distributions deviated from normality, non-parametric methods were applied to evaluate differences between groups [22].

Correlation analyses were conducted to examine the relationships among epidermal thickness, mesophyll structure, vascular tissue parameters, and other anatomical features. Pearson's correlation coefficients were calculated for variables with normal distributions, while Spearman's rank correlation coefficients were applied for non-normally distributed data [23]. The strength of the observed correlations was interpreted following the classification of Evans (1996) [24], a standard reference widely used in biological research. To assess inter- and intra-population variability of morphometric traits, variance, standard deviation, and the coefficient of variation (CV) were calculated, enabling comparison of the degree of variability in tissue structural parameters [25]. Mean values between samples were compared using one-way analysis of variance ANOVA when assumptions of normality and homogeneity of variances were met. Homogeneity of variances was tested using Levene's test [26]. All statistical analyses were performed using RStudio (version 4.3.1) and Statistica 13.0, as well as ImageJ plugins for image analysis. This statistical approach not only quantitatively confirmed differences in anatomical parameters but also identified key structural relationships reflecting the adaptive mechanisms of *S. altaiensis* to the environmental conditions of Eastern part of Kazakhstan.

Results and Discussion

The analysis of *S. altaiensis* leaves from natural populations of Eastern Kazakhstan revealed a pronounced set of xeromorphic and oromorphic traits characteristic of high-mountain plants of Central Asia. Leaf blade thickness varied within a narrow range (447–512 μm), which is consistent with reported data on stable morphological characteristics of montane Rosaceae species (Table 1). Under the environmental conditions of Katon-Karagay National Park, plants are exposed to intense solar radiation, sharp diurnal temperature fluctuations, and periodic moisture deficits (Fig. 2–5). In such conditions, a compact and weakly variable leaf blade serves as a key adaptive mechanism that helps maintain turgor and reduce transpirational water loss. Similar patterns have been documented in species of the genera *Dasiphora* Raf., *Rosa* L., and *Spiraea* L., supporting the shared adaptive strategies of Rosaceae in response to extreme mountain environments [27].

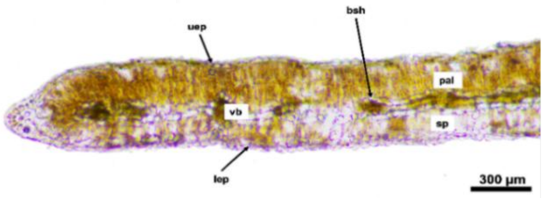

Figure 2. Marginal part of the leaf blade (*Margo folii*) in cross-section: uep — upper epidermis; lep — lower epidermis; pal — palisade parenchyma; sp — spongy parenchyma; bsh — bundle of sclerenchyma; vb — vascular bundle

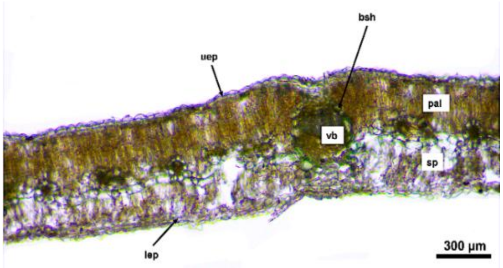

Figure 3. Central part of the leaf blade (*Pars centralis laminae folii*) in cross-section: uep — upper epidermis; lep — lower epidermis; pal — palisade parenchyma; sp — spongy parenchyma; bsh — bundle of sclerenchyma; vb — vascular bundle

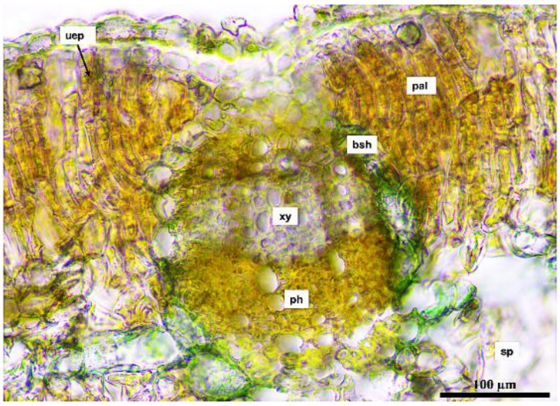

Figure 4. Central vein of the leaf blade (*Vena media laminae folii*) in cross-section: uep — upper epidermis; pal — palisade parenchyma; sp — spongy parenchyma; bsh — bundle of sclerenchyma; xy — xylem; ph — phloem

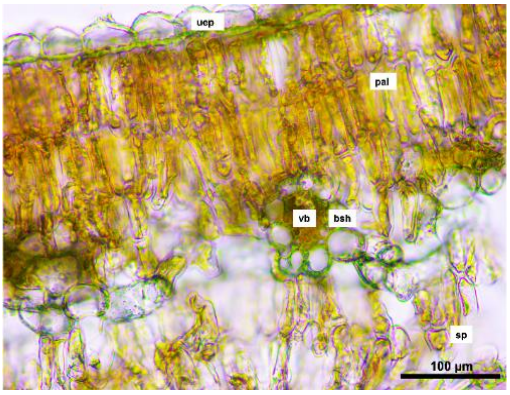

Figure 5. Upper part of the leaf blade (*Pars superior laminae folii*) in cross-section: uep — upper epidermis; pal — palisade parenchyma; sp — spongy parenchyma; bsh — bundle of sclerenchyma; vb — vascular bundle

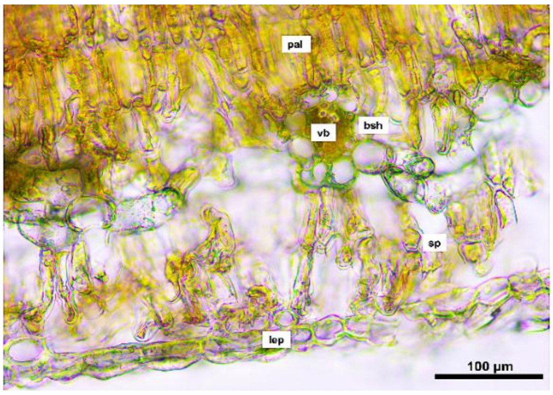

Figure 6. Lower part of the leaf blade (*Pars inferior laminae folii*) in cross-section: lep — lower epidermis; pal — palisade parenchyma; sp — spongy parenchyma; bsh — bundle of sclerenchyma; vb — vascular bundle

Table 1

Anatomical characteristics of the leaf (µm)

Indicator	Average	Standard deviation	Minimum	25 %	Median	75 %	Maximum
Leaf blade thickness (TLP)	476,55	19,79	447,10	461,91	473,53	491,94	511,65
Thickness of the upper epidermis (TVE)	22,66	2,08	20,20	21,09	22,59	23,27	27,23
Thickness of the lower epidermis (TLE)	24,12	2,78	19,81	21,76	24,93	26,45	27,40
Thickness of the palisade mesophyll (TPM)	194,62	23,18	164,61	170,48	201,67	208,62	227,34
Thickness of the spongy mesophyll (TGM)	126,49	18,09	94,66	114,33	128,26	135,23	153,77
Diameter of the main vascular bundle (DVB)	244,43	16,49	215,25	239,08	246,94	255,49	264,93

A thickened upper epidermis (up to 27 µm) and the formation of a dense cuticle are reliable barrier structures that, combined with the hypostomatic leaf type, limit water loss and protect tissues from photodestructive effects. Similar adaptations have been observed in species such as *Juniperus sabina* L., *Betula fruticosa* Pall., and *Spiraea alpina* Pall., which grow on rocky substrates in the East Kazakhstan and the Altai [28].

The palisade mesophyll of *S. altaiensis* was considerably thick (up to 227 μm), indicating a high level of photosynthetic activity. In mountain xeromorphic plants, an increase in the volume of palisade tissue is considered a key mechanism for enhancing photosynthetic efficiency under bright but often intermittent light [29]. A thick palisade mesophyll ensures effective light absorption and maintains high productivity of the photosynthetic apparatus, despite frequent cloud cover, fog, and daytime shading, which are typical for the Sarymsakty Ridge (Fig. 6–12).

The high variability in spongy mesophyll thickness (94–153 μm) may reflect the sensitivity of the aerenchyma structure to soil moisture and macronutrient availability. Comparative studies on *Tilia cordata* Mill. [30], *Caragana pygmaea* (L.) DC., and *Populus suaveolens* Fisch. have shown that the spongy mesophyll is the most plastic element of leaf anatomy, changing in response to fluctuations in water availability. The presence of mucilage canals and calcium oxalate druses corresponds to high metabolic activity of the tissues and specialized protective mechanisms against excess ions or herbivory.

The low variability in xylem thickness (CV < 3 %) confirms the structural stability. This is consistent with data from resilient oromorphic species such as *J. sabina*, *Spiraea chamaedryfolia* L., and *Dasiphora fruticosa* (L.) O. Schwarz, whose secondary xylem also demonstrates stability regardless of environmental variability [31].

The diameter of the main vascular bundle (215–265 μm) shows low variability, which is consistent with patterns observed in *Spiraea media* Schmidt. and *Prunus fruticosa* Pall. [32]. On mountain slopes, water transport is limited not only by moisture deficiency but also by sharp temperature fluctuations that can disrupt the continuity of transport pathways.

The stability of the vascular system parameters indicates a conservative water transport mechanism and a high degree of adaptation to stressful conditions. A pronounced sclerenchymatous sheath around the veins confirms the mechanical reinforcement of the leaf. The dense mechanical framework provides resistance to bending and tearing caused by strong winds typical of the montane-meadow regions of the Southern Altai. Similar traits have been observed in steppe and subalpine species such as *Rosa acicularis* Lindl. and *Cotoneaster melanocarpus* Ledeb., indicating common oromorphic adaptations of Rosaceae to physical stress (Table 2). In the stems of *S. altaiensis*, this represents one of the most important adaptive traits. Such reinforcement of the conductive xylem (778–854 μm) is typical for plants growing under conditions of cold nights, frost, and sharp temperature fluctuations, in which xylem is susceptible to cavitation. According to the works of Esau and Fahn, compensatory expansion of xylem elements is a typical response to the risk of disruption in the water column.

Table 2

Anatomical parameters of the stem (μm)

Indicator	**Average**	**Standard deviation**	**Minimum**	**25 %**	**Median**	**75 %**	**Maximum**
Periderm thickness (TPR)	74,29	2,78	69,35	73,31	74,37	75,76	78,86
Diameter of primary cortex parenchyma cells (DPC)	43,25	5,42	36,07	38,83	43,56	47,92	51,35
Phloem thickness (TFL)	432,17	137,80	44,73	462,84	474,96	481,89	517,85
Xylem thickness (TXL)	820,82	21,58	778,77	812,52	822,41	833,85	853,72
Diameter of pith cells (DPCe)	39,61	7,50	29,57	34,97	39,51	44,62	53,12

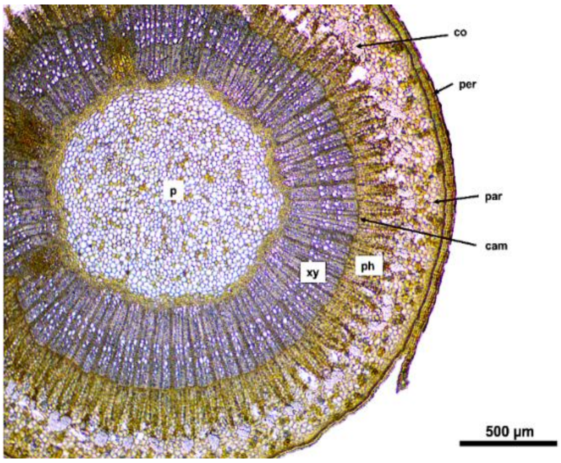

Figure 7. Cross-section of the stem (caulis): co — protective tissue (cuticle and epidermis); per — primary cortex; par — parenchyma tissue; cam — cambium; ph — phloem; xy — xylem; p — pith

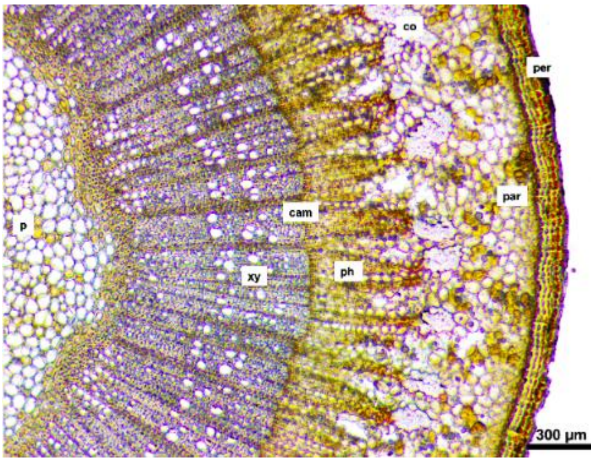

Figure 8. Right half of the stem (pars dextra caulis) in cross-section: co — protective cortex; par — parenchyma; cam — cambium; ph — phloem; xy — xylem; p — pith

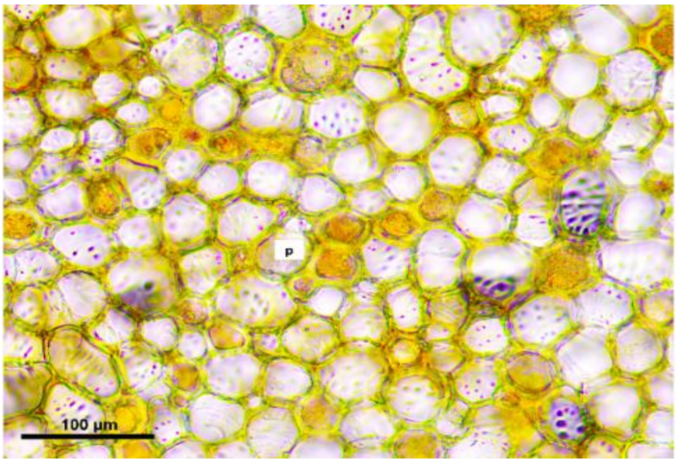

Figure 9. Pith of the stem (medulla caulis) in cross-section: p — pith parenchyma

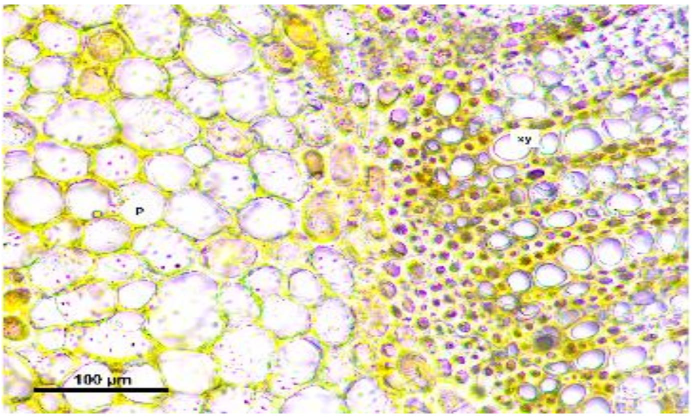

Figure 10. Transitional zone between the pith and the vascular system of the stem
(zona transitionis inter medullam et systema vascularium caulis)
in cross-section: p — pith parenchyma; xy — xylem

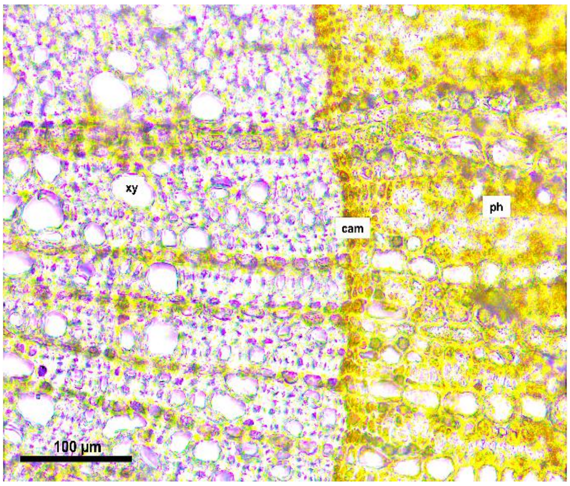

Figure 11. Cambial zone of the stem (zona cambialis caulis)
in cross-section: xy — xylem; cam — cambium; ph — phloem

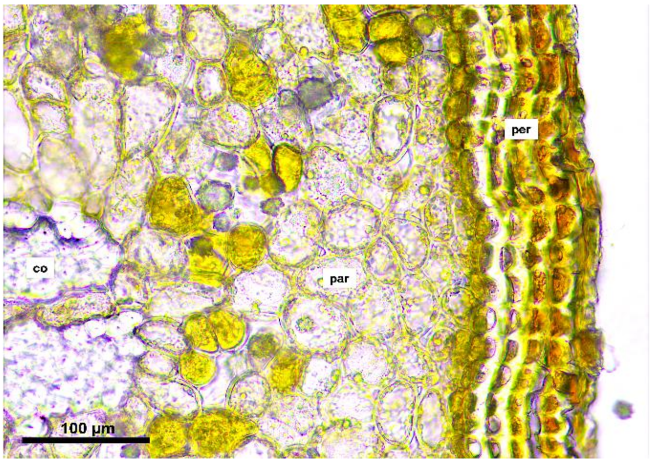

Figure 12. Peripheral part of the stem (margo caulis) in cross-section:
co — protective tissue (cuticle and epidermis); per — primary cortex; par — parenchyma

The phloem and primary cortex exhibited higher variability, which may reflect seasonal fluctuations in assimilate flow and carbohydrate redistribution. Similar fluctuations have been described in *T. cordata*, confirming general trends in woody plants of temperate-cold regions.

Soils at the studied sites were slightly acidic (pH 4.95–5.13) with moderate electrical conductivity (49–84 mV). These conditions are typical of high-mountain meadow soils, which are prone to leaching and base deficiency [33]. It was found that in areas with higher electrical conductivity, mesophyll thickening and reinforcement of vascular tissues were observed. This is consistent with models of soil ionic composition effects on the photosynthetic apparatus of plants.

The correlation matrix (Fig. 13) showed that leaf blade thickness is closely related to the diameter of the vascular bundle (r = 0.91); pith cell diameters negatively correlate with mesophyll thickness (r = –0.64); and stem xylem parameters correlate with phloem (r > 0.7).

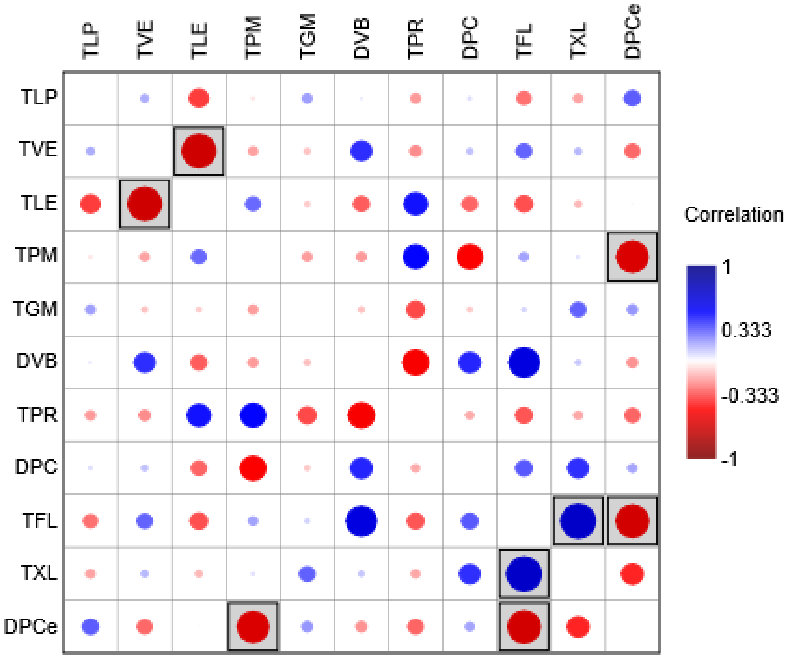

Figure 13. Correlation matrix of morpho-anatomical parameters of leaves and stems *S. altaiensis*

The strong correlation between leaf blade thickness and palisade mesophyll thickness (r = 0.88) highlights the structural integration of the photosynthetic apparatus. A similar relationship has been reported in arcto-alpine species such as *Salix glauca* L. and *Betula nana* L., where photosynthetic tissues form a stable adaptive module that enables plants to withstand extreme environmental conditions [34].

Such correlations indicate the presence of an interconnected anatomical system optimized for the mountain climate. Comparable structural linkages among anatomical modules have been documented in many high-mountain species, including *Betula rotundifolia* Spach, *S. glauca*, and various *Caragana* spp.

Anatomical and morphological analyses demonstrated that *S. altaiensis* develops a unique set of adaptive structures that ensure resilience under the high-altitude landscapes of Eastern Kazakhstan. The combination of a thickened palisade mesophyll, consistently developed xylem, a robust sclerenchymatous framework, and a hypostomatic leaf surface reflects an integrated survival strategy aimed at maintaining water balance, reducing transpiration, and enhancing mechanical strength of tissues. These features make *S. altaiensis* a valuable model species for understanding the adaptive responses of Central Asian flora to climate change and extreme ecological conditions.

Conclusion

Anatomical and morphological investigations of *S. altaiensis* revealed a set of stable structural features reflecting the species' profound adaptation to the extreme conditions of high-mountain ecosystems in Eastern Kazakhstan. The leaf blade exhibits pronounced xeromorphic traits, including a thick upper epidermis with a well-developed cuticle, a hypostomatic leaf type, and a compact mesophyll organization. The thick palisade mesophyll ensures high photosynthetic efficiency under intense solar radiation, whereas the spongy mesophyll regulates gas exchange and contributes to maintaining water balance under limited moisture availability.

The presence of a robust sclerenchymatous sheath surrounding the veins and the stable dimensions of vascular bundles indicate high mechanical resistance of the leaf—an essential adaptation to withstand wind exposure and mechanical stress typical of mountainous landscapes. Stem anatomy, characterized by a well-developed xylem, stable wood parameters, and moderately variable phloem, further supports the adaptive strategy of the species, ensuring efficient water transport and structural stability of shoots under sharp temperature fluctuations and periodic water deficits.

Correlation analysis of morphometric traits revealed strong relationships among leaf blade thickness, mesophyll parameters, vascular bundle diameter, and the development of stem xylem. These interconnections confirm the presence of an integrated anatomical system capable of optimizing plant functions in response to abiotic conditions. Such structural coherence is typical of high-mountain species of Central Asia and reflects an evolutionarily established survival strategy in extreme environments.

Thus, *S. altaiensis* represents a highly adapted species with well-defined anatomical and morphological features that confer resilience to climatic and edaphic stresses of the Kazakh Altai. The findings expand current scientific understanding of ecological–anatomical adaptations in Rosaceae under mountain conditions, refine the diagnostic characteristics of the species, and may serve as a basis for future taxonomic, floristic, and ecological research. The results are also significant for monitoring natural populations of *S. altaiensis* and for developing biodiversity conservation strategies under intensifying climate change.

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Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript. CRediT: **Alemseitova Zh.K. —** data collection and primary processing of research materials; **Myrzagaliyeva A.B. —** supervision, methodological guidance, and project oversight; **Kusmangazinov A.B. —** investigation, anatomical analyses, and fieldwork support; **Alimtay G.A. —** investigation, anatomical analyses, and fieldwork support; **Irsaliyev S.A. —** supervision, methodological guidance, and total funding; **Orazov A.E. —** validation, verification of analytical procedures, and scientific editing.

Conflict of Interest

The authors declare no conflict of interest.

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Sibiraea altaiensis **(L.) Schneid. өсімдігінің Шығыс Қазақстан жағдайындағы экологиялық-анатомиялық ерекшеліктері мен бейімделуі**

Sibiraea altaiensis (L.) Schneid. өсімдіктері қарқынды күн радиациясының, температураның күрт ауытқуының, төмен ылғалдылықты және топырақтың әсерін нашар сезінетін Шығыс Қазақстанның биік таулы экожүйелеріне тән түр. Бұл зерттеуде Катонқарағай ұлттық паркінің табиғи популяцияларынан *S. altaiensis* жапырақтары мен сабақтарына кешенді экологиялық-анатомиялық талдау жасалды. Анатомиялық параметрлер классикалық микротехникалық әдістерді, морфометрияны және статистиканы қолдана отырып зерттелген. *S. altaiensis* жапырағы ксеро- және ороморфты белгілердің айқын кешенін көрсетеді. Жапырақ тақтасының қалыңдығы тұрақты, қабығы жақсы дамыған, эпидермисі гипостоматты және бірнеше типті. Дорсивентральды мезофилл қалың палисадты қабатымен және орташа өзгермелі борпылдақ қабатымен сипатталып, бұл жоғары инсоляция мен шектеулі ылғал жағдайына бейімделгенін көрсетеді. Өткізгіш шоқтар склеренхимамен нығайтылған, бұл қатты желдерге механикалық төзімділікті арттырады. Сабағы жақсы дамыған ксилемамен, өткізгіш элементтердің тұрақты өлшемдерімен және қалың перидерма қабатымен ерекшеленеді, бұл құрылым су транспортының тиімді жүйесін қалыптастырады. Корреляциялық талдау негізгі анатомиялық параметрлердің дәйектілігін көрсетті, олар: жапырақ қалыңдығы, мезофилл құрылымы, өткізгіш сәулелердің мөлшері және ксилеманың дамуы. Тіршілік ету ортасының топырағы аздап қышқыл, минералдануы төмен-мезофилл мен өткізгіш тіндердің орташа икемділігіне сәйкес келеді. Осылайша *S. altaiensis* қазақстандық Алтайдың биік тауларының экстремалды жағдайларында өмір сүруді қамтамасыз ететін анатомиялық-морфологиялық бейімделулердің бірегей кешеніне ие. Алынған мәліметтер Орталық Азиядағы *Rosaceae* тұқымдасының өкілдерінің бейімделу эволюциясын тереңірек түсінуге мүмкіндік береді және таксономиялық әрі табиғат қорғау зерттеулері үшін маңызды.

Кілт сөздер: Sibiraea altaiensis, жапырақ анатомиясы, сабақ анатомиясы, биіктаулы бейімделулер, экологиялық-анатомиялық талдау, Шығыс Қазақстан, Катонқарағай.

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Эколого-анатомические особенности строения и адаптаций *Sibiraea altaiensis* (L.) Schneid. в условиях Восточного Казахстана

Sibiraea altaiensis (L.) Schneid. — характерный вид высокогорных экосистем Восточного Казахстана, где растения испытывают воздействие интенсивной солнечной радиации, резких температурных колебаний, низкой влажности и бедных почв. В данном исследовании выполнен комплексный эколого-анатомический анализ листьев и стеблей *S. altaiensis* из природных популяций Катон-Карагайского национального парка. Анатомические параметры изучены с использованием классических микротехнических методик, морфометрии и статистики. Лист *S. altaiensis* демонстрирует выраженный комплекс ксеро- и ороморфных признаков. Листовая пластинка имеет стабильную толщину, хорошо развитую кутикулу, гипостоматический эпидермис. Дорсивентральный мезофилл характеризуется утолщённым палисадным слоем и умеренно вариабельным губчатым слоем, что отражает адаптацию к высокой инсоляции и ограниченной влаге. Проводящие пучки усилены склеренхимой, обеспечивая механическую устойчивость при сильных ветрах. Стебель отличается развитой ксилемой, стабильными размерами сосудистых элементов и толстой перидермой, формирующими эффективную систему водного транспорта. Корреляционный анализ показал согласованность основных анатомических параметров — толщины листа, структуры мезофилла, размеров проводящих пучков и развития ксилемы. Почвы местообитаний — слабокислые, с низкой минерализацией — соответствуют умеренной пластичности мезофилла и проводящих тканей. Таким образом, *S. altaiensis* обладает уникальным комплексом анатомо-морфологических адаптаций, обеспечивающих выживание в экстремальных условиях высокогорий Казахстанского Алтая. Полученные данные углубляют понимание адаптивной эволюции представителей Rosaceae Центральной Азии и важны для дальнейших таксономических и природоохранных исследований.

Ключевые слова: Sibiraea altaiensis, анатомия листа, анатомия стебля, высокогорные адаптации, эколого-анатомический анализ, Восточный Казахстан, Катон-Карагай.

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