



Adaptation Features of *Gentiana tianschanica* Rupr. Populations to Environmental Factors in Kazakhstan

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Abstract

The study investigates the current state, floristic composition, and ecological characteristics of *Gentiana tianschanica* populations in the Ile-Alatau region, part of the Ile-Alatau National Park, Kazakhstan. *Gentiana L.*, an ancient boreal genus, includes 31 species in Kazakhstan, such as the endemic *Gentiana dschungarica*. Known for medicinal uses, especially for gastrointestinal and urogenital disorders, interest in gentians has risen for ornamental and pharmacological applications. Nine natural populations of *G. tianschanica* were studied in diverse ecological and phytocoenotic conditions of the Ile-Alatau mountains. Soil analyses revealed significant differences in the physicochemical properties of the species' habitats. In the Kimasar Gorge, mountain-meadow chestnut soils with a light loamy texture were observed, while the Big Almaty Gorge featured dark chestnut soils rich in humus (7.36–18.78%) and nutrients such as nitrogen (120.4–140.0 mg/kg), phosphorus (58–98 mg/kg), and potassium (470–1000 mg/kg). These findings emphasize the species' adaptation to varying altitudinal and climatic zones. Phytochemical analysis showed *G. tianschanica* is rich in bioactive compounds, including phenolics, bitter glycosides, flavonoids, and alkaloids. Total phenol content reached 1567.17–9008.20 mg of gallic acid/100 g, with the highest levels in leaves. Flavonoids (up to 1358.25 mg catechin/100 g) and vitamin C (up to 244.7 mg/100 g) were significant. Syringic acid (1685.8 mg/100 g), quercetin (317.4 mg/100 g), and chlorogenic acid (237.5 mg/100 g) highlighted antioxidant and anti-inflammatory potential. The antioxidant activity, particularly in leaves, reached 530.30 mg Trolox/100 g. Anthropogenic threats, including overgrazing and habitat disturbance, have led to declining populations, necessitating conservation strategies like habitat monitoring, protective regimes, and sustainable medicinal plant use. This study underscores the ecological and phytochemical significance of *G. tianschanica*, which is vital for biodiversity conservation and pharmaceutical development.

Keywords: *G. tianschanica*; Ile-Alatau; Population; Ecological adaptation; Medicinal plants; Soil; Phenolic compounds.

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1. Introduction

The genus *Gentiana* is one of the oldest boreal genera, comprising over 350 species distributed in the temperate latitudes of Eurasia, North America, and the Himalayas. (Fig. 1) These plants play a key role in mountain and foothill

ecosystems by stabilizing the soil, preventing erosion, and providing nourishment for pollinating insects. In Kazakhstan, 31 species of the genus are registered, including the endemic *Gentiana dschungarica* Regel., highlighting the richness and uniqueness of the region's flora.^[1,2]

Historical data indicate that plants of the genus *Gentiana*, including *G. tianschanica*, have been used by humans for millennia. In Ancient Egypt, gentians were used to treat digestive diseases, infections, and fevers. In Ancient Greece, the plant is mentioned in the works of Dioscorides, who described it as a remedy to strengthen the body and treat various illnesses. The name of the genus is linked to the Illyrian king Gentius, who, according to legend, used gentian to combat epidemics. In Ancient Rome, it was used to improve digestion, treat liver diseases, and stimulate appetite.^[3]

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Fig. 1 *G. tianschanica* in the Kaskelen Gorge (A), Big Almaty Gorge (B) and Kimasar Gorge (C) population.

In the Middle Ages, gentian was one of the main plants used in European pharmacy. It was used to treat inflammatory diseases, infections, liver and stomach disorders. The plant was grown in monastery gardens and widely used in tinctures and decoctions as an antiseptic and antipyretic agent.^[4]

Traditional medicine in Asia is also highly valued gentian. In Tibetan and Chinese medicine, plants of the genus *Gentiana* were used to reduce inflammation, treat gastrointestinal diseases, improve blood circulation, and restore energy. These properties remain relevant in modern medicine, where gentian-based preparations are used for the prevention and treatment of chronic diseases.^[5]

G. tianschanica is a representative of the high-mountain ecosystems of Central Asia and is found on grassy slopes, in spruce forests, and among shrub vegetation. This species plays an important role in maintaining ecosystem balance, being part of complex herbaceous communities that provide biodiversity and soil stabilization.^[6] The flowers of the plant attract pollinating insects, supporting the pollination process and contributing to the overall productivity of the ecosystem. The

root systems of *G. tianschanica* strengthen mountain slopes, preventing soil erosion.^[7]

From a pharmacological perspective, *G. tianschanica* is a promising subject for study due to its content of biologically active compounds, including bitter compounds, phenolic acids, flavonoids, and alkaloids. These compounds possess antioxidant, anti-inflammatory, and antimicrobial properties, making the plant valuable for the development of modern pharmaceutical drugs.^[8]

Historically, plants of the genus *Gentiana* have been used in many different cultures due to their unique properties. They have been used both for medicinal purposes and in culinary applications, particularly in the creation of beverages and functional foods. Their bitter taste and rich composition contributed to their popularity in traditional dietary systems.^[9] The plants of the genus *Gentiana* have long been used to prepare beverages that stimulate appetite and digestion. In France and Italy, the roots of gentians were used to create herbal liqueurs, which were consumed before meals as aperitifs.^[10] These drinks not only stimulated digestion but were also considered to strengthen the body. Italian bitters and French tinctures included gentian as a main ingredient, giving the drinks a unique bitter taste.^[11]

In the Alpine region, gentian-based beverages were traditionally considered remedies for restoring strength after strenuous physical labor. In Germany and Switzerland, gentian tinctures were used to improve digestion and treat stomach disorders.^[12]

In Asia, gentian was used to create herbal teas and medicinal infusions. In Tibetan medicine, gentian drinks were used for detoxification and energy restoration, while in Chinese culture, they were considered a means to strengthen health and fight infections. Despite the bitter taste, some parts of gentian were consumed in food. In the mountainous regions of Asia, young shoots and leaves of the plant were added to vegetable dishes, soups, and stews. They were soaked or

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boiled to reduce bitterness before being included in nutritious and medicinal meals. In Europe, gentian was sometimes added to herbal mixtures used for making soups. These dishes were popular during epidemics, as it was believed they strengthened the body and prevented diseases.^[13]

The main nutritional value of gentian is linked to its ability to stimulate appetite and improve digestion. Gentian tinctures and decoctions have long been used to treat digestive disorders, improve appetite, and relieve stomach heaviness. Its bitter substances stimulate receptors on the tongue, activating the production of gastric juices and other enzymes. This property has made gentian an important component in both folk and modern medicine.^[14]

Gentian is becoming an increasingly popular ingredient in functional foods. The plant's extracts are used to enrich vitamin complexes, herbal teas, and dietary beverages. They not only give products a characteristic taste but also enhance their nutritional value due to their antioxidant and anti-inflammatory properties.^[15]

Teas and beverages based on gentian help improve metabolism, relieve fatigue, and restore strength. Modern functional products with gentian include energy drinks, herbal infusions, and vitamin complexes.^[16]

Gentian has traditionally been used in the creation of pharmaceuticals and supplements aimed at improving digestion. Due to its content of antioxidants and other active substances, it could also become an ingredient in foods aimed at preventing chronic diseases associated with inflammatory processes.^[17]

In animal husbandry, gentian has been used as a feed additive to improve animals' appetite and increase their productivity. This experience could be used to create natural additives in modern agro-industry.^[18]

Gentian has entered the folklore and cultural traditions of many peoples. In the Alps, gentian was considered a symbol of health and longevity, and in some Eastern cultures, it was believed to be a plant capable of cleansing the body from toxins. These beliefs contributed to its use not only in medicine but also in rituals and culinary practices.^[19]

Modern research confirms the significance of gentian in the creation of functional and medicinal products. Its extracts could become the basis for natural tonics, herbal teas, vitamin drinks, and even dietary bars. This makes gentian a promising plant for further study and use in the food industry.^[20]

This species is rare and occupies a limited range, including the mountainous regions of Central Asia, particularly Kazakhstan, where it is found predominantly in the Ile-Alatau. However, anthropogenic impacts such as overgrazing, plant collection, and habitat destruction have led to a decline in population numbers. These threats are exacerbated by the species' limited range and climate change, making it especially vulnerable.^[21]

The relevance of studying *G. tianschanica* lies in the need to develop scientifically justified conservation measures. Studying the ecological and phytocoenotic characteristics of

its habitats, the factors influencing population numbers, and the pharmacological potential of the plant will not only help preserve this species but also utilize its potential for the development of the pharmaceutical and biomedical industries.^[22]

The aim of this research is to study the state of *G. tianschanica* populations in the Ile-Alatau region, with a focus on their ecological features and the factors of anthropogenic influence. The research objectives include analyzing habitat conditions, assessing the impact of anthropogenic factors on population numbers, and developing recommendations for the conservation and sustainable use of the species.^[23]

2. Materials and methods

2.1 Material preparation

The study was conducted during the spring periods of 2023 and 2024 in the southeastern part of Kazakhstan, in the Ile-Alatau region. The work focused on three main gorges: the Kimasar Gorge, the Big Almaty Gorge, and the Kaskelen Gorge. These areas are located within the State National Natural Park "Ile-Alatau" and are characterized by unique topographical, climatic, and ecological conditions, making them significant for studying biodiversity and ecosystem processes. The Big Almaty Gorge is located on the northern slope of the Ile-Alatau along the Big Almaty River. The gorge is divided into two large branches — the Prokhodnaya River valley and the Ozernoe Gorge. This area is known for its picturesque landscapes and rich flora, including rare and endemic species, making it important for ecological and geological research. The Kimasar Gorge, also known as Kimasar, is part of a complex ravine system located in the Small Almaty Valley. The Kimasar camp is located here, and the Gorge ends at the Kimasar Pass. The area is characterized by a variety of herbaceous and shrub vegetation, unique microclimates, making it a key site for studying the ecosystems of mountain regions. The Kaskelen Gorge is located in the western part of the Ile-Alatau and has been part of the State National Natural Park "Ile-Alatau" for over ten years. The area is rich in plant communities, has a complex terrain, and a variety of ecological conditions. It serves as an important site for monitoring environmental changes and their impact on local plant populations.^[24]

The topography of the Ile-Alatau region is characterized by a complex structure formed by a combination of erosion and tectonic processes. The mountainous areas consist of highland and mid-mountain zones with steep slopes formed by tectonic processes. The plain areas are located in the foothills and include lowland areas with gentle terrain, covered with dense herbaceous and shrub communities. This diversity of terrain contributes to the formation of unique habitats and enriches the region's ecosystem.^[25]

Voucher specimens were deposited in the herbarium at the Institute of Botany and Phytointroduction, Almaty, Kazakhstan. Plant species collected during the field geobotanical expedition were verified using the "Illustrated

Guide to Identification of Plants of Kazakhstan." The classification of genera followed Abdullina, and species names were cross-referenced with S.K. Cherepanov. Plant identification was conducted using the identification keys provided in the *Flora of Kazakhstan*. The voucher samples were transferred for storage to the herbarium fund of the "Institute of Botany and Phytointroduction," Almaty, Kazakhstan. Herbarium No. 6509.^[26]

2.2 Geobotanical methods

To study the current state of *G. tianschanica* populations in their natural habitats, fieldwork using a route reconnaissance method was planned for the territory of the Ile-Alatau in the Almaty region. Four expeditions were conducted during different periods of the species' vegetation. The expedition routes in the western part of the Ile Alatau passed through mid-mountain and high-mountain areas, covering the ridges of the Ile Alatau.

Methodology for Plot Establishment. The methodology for assessing the density and abundance of the studied species follows the program and methodology for observing cenopopulations of species. The population studies of *G. tianschanica*, including plant morphology, ecological-phytocenotic characteristics of populations, age structure, seed productivity, and the viability of cenopopulations and individuals, will be conducted in accordance with existing methodologies. To characterize the ecological features of the species, descriptions of the ecological factor levels were used. The ecological scale levels were determined on-site in specific natural habitats.^[27]

To study the geographical distribution of *G. tianschanica*, a route reconnaissance method was applied, and classical, widely accepted methodologies for studying plant morphology in cenopopulations, phytocoenoses, ecology, and biology were also used. Determining the species composition of plant communities was carried out using relevant botanical guides, handbooks, and other sources such as *Flora of Kazakhstan*, *Plant Identifier of Central Asia*, and family structures based on A.L. Takhtejan's system. Species and genera within families are arranged alphabetically.^[28]

2.3 Phytochemical research methods

The analysis of phenolic compounds in the roots of *G. tianschanica* was conducted using high-pressure liquid chromatography. For this, the samples were dried, ground, and subjected to extraction using aqueous-organic solutions. The extracts were filtered and concentrated. Chromatographic columns were used for component separation, and identification was carried out using standard samples.^[29]

The vitamin C content was determined using the same method. Samples of flowers and roots were dried, ground, and extracted. Component separation was performed on chromatographic columns, and comparison of characteristics was done using standards.^[30]

The sugar content in the leaves was analyzed using chromatography. The leaves were dried, ground, and extracted with aqueous solutions. Identification of glucose, fructose, and sucrose was performed using standard samples.^[31]

All methods allowed for accurate identification and quantitative assessment of biologically active substances, vitamins, and carbohydrates in the plant.^[32]

2.4 Mapping and fieldwork

Crop production mapping at a medium scale (1:250,000) was conducted using topographic maps and satellite imagery. To achieve this, detailed route and landscape-ecological profiling were applied. The contour map was created using ArcGIS 10.8 software, utilizing satellite images with a medium spatial resolution shuttle radar topography mission (SRTM) at 90 m resolution) and compared with topographic maps (Fig. 2).

Fieldwork followed the methodologies established by Alibek Ydyrys et.al., which served as the foundation for research and literature from the Zhongar Alatau. In addition, herbarium specimens from the Institute of Botany and Phytointroduction were incorporated into the study.^[33]

Drawing on these sources, systematic geobotanical characteristics were formulated for the study area, including ecological and phytocenotic classifications, which involved processing, analyzing, and organizing the collected data. The geobotanical characterization of plant communities and landscape-ecological profiling were conducted, with herbarium specimens being collected alongside vegetation surveys in all studied habitats.^[34]

2.5 Air Temperature, precipitation, and growing season characteristics

The climate of the region varies depending on the altitude and distance from the oceans. In the foothills, mild climatic conditions prevail, with warm summers and cool winters. In the spruce belt, summers become moderately warm, and winters are mild with abundant sunny days. The high-mountain areas are characterized by a long snow cover, harsh climate, and significant temperature fluctuations. In such conditions, specialized plant communities are formed and adapted to the extreme environmental factors.^[35]

These climatic and topographical features make the Ile-Alatau region a unique area for studying plant adaptation to challenging conditions. The studied Gorges provide important data for analyzing the ecological behavior and adaptive mechanisms of species such as *G. tianschanica*. These studies allow for a deeper understanding of the functioning of mountain ecosystems and the development of effective conservation measures.

Figure 2 presents the air temperature, precipitation, and growing season characteristics for 2023-2024 in the study area. The meteorological data were sourced from the official website of "Kazhydromet" (<https://www.kazhydromet.kz/ru/>), specifically from the "Meteorological Database" section under

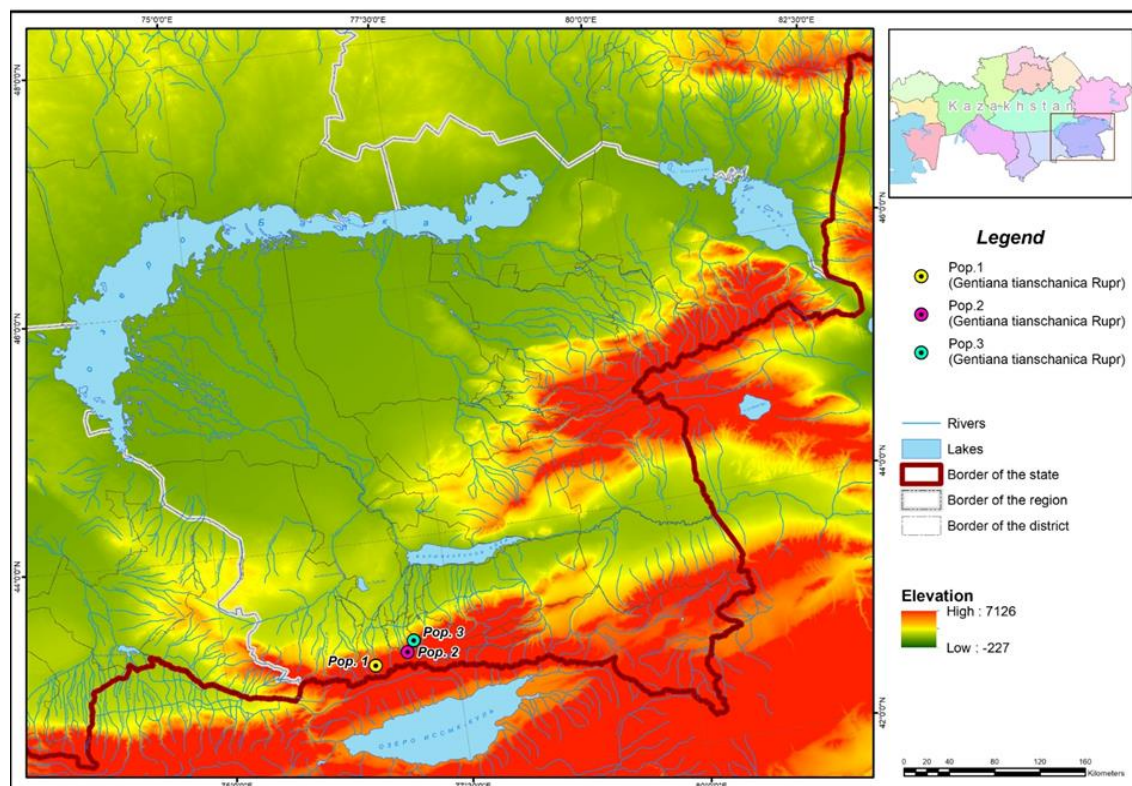


Fig. 2 Map of Study Areas. Population 1: Degeres-say Gorge, north-western slope, elevation 937 m. Population 2: Arkharly Pass, north-eastern slope, elevation 1041 m. Population 3: Ile River floodplain, north-eastern slope, elevation 610 m.

"Interactive Maps and Data."

The comparative description of the climatic characteristics of the elevation belts shown in the figure demonstrates the changes in climatic conditions depending on the altitude, which is clearly reflected in the comparison of three elevation zones: the foothills, the spruce belt, and the alpine belt. Each zone has its own specific features, which depend on the altitude and the associated climatic factors. Summer temperatures gradually decrease with increasing altitude. In the foothills, summer is the warmest, promoting active

vegetation growth. In the spruce belt, temperatures are moderate, creating suitable conditions for coniferous forests. In the alpine belt, summer is short and cool, limiting vegetation to mainly herbaceous and shrub forms. Winter temperatures also change with altitude. In the foothills, winters are relatively mild, although temperatures can drop below zero. In the spruce belt, winter conditions become colder, which is typical for coniferous forests. In the alpine belt, winters are the harshest, with consistently low temperatures, creating extreme conditions for plant survival.

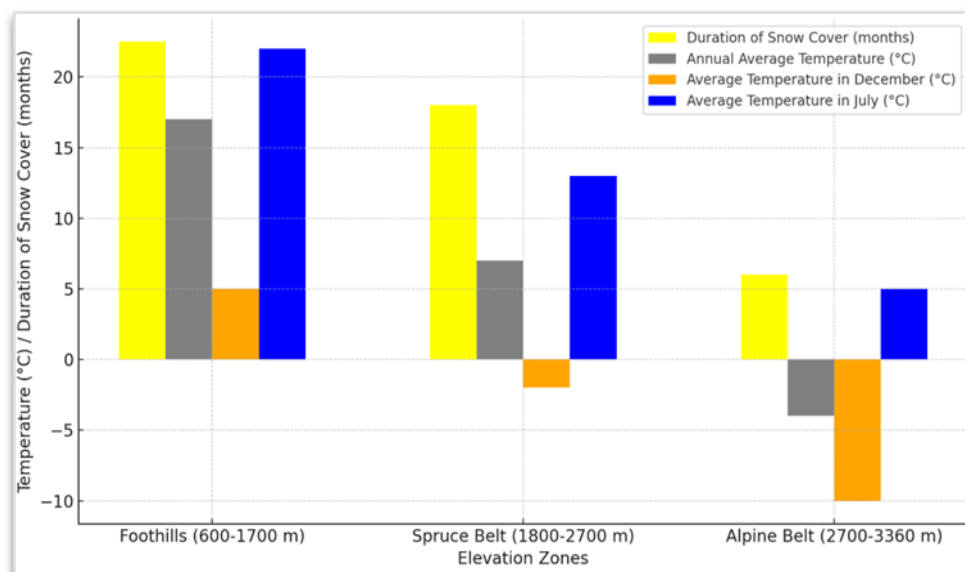


Fig. 3 Climatic characteristics across elevation zones.

The annual average temperature gradually decreases from the foothills to the alpine belt. The climate in the foothills is more favorable for diverse flora and fauna, while in the spruce belt, the temperature is lower, which supports the dominance of cold-resistant plants. (Fig. 3) In the alpine belt, the annual average temperature is the lowest, which is explained by long snow periods and a short growing season. The duration of snow cover increases with altitude. In the foothills, snow cover lasts for a short period due to the milder climate. In the spruce belt, snow remains for a longer time, related to the higher precipitation and cold climate. In the alpine belt, snow cover persists for most of the year, creating extreme conditions for vegetation and soil processes.^[36]

2.6 Soil analysis

The research employed a combination of field work and laboratory analysis to comprehensively study the soil characteristics of the *G. tianschanica* populations across the Kimasar, Big Almaty, and Kaskelen Gorges.

Field studies involved documenting the natural conditions of the study sites and establishing soil transect profiles to evaluate their morphological characteristics. Soil samples were collected systematically from varying depths for subsequent laboratory analysis. Field procedures, including sampling and sample preparation, followed standardized methodologies ensuring consistency and accuracy in data collection.^[37]

Laboratory analysis was conducted to determine the chemical properties and granulometric composition of the collected soil samples. The following parameters were analyzed using established GOST standards (state standard): *Mobile nutrient elements*: Nitrogen, phosphorus, and potassium (GOST 26205-91). Salt content and ionic composition: *Anions* (CO_3^- , HCO_3^- , Cl^- , SO_4^{2-}) and cations (Ca^{2+} , Mg^{2+} , Na^+ , K^+) (GOST 26425-85). pH levels: Measured in aqueous soil extracts (GOST 26423-85). Organic matter content: Humus (GOST 23740-79). *Carbonates*: CO_2 content (GOST 26425-85).

The granulometric composition of the soil was also analyzed to classify its texture and understand its impact on soil fertility, water retention, and plant growth.

This comprehensive methodology provided a detailed understanding of the soil profiles and their chemical and physical properties, allowing for meaningful comparisons between the studied populations and contributing to insights into the habitat requirements of *G. tianschanica*.^[38]

2.7 Vegetation sampling

In the study area, 100 m² sample plots were used to record vegetation cover and ecological characteristics. A detailed form was used to document data including GPS coordinates, elevation, topography, soil type, and vegetation cover. Life forms of plant species identified on the southern macrosurface were classified according to the systems.^[39]

The data obtained were analyzed using the Statistical

Package for the Social Sciences (SPSS, version 20 and the independent sample t-test, with a significance level set at 5%. Data analysis was conducted using Microsoft Office software for statistical processing. Correlation analysis was performed using RStudio software (RStudio Team, 2015).^[40]

3. Results and discussion

3.1 Botanical features and geographical location

G. tianschanica is a mesophyte with a Tarbagatai-Tian-Shan-Himalayan range, a perennial plant, 15-30(35) cm in height. The rhizome is short, with cord-like vertical roots. The stems are solitary or in groups of 2-3, erect or ascending, glabrous, and at the base, they are covered with fibrous sheaths of old leaves. The leaves are linear-lanceolate, 7-20 cm long, 10-20 mm wide, collected in a basal rosette at the base of the stem, numerous, tapering to the base and apex, 3-5-veined, with rough or smooth edges; the stem leaves are linear-lanceolate, 5-8 cm long, 6-15 mm wide, spaced apart, and fused at the base into a sheath. The flowers are on short pedicels, located in the axils of the upper leaves, and form a loose inflorescence or clusters. It blooms in July-August and fruits in August-September.

It grows in steppes, along river valleys, in spruce forests, and on grassy mountain slopes, in open areas, among herbaceous and shrub vegetation, at an altitude of 1800–2700m.

The distribution area of *G. tianschanica* includes the western part of China, Tibet, and the Himalayas.

Description of habitats of *G. tianschanica* :

We studied 9 natural cenopopulations (CP) of *G. tianschanica* growing in different communities in the Ile Alatau region. The first population of *G. tianschanica* is located in the Kaskelen Gorge of the Kaskelen District, Almaty Region. The Kaskelen Gorge is approximately 30 kilometers southwest of Almaty, in the northern part of the Ile Alatau. The Gorge extends for several tens of kilometers and is part of the Ile-Alatau National Park. The Kaskelen Gorge is a very picturesque and quite popular spot located in the Ile Alatau within the Ile-Alatau National Park (Fig. 4).

The second population of *G. tianschanica* is located in the upper part of the Small Almaty Gorge, in the Kimasar Gorge, which starts from the final stop at Medeu, located in the Ile-Alatau National Park, Medeu District, Almaty Region. The third population of *G. tianschanica* was discovered in the area of the Big Almaty Lake, in the Big Almaty Gorge of the Bostandyk District, Almaty Region Table 1.

3.2 Floristic description of *G. tianschanica* populations

In the studied area, three populations of *G. tianschanica* have been discovered. The *G. tianschanica* population is one of the species that is critically affected by anthropogenic impacts, including trampling by livestock and collection for bouquets. The populations of this species require not only comprehensive study but also the development of conservation measures to protect their habitats. The territory

Table 1. Ecological and vitality characteristics of populations in different phytocenotic associations.

Population name and locality	Ecological and Phytocenotic association	Area of CP (m ²)	Number of Pre-generative Individuals per 10 m ²	Vitality indicators of CP
Kaskelen Population	Shrub-grassland-herbaceous phytocenosis	150	4	58 generative individuals. Young, weakly progressing, capable of self-maintenance through both seed and vegetative means, steadily maintaining its territory.
Kaskelen Population (1)	Shrub-grassland-herbaceous phytocenosis	150	6	45 generative individuals. Normal type, actively progressing, reproducing both sexually and vegetatively.
Kaskelen Population (2)	Shrub-meadow-herbaceous phytocenosis	150	5	95 generative individuals. Weakly progressing, with a right-sided spectrum, aging, but with satisfactory renewal. Despite strong suppression and competition in the phytocenosis, the population is striving to occupy new territories.
Kaskelen Population (3)	Creeping grass-herbaceous phytocenosis	120	3	150 generative individuals. Ecotype in meadow-herbaceous phytocenoses actively progressing, left-sided spectrum, highly regenerating by seed.
Kimasar Population (1)	Shrub-meadow-herbaceous phytocenosis	100	3	89 generative individuals. The population's state in meadow-herbaceous communities is good, the species steadily occupies new territories. Ecological amplitude is low. Renewal is stable and high.
Kimasar Population (2)	Tree-shrub-herbaceous meadow phytocenosis	170	2	30 generative individuals. The population in sedge and horsetail phytocenoses is characterized as normal, with a left-sided spectrum, progressing, with high renewal.
Kimasar Population (3)	Tree-shrub-herbaceous meadow phytocenosis	200	3	107 generative individuals. Stable, slow-developing communities with high density and competition. Ecotype reproduces predominantly by seed, with high renewal.
Big Almaty Gorge Population (1)	Meadow-herbaceous phytocenosis	250	5	165 generative individuals. Ecotype in meadow-grassland phytocenoses actively progressing, left-sided spectrum, progressing with high seed renewal. Capable of occupying new territories.
Big Almaty Gorge Population (2)	Meadow-sedge phytocenosis	180	6	315 generative individuals. Developed, normal, with satisfactory renewal. Despite extreme conditions, the ecotype occupies new territories and faces high competition in the vegetation.
Big Almaty Gorge Population (3)	Tree-herbaceous meadow phytocenosis	250	7	165 generative individuals. Stable, with a high regeneration rate. The population remains viable under tough conditions.

of the studied area in the Ile Alatau is characterized by complex and highly dissected terrain.

As a result of expeditionary surveys, three main populations were identified and named according to the geographical location of the sites: Kaskelen population (Pop. 1), Kimasar population (Pop. 2), and Small Almaty population

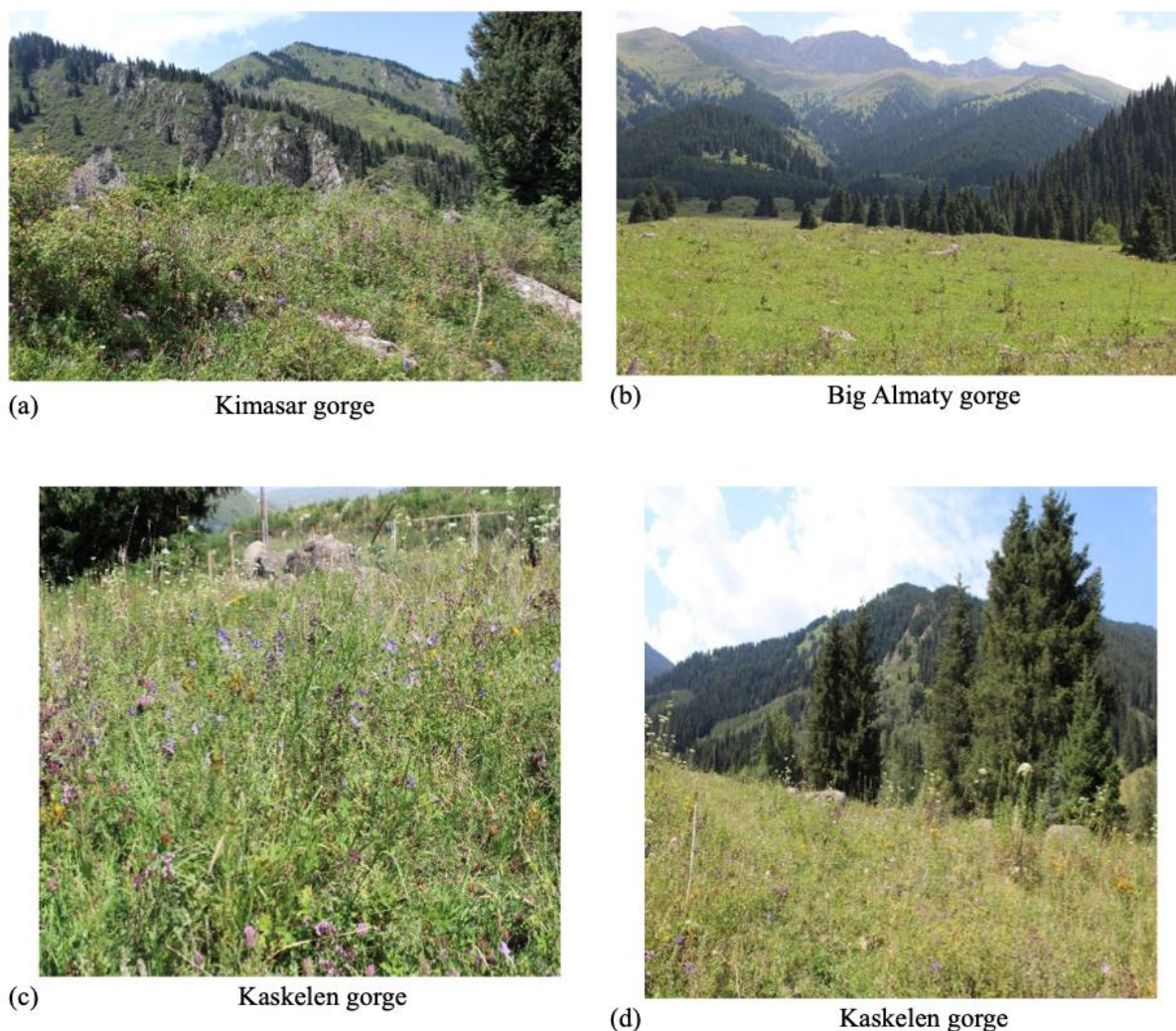


Fig. 4 Populations of *G. tianschanica* in Different Gorges of Kazakhstan.

(Pop. 3). Three locations of *G. tianschanica* populations were recorded in different ecological-phylogenetic conditions: among forest-meadow mixed herbaceous, shrub-herbaceous-grass vegetation.

3.3 Specific population details

3.3.1 Description of the *G. tianschanica* population (Pop 1)

The study of the *G. tianschanica* populations was conducted in the Kaskelen Gorge, located in the Ile-Alatau region of the Almaty Province. This area is known for its diversity of ecosystems, making it an ideal site for studying the biological and ecological characteristics of rare and valuable plant species. During the study, three spatially isolated populations were identified, each with unique ecological and phytocenotic characteristics. This allowed for a detailed study of the influence of various natural factors such as light, humidity, soil composition, and phytocenotic environment on the adaptive capabilities of *G. tianschanica*.

Each population was thoroughly described in terms of topography, vegetation cover, and age structure. The habitat conditions ranged from dense coniferous forests to open meadow slopes, which revealed a wide range of ecological

preferences for the species. Additionally, the study included an analysis of the impact of anthropogenic factors, such as livestock grazing, recreational load, and changing climatic conditions, on the state and stability of the populations.

The data obtained not only expand our knowledge of the ecology and biology of *G. tianschanica*, but also highlight the importance of preserving the biodiversity of the region, especially in the face of increasing anthropogenic impact and climate change. The results of the study serve as the basis for developing recommendations for conservation and sustainable use of natural resources, and underscore the importance of the species as an object for further ecological, pharmacological, and biological research.

The population is located on the northeastern slope in the middle mountain zone, providing optimal conditions for its development [Table 2](#). The topography of the area is characterized by undulating slopes, creating a variety of microhabitats that are favorable for plant growth. The soils are rich in humus, with good water retention and aeration, which promotes vegetation productivity and the formation of a stable plant community.

Table 2. The herbaceous cover of the population is dense and clearly divided into four layers.

	Height (cm)	Main Species	Functions and Role in the Ecosystem
First Layer	150-250	<i>Cotoneaster oliganthus</i> , <i>Rosa alberti</i> , <i>Juniperus sabina</i>	Forms the upper layer, creating shade and protecting lower layers from wind and erosion.
Second Layer	70-120	<i>Helictotrichon tianschanicum</i> , <i>Aconitum soongaricum</i>	Maintains the structure of the phytocenosis, supports community stability, and serves as a food base for insects.
Third Layer	40-75	<i>Poa nemoralis</i> , <i>Geranium rectum</i>	Strengthens the soil, helps retain moisture, and forms the base of the herbaceous cover.
Fourth Layer	Up to 30	<i>Trifolium repens</i> , <i>Fragaria vesca</i>	Protects the soil from erosion and maintains its moisture and nitrogen fixation ability.

3.3.2 Description of the *G. tianschanica* population in Kaskelen Gorge (Pop 1)

The study of *G. tianschanica* populations was conducted in the Kaskelen Gorge, located in the Ile-Alatau region of the Almaty Province. This region is known for its diverse ecosystems, making it an ideal site for studying the biological and ecological characteristics of rare and valuable plant species. During the study, three spatially isolated populations were identified, each with unique ecological and phytocenotic characteristics. This allowed for a detailed study of the influence of various natural factors, such as light, humidity, soil composition, and phytocenotic environment, on the adaptive abilities of *G. tianschanica*

Each population was thoroughly described in terms of topography, vegetation cover, and age structure (Table 3). The habitat conditions ranged from dense coniferous forests to open meadow slopes, which revealed a wide range of ecological preferences for the species. Additionally, the study

included an analysis of the impact of anthropogenic factors, such as livestock grazing, recreational pressure, and changing climatic conditions, on the state and stability of the populations.

The data obtained not only expand our knowledge of the ecology and biology of *G. tianschanica*, but also highlight the importance of preserving the biodiversity of the region, especially in the context of increasing anthropogenic impact and climate change. The results of the study serve as the foundation for developing recommendations for the conservation and sustainable use of natural resources and emphasize the significance of the species as an object for further ecological, pharmacological, and biological research. The population is located on the northeastern slope in the middle mountain zone, providing optimal conditions for its development. The topography of the site is characterized by undulating slopes, creating diverse microhabitats that are favorable for plant growth. The soils are rich in humus, with

Table 3. Structural layers and their ecological roles in phytocenoses.

Layer	Description	Key Species	Role in Ecosystem
First Layer	The first layer consists of shrubs, such as <i>Cotoneaster oliganthus</i> , <i>Rosa alberti</i> , and <i>Juniperus sabina</i> . These plants create the upper layer.	<i>Cotoneaster oliganthus</i> , <i>Rosa alberti</i> , <i>Juniperus sabina</i>	Protects lower layers from drying out and wind, provides shade, improving conditions for other plants.
Second Layer	The second layer includes tall herbaceous plants, such as <i>Helictotrichon tianschanicum</i> and <i>Aconitum soongaricum</i> . These plants play an important role in maintaining the structure of the community.	<i>Helictotrichon tianschanicum</i> , <i>Aconitum soongaricum</i>	Maintains phytocenosis structure and stability, provides food for insects and animals.
Third Layer	The third layer consists of medium-height grasses, such as <i>Poa nemoralis</i> and <i>Geranium rectum</i> . These species help strengthen the soil, retain moisture, and form the basis of the herbaceous cover.	<i>Poa nemoralis</i> , <i>Geranium rectum</i>	Strengthens soil, retains moisture, forms the basis of herbaceous cover.
Fourth Layer	The fourth layer is represented by low-growing species, such as <i>Trifolium repens</i> and <i>Fragaria vesca</i> . These plants perform an important function in the ecosystem.	<i>Trifolium repens</i> , <i>Fragaria vesca</i>	Protects soil from erosion, maintains moisture, promotes nitrogen fixation, improves soil quality.

good moisture retention and aeration, which promotes vegetation productivity and the formation of a stable plant community.

The herbaceous cover of the population is dense and clearly expressed in four layers:

The ecological conditions of the population include humus-rich soils, moderate humidity, and diffuse lighting, which create a favorable microclimate. The site is protected from strong winds due to the topography, supporting the stability of the ecosystem. The species composition is diverse, including grasses, shrubs, and herbs, which collectively ensure the stability of the plant community. Among them, certain species play a key role in maintaining the structure of the phytocenosis and improving soil conditions.

The population performs important functions in the ecosystem. It protects the soil from erosion, enriches it with organic matter, supports biodiversity by providing habitat for various organisms, and regulates the microclimate by reducing temperature and humidity fluctuations. However, anthropogenic factors, such as livestock grazing and recreational activities, impact the population and may lead to habitat degradation. Grazing contributes to soil compaction and destruction of the herbaceous cover, while tourist pressure exacerbates these processes.

To conserve the population, measures should be implemented to protect its habitat, including controlling livestock grazing, regulating tourist activities, and monitoring the state of plant communities. These measures will help maintain its stability and biodiversity, as well as support the ecosystem functions of the area.

The population is characterized by the dominance of adult generative individuals, which form the core of its structure. These plants ensure the population's stability, serving as the primary reproductive units. They actively participate in seed reproduction, forming a new generation of plants and maintaining the population's numbers.

Juvenile and immature individuals are fewer in number and are primarily concentrated in areas with favorable ecological conditions, such as sites with optimal moisture levels and soft

soils. Such habitats support their survival and growth, providing the necessary conditions for their development. Young plants are particularly sensitive to changes in the microclimate and humidity, so their distribution reflects the most stable and favorable microhabitats.

The age structure of the population is balanced, which indicates its viability and ability to sustain itself. The presence of all age groups, including juvenile, immature, and generative individuals, points to an active process of renewal and adaptation to environmental conditions. This also highlights the importance of preserving habitats with optimal ecological parameters to support population size and stability.

The phytocenosis is characterized by high biodiversity, with dominant and accompanying species that play key roles in defining its structure, ecological functions, and stability. The distribution of species in the phytocenosis can be described as follows: Dominant plants, such as *Elytrigia repens*, make up 40% of the total herbaceous cover. These plants play a crucial role in strengthening the soil and forming the lower layer. Shrub species, including *Rosa alberti*, *Cotoneaster oliganthus*, and *Juniperus sabina*, occupy 20%. They form the upper layer, protecting the lower layers of vegetation and creating a favorable microclimate.

Tall herbaceous species, such as *Aconitum soongaricum* and *Helictotrichon tianschanicum*, constitute 15%. These plants help with pollination and form the middle layer, protecting the lower layers from excessive sunlight. Medium-height grasses, including *Dracocephalum nutans* and *Poa nemoralis*, also make up 15%. They contribute to biodiversity and the resilience of the ecosystem.

Low-growing plants, such as *Fragaria vesca* and *Trifolium repens*, occupy 10%. These species play an important role in nitrogen fixation, improving soil fertility, and maintaining the microclimate. This distribution of species demonstrates how the phytocenosis is effectively organized to maintain stability and ecological resilience.

3.3.3 Description of the *G. tianschanica* population in big Almaty Gorge (Pop 2)

Table 4. Community composition and dominance of plant categories.

Category of Plants	Main Species	Percentage in the Community Composition (%)
Dominant Grasses	<i>Elytrigia repens</i>	40
Shrub Species	<i>Rosa alberti</i> , <i>Cotoneaster</i> , <i>Juniperus</i>	20
Tall Herbaceous Species	<i>Aconitum soongaricum</i> , <i>Helictotrichon</i>	15
Medium-height Grasses	<i>Dracocephalum nutans</i> , <i>Poa nemoralis</i>	15
Low-growing Species	<i>Fragaria vesca</i> , <i>Trifolium repens</i>	10

The plant cover of the area located on the northeast slope at an altitude of 1992 meters above sea level is characterized by high density, with a projected coverage of up to 100%. It is composed of four tiers, each with its own specific features.

The first tier reaches a height of 150 to 200 centimeters and is represented by shrubs such as *Spiraea lasiocarpa*, *Juniperus sabina*, and *Rosa alberti*. These plants play an important role in the ecosystem by forming dense thickets that protect the soil from erosion and contribute to moisture retention Table 4.

The second tier includes tall herbaceous plants, ranging in height from 70 to 110 centimeters. These include *Anthoxanthum odoratum* and *Helictotrichon tianschanicum*, which actively participate in biomass accumulation and soil stabilization. These species help prevent erosion and create favorable conditions for the growth of other plants.

The third tier consists of medium-height grasses, ranging from 35 to 75 centimeters. These include *Geranium rectum* and *Poa nemoralis*. These plants play a key role in improving soil structure, retaining moisture, and maintaining biodiversity. The plant cover of this site is characterized by resilience to external influences and high density. The multi-layered structure of the vegetation creates favorable conditions for various organisms, promotes the circulation of nutrients, and supports the stability of the ecosystem.

The fourth tier (up to 30 cm) consists of low-growing plants such as *Astragalus chlorodontus* and *Fragaria vesca*. The age spectrum of the population demonstrates its stable state, as it includes both generative adult individuals, ensuring reproduction, and a significant number of young plants, indicating successful natural regeneration. This ratio of age groups helps maintain the population's numbers and stability in complex ecological conditions.

Dominant species include grasses such as *Elymus tianschanigenus*, *Elymus sibiricus*, and associated species such as *Mentha asiatica* and *Aconitum soongaricum*. These

species ensure the stability of the phytocoenosis. The phytocoenosis of the second population of *G. tianschanica* is characterized by a rich species composition and a high degree of biodiversity (Fig. 5). Despite the presence of *G. tianschanica* in this community, it plays a secondary role, comprising about 1.5% of the total plant cover. Its low proportion in the vegetation suggests that the species is not dominant but occupies more of a companion ecological niche.

The basis of the herbaceous layer is formed by several species, primarily from the grass family: *Elymus tianschanigenus* Czerep., *Elymus caninus* (L.) L., *Elymus sibiricus* L., and *Elytrigia repens* (L.) Nevski. These plants exhibit high ecological plasticity, are well adapted to local conditions, and play a crucial role in stabilizing the soil cover. Their dense growth forms the dominant structure of the phytocoenosis, supporting biogeochemical cycles and creating favorable conditions for other plants. Additionally, the phytocoenosis contains a significant number of secondary companion species, whose diversity highlights the high degree of heterogeneity of the community. These species are unevenly distributed across the space and occupy various ecological niches, playing an important role in maintaining the biodiversity of the ecosystem. Among them are both grasses and members of other families. The most frequently encountered species include *Vicia sepium* L. (sol), *Poa bulbosa* L. (cop2), *Dactylis glomerata* L. (sol), *Alyssum desertorum* Stapf. (sp), *Geranium collinum* Steph. (sol), *Asperugo procumbens* L. (sol), *Nonea caspica* (Willd.) G. Don. (sp), *Ixiolirion tataricum* (Pall.) Schult. & Schult. (sp), and *Geranium transversale* (Kar. & Kir.) Vved. (cop1). These plants are important elements of the herbaceous layer, enriching the ecosystem with a diversity of forms, sizes, and adaptive strategies (Fig. 6). Also present are species with rare occurrences, such as *Stellaria media* (L.) Vill., *Achillea asiatica* Serg., *Achillea millefolium* L., *Taraxacum*

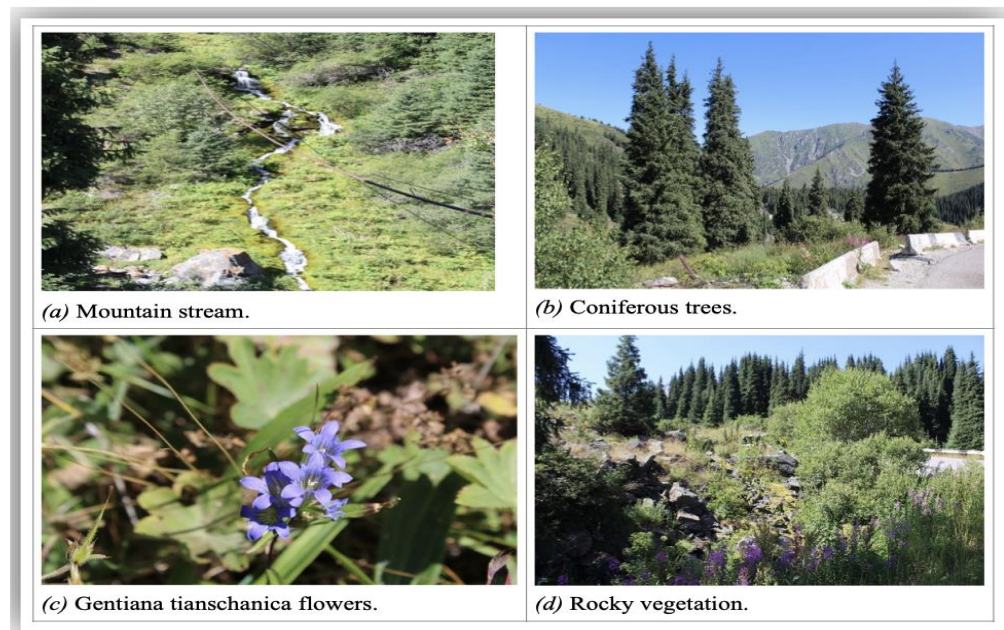


Fig. 5 Landscape features of population 2 in the Big Almaty gorge.

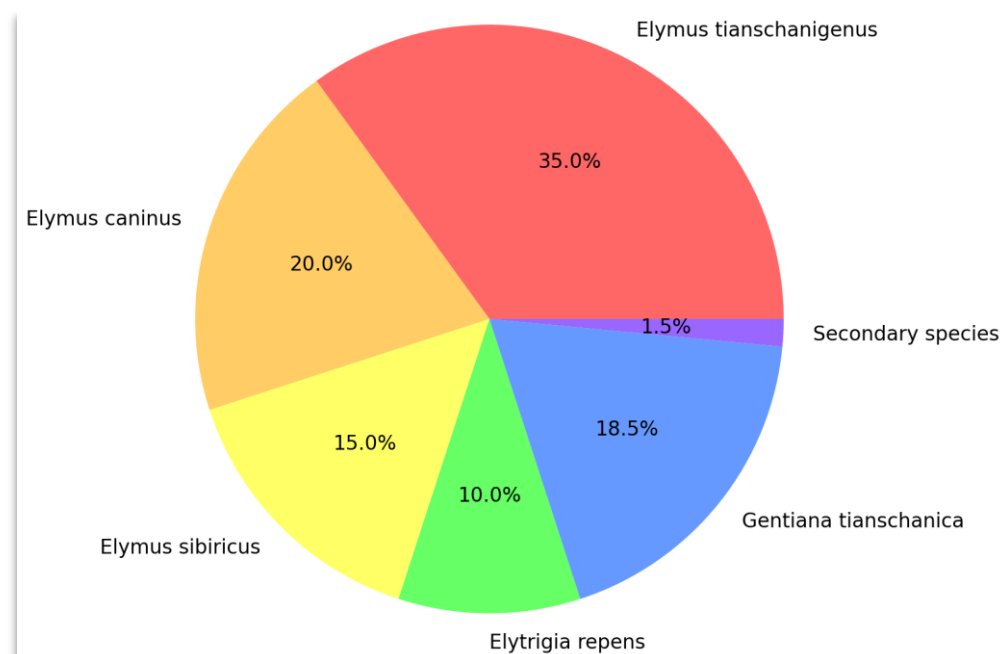


Fig. 6 Percentage composition of species in the second phytocoenosis of *G. tianschanica*.

longipyramidatum Schischk., *Arctium lappa* L., and *Cerastium arvense* L., which play a supportive role in the biocoenosis. These plants complement the ecosystem with their specific properties, influencing soil structure, microclimate, and nutrient cycling.

Special attention is given to members of the genus *Euphorbia*, such as *Euphorbia rapulum* Kar. & Kir. and *Euphorbia pilosa* L., whose chemical composition may affect the growth and development of other plants. Other species, such as *Iris alberti* Regel. and *Ranunculus polyrhizos* Stephan ex Willd., add aesthetic value to this phytocoenosis and also enrich the soil with organic matter.

Among the grasses, notable species include *Festuca sulcata* Hack., *Agropyron pectiniforme* Roemer & Schultes, and *Anisantha tectorum* L., which play an important role in preventing soil erosion and forming a stable turf layer.

Less frequent but still important species include *Sisymbrium loeselii* L., *Berteroa incana* (L.) DC., *Cardamine impatiens* L., *Myosotis sylvatica* Ehrh. & Hoffm., and *Medicago lupulina* L., which contribute to maintaining ecosystem balance and perform auxiliary functions in the biocoenosis.

Thus, the second phytocoenosis of *G. tianschanica* represents a complex and diverse plant community, where grasses play a dominant role, and a variety of secondary species support the ecological balance and resilience of the entire ecosystem. The high species richness and functional diversity highlight the importance of preserving such communities for maintaining biodiversity and the natural balance of the region.

3.3.4 Description of the *G. tianschanica* population in Kimasar Gorge (Pop 3)

Located on the northeast slope at an altitude of 2200 meters

above sea level, this population forms a shrub-grassland-forb phytocoenosis (Fig. 7). The plant cover is characterized by high density, reaching a projected coverage of up to 100%. The ecological conditions of the area are favorable for plant development: the moderate slope helps retain moisture, and the dark-brown clay soils, rich in humus, provide high productivity for vegetation. The relief, climatic features, and soil fertility create a stable ecosystem that supports biodiversity. The plant cover of this phytocoenosis exhibits distinct stratification, which is an indicator of the complex structure of the community and the adaptation of plants to various conditions of light, humidity, and soil fertility (Table 5).

The first layer consists of shrubs such as *Spiraea lasiocarpa* and *Cotoneaster melanocarpus*. These plants play a key role in protecting the lower layers from direct sunlight, helping retain moisture in the soil, and preventing erosion. *Cotoneaster melanocarpus* also has ornamental value and serves as a food source for some bird species.

The first layer consists of shrubs such as *Spiraea lasiocarpa* and *Cotoneaster melanocarpus*. These plants play a key role in protecting the lower layers from direct sunlight, helping retain moisture in the soil, and preventing erosion. *Cotoneaster melanocarpus* also has ornamental value and serves as a food source for some bird species.

The second layer includes tall herbaceous plants, such as *Artemisia dracunculus*, known for its essential oils and biochemical activity, and *Helictotrichon tianschanicum*, a grass species actively involved in strengthening the soil cover and forming the herbaceous layer. These plants also help maintain ecological balance by playing a role in nutrient cycling.

The third layer consists of medium-height grasses, such as *Geranium pratense*, which has medicinal properties and

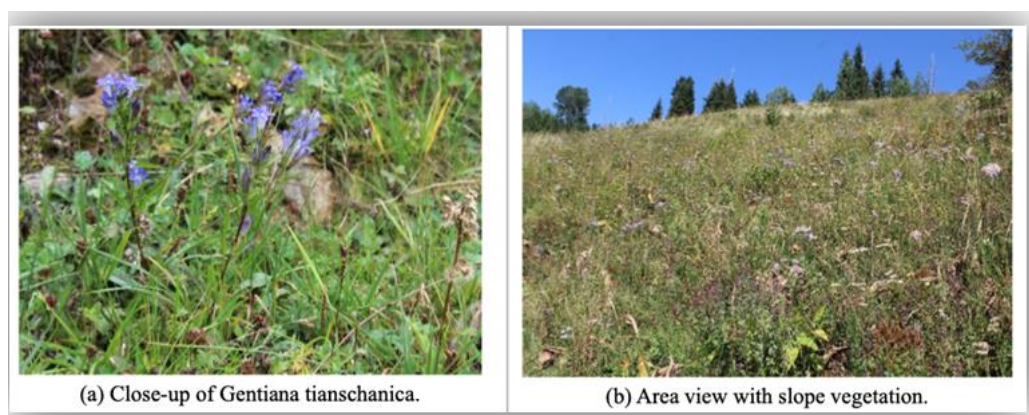


Fig. 7 Habitat features of population 3.

Table 5. Functional roles of plant Layers in the ecosystem.

Layer	Plants	Role in the Ecosystem
First Layer	<i>Spiraea lasiocarpa</i> , <i>Cotoneaster melanocarpus</i>	Protects lower layers from direct sunlight, retains soil moisture, prevents erosion, provides food for birds.
Second Layer	<i>Artemisia dracunculus</i> , <i>Helictotrichon tianschanicum</i>	Contributes to soil cover strength, participates in nutrient cycling, maintains ecological balance.
Third Layer	<i>Geranium pratense</i> , <i>Poa pratensis</i>	Provides medicinal benefits, enhances herbaceous layer with large flowers, protects soil from evaporation/compaction.
Fourth Layer	<i>Trifolium repens</i> , <i>Fragaria vesca</i>	Fixes nitrogen to improve soil fertility, provides food for insects and small animals.

enhances the herbaceous layer with its large flowers, and *Poa pratensis*, which helps create a dense grass cover that protects the soil from evaporation and compaction.

The fourth layer consists of low-growing plants, including *Trifolium repens* and *Fragaria vesca*. *Trifolium repens* (white clover) has the ability to fix nitrogen from the air, which improves soil fertility, while *Fragaria vesca* (wild strawberry) plays an important ecological role by providing a food base for insects and small animals.

The phytocoenosis in the Kimasar Gorge demonstrates a high degree of species diversity. In addition to the main species, numerous companion plants are found, which play an important role in maintaining ecosystem balance. For example, grass species such as *Festuca sulcata* and *Agropyron pectiniforme* contribute to soil stabilization, while leguminous species like *Astragalus skorniakowii* enrich the soil with nitrogen.

The plants forming the phytocoenosis not only ensure the stability of the ecosystem but also support the diversity of fauna. Shrubs and grasses provide shelter and food for birds, small mammals, insects, and microorganisms. Nitrogen-fixing species such as *Trifolium repens* and endemic plants like *Helictotrichon tianschanicum* play a key role in nutrient cycling.

The Kimasar Gorge ecosystem plays an important role in maintaining the ecological balance of the region. Its high productivity and biodiversity contribute to soil stabilization,

prevention of erosion, and preservation of the water balance. Given the richness of the flora, the ecosystem requires constant monitoring, as anthropogenic factors such as grazing, plant collection, and climate change may negatively affect its condition.

It is recommended to conduct regular studies on the dynamics of plant composition and soil condition in order to develop measures for the conservation and restoration of the ecosystem. Engaging the local community in ecological education and sustainable natural resource management will help preserve the unique nature of the Kimasar Gorge.

The age composition of the population shows an even distribution between generative and young individuals, indicating its stability and ability for natural regeneration. Generative plants provide active flowering and fruiting, maintaining population numbers, while young individuals form the foundation for long-term survival. Juvenile plants are predominantly found in areas with high moisture levels, which are optimal conditions for rooting and growth. These areas are characterized by high humus content and stable soil moisture, creating a favorable environment for seed germination and the development of young plants.

The even distribution of age groups indicates balanced ecological processes within the population and its adaptability to various environmental conditions. These features of the age spectrum play an important role in maintaining the ecological stability and biodiversity of this community.

The phytocoenosis of the third population of *G. tianschanica* is characterized by a diverse species composition, indicating a high level of biodiversity and ecosystem resilience. However, as in the second phytocoenosis, *G. tianschanica* occupies a secondary position, comprising about 11-17% of the overall structure of the community. Dominant grasses make up 65%, *G. tianschanica* occupies 15%, and secondary species account for 20% (Fig. 8). This emphasizes the role of grasses in ensuring community stability, as well as the significance of secondary species and *G. tianschanica* in maintaining biodiversity.

The herbaceous layer is dominated by grass species such as *Elymus tianschanigenus*, *Elymus caninus*, *Elymus sibiricus*, and *Elytrigia repens*. These species form a dense cover, performing functions of soil stabilization, erosion prevention, and moisture retention, which creates favorable conditions for the growth of other plants.

Secondary species make a significant contribution to the ecological resilience of the phytocoenosis. These include plants that participate in forming the herbaceous layer, such as *Vicia sepium*, *Poa bulbosa*, and *Dactylis glomerata*. *Alyssum desertorum*, *Geranium collinum*, and *Asperugo procumbens* enrich the soil with organic matter, improving its fertility. Plants such as *Achillea asiatica* and *Achillea millefolium* have ornamental and medicinal value, while species like *Taraxacum longipyramidatum*, *Arctium lappa*, and *Euphorbia rapulum* play a role in the food chain, providing a food base for local fauna.

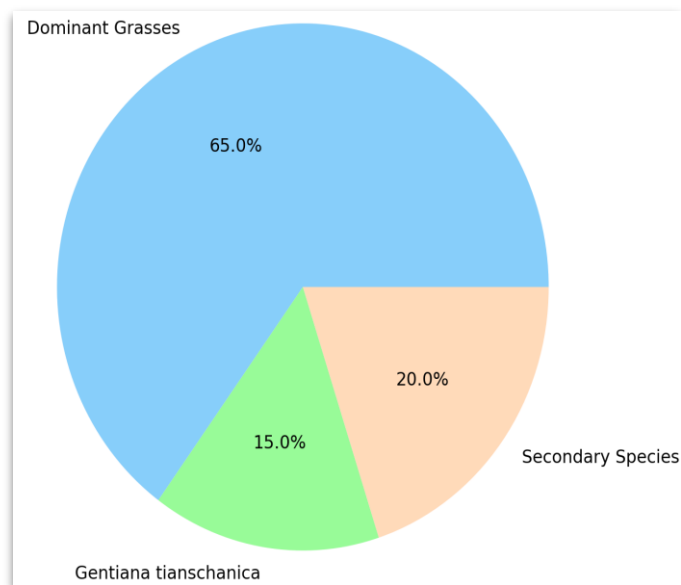


Fig. 8 Composition of vegetation in the phytocenosis.

Additional components of the community are species adapted to specific environmental conditions. *Anisantha tectorum*, *Festuca sulcata*, and *Astragalus skorniakowii* contribute to the stabilization of ecosystem processes. *Origanum vulgare* and *Iris alberti* provide food and shelter for pollinating insects, while legumes like *Medicago lupulina* and *Astragalus chlorodontus* improve soil fertility through nitrogen fixation.

Thus, the phytocoenosis of the third population of *G. tianschanica* represents a stable ecosystem with a high level of structural and functional diversity. Dominant grass species ensure the stability of the community and protect the soil, while secondary species contribute significantly to ecosystem stability and biodiversity maintenance. This makes the phytocoenosis a valuable subject for study and conservation, as it plays an important role in the ecosystem of the region.

The analysis of the age group distribution across the three populations shows that representatives of the latent period (Se) and virgin seedlings (P) are absent in all populations. This may be due to unfavorable conditions for seed germination or slow rooting rates. The number of juvenile individuals varies: there are five in the first and second populations, and seven in the third. The mean is 5.67, with a standard deviation of 1.15, indicating moderate homogeneity in this category. The second population shows a slightly higher number of immature individuals (13) compared to the first (10) and third (12). The mean is 11.67, with a standard deviation of 1.53, which indicates greater variability.

There is significant variation among the virgin individuals: from 15 in the first population to 25 in the second. The mean is 19, with a standard deviation of 5.29, which indicates substantial differences between populations. Among the young generative individuals (G1), the third population has the highest number—24, while the first and second populations have fewer—18 and 9, respectively. The standard deviation of 6.75 reflects significant differences between populations. Adult generative individuals (G2) are most numerous in the third population—69, which significantly exceeds the numbers in the first (36) and second (34). The high standard deviation in this group indicates strong variability. Among the old generative individuals (G3), the populations show similar numbers—4, 2, and 2—indicating low variability (Fig. 9).

Subsenile individuals (Ss) are represented only in the first population (1 individual), while they are absent in the other populations. Senile individuals (Se) are also absent in all populations. The highest number of reproductive individuals in the third population indicates its maturity and high biological productivity. The uniformity in the categories of old generative (G3) and subsenile (Ss) individuals suggests the stability of age structures in the later stages of reproduction. Significant differences in the numbers of virgin and young generative individuals between populations indicate different rates of population replenishment or the influence of environment.

The absence of latent and senile stages in all populations suggests that the populations are in a stable phase of development but may face limitations in reproduction.

The graph shows the distribution of age categories for the three populations, considering the mean value and standard error. The black lines at the top of the bars indicate the magnitude of the standard error, which illustrates the level of variability in the data between populations. It is evident that the "Mature Generative (G2)" and "Young Generative (G1)"

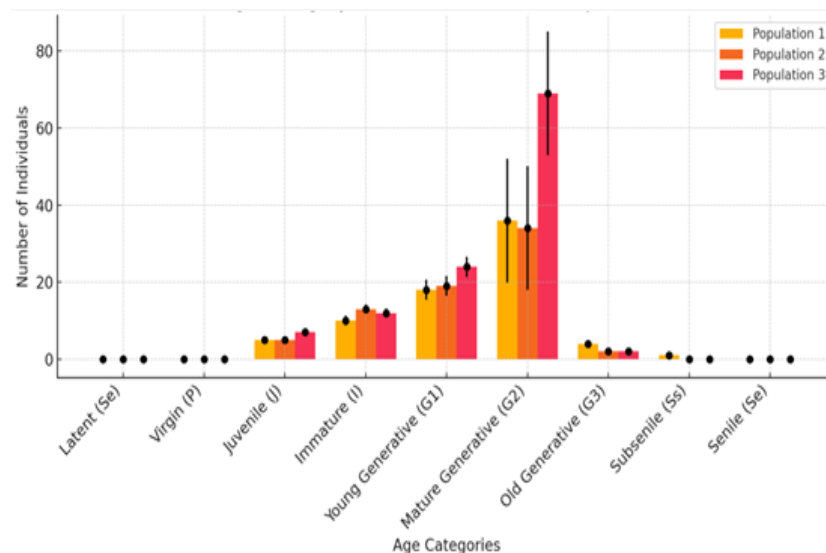


Fig. 9 Age category distribution for three populations conditions.

categories have the highest numbers, as well as more pronounced variability. In contrast, early and late stages, such as "Latent (Se)" and "Senile (Se)," are absent or minimally represented. This points to the maturity of the populations with the dominance of generative stages.

3.4 Soils

3.4.1 Soil morphological description

Population-1, Kaskelen gorge. The gorge represents the westernmost segment in the chain of forested spurs of the Ile Alatau. As one progresses further, the mountains gradually decrease in height, shedding their spruce cover and adopting a landscape more akin to steppes (Table 6).

Soil type: Mountain-steppe thermoxeromorphic dark chestnut. Population-2, Big Almaty gorge. The gorge comprises both western and eastern branches. The western branch extends towards the Alma-Arasan Valley, while the eastern branch leads to the Big Almaty Lake, renowned as a prominent local natural attraction (Table 7).

Soil type: Mountain-meadow sod dark chestnut.

Population-3, Kimasar gorge. Kimasar gorge is a gorge of the Komissarovka River, a left tributary of the Kishy Almaty. Towards its upper reaches, the gorge branches off (Table 8).

Soil type: Mountain-meadow chestnut.

3.4.2 Soil chemistry

Laboratory analysis of mountain meadow chestnut soils from the Kimasar gorge revealed medium humus content ranging from 2.84% to 6.18% within the 0-80 cm soil layer. Soil pH levels indicated an acidic reaction, ranging from 6.01 to 6.53, with acidity decreasing with soil depth. Additionally, CO₂ content varied from 0.17 to 0.27.

In contrast, mountain-meadow dark chestnut soils sampled from the Big Almaty gorge exhibited high humus content within the 0-80 cm soil layer, ranging from 7.36% to 18.78%. Soil pH levels ranged from 6.48 to 6.66, indicating an acidic reaction, with decreasing acidity observed with soil depth. CO₂ content ranged from 0.27 to 0.44.

Table 6. Soil morphological description of population №1 (Kaskelen gorge)

Population	Horizon	Depth (cm)	Description
	A	$\frac{0-9}{9}$	Dark chestnut brown, fresh, unconsolidated, nutty-grained, abundant roots, loamy, not boiling
	B ₁	$\frac{9-40}{31}$	Chestnut, slightly compacted, nutty-grained, loamy, plant roots, inclusion of stones, no boiled, transition clear
	BC	$\frac{40-70}{30}$	Light chestnut, fine-grained, stony and rubbly, inclusion of abundant roots, loamy, weakly boiled, transition gradual
	C ₁	$\frac{70-90}{20}$	Light chestnut brown, powdery-grained, loamy, stony and rubbly, the inclusion of large stones, weakly boiled

Table 7. Soil morphological description of population №2 (Big Almaty gorge).

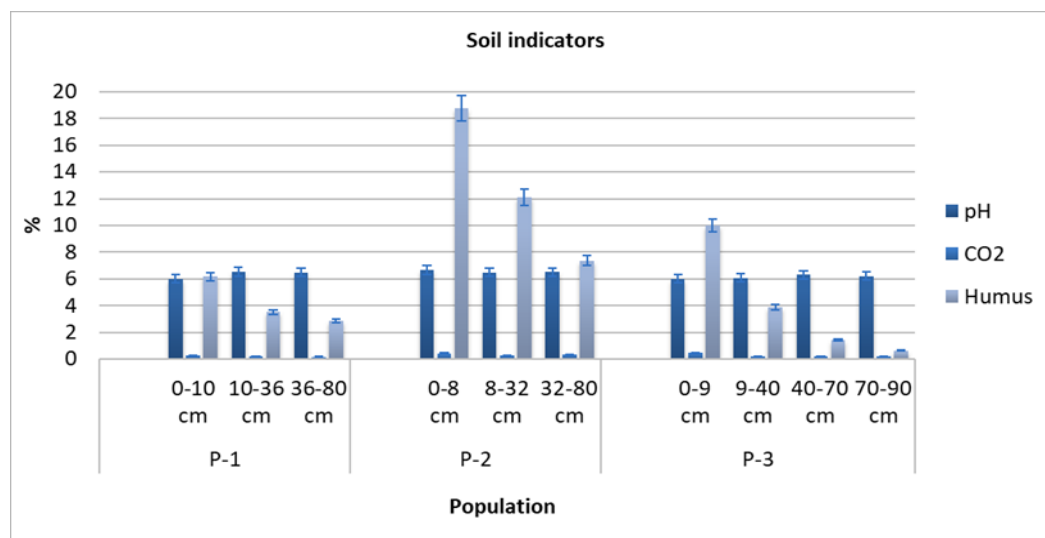
Population	Horizon	Depth (cm)	Description
	A	$\frac{0-8}{8}$	Dark brown, fresh, loose, loamy, nutty-grained, abundant fine roots, not boiled
	B ₁	$\frac{8-32}{24}$	Dark brown, fresh, loose, slightly compacted, loamy, granular, plant roots, inclusion of large stones, stony-gravelly, weakly boiled, the transition to the next horizon is clear
	BC	$\frac{32-80}{48}$	Brown, compacted, loamy, small roots, stony and rubbly, weakly boiled

Table 8. Soil morphological description of population №3 (Kimasar gorge).

Population	Horizon	Depth (cm)	Description
	A	$\frac{0-10}{10}$	Dark chestnut, unconsolidated, fresh, loamy, lumpy-grained, abundant roots, not boiling, transition gradual
	B ₁	$\frac{10-36}{26}$	Chestnut, nutty-grained, slightly compacted, loamy, abundance roots, rocky, insect passages and burrows, weakly boils, transition clear
	BC	$\frac{36-80}{44}$	Light chestnut, powdery-fine-grained, stony-rubble, loamy, many stones, due to which the horizon is dense, weakly boiled.

The mountain-steppe thermoxerophilic dark chestnut soils of the Kaskelen gorge displayed high humus content within the 0-90 cm layer, ranging from 0.64% to 10%. Soil pH levels ranged from 6.00 to 6.30, also indicating an acidic reaction, with decreasing acidity observed from the upper to lower

horizons. CO₂ content ranged from 0.20 to 0.47. pH level decreased acidity from the upper horizon to the lower horizon (Fig. 10). Comparatively, the mountain-meadow sod dark chestnut soil of the Big Almaty gorge exhibited the highest humus content among the studied populations.

**Fig. 10** Indicators of humus content, CO₂ levels and pH in the soils of the study area, %.

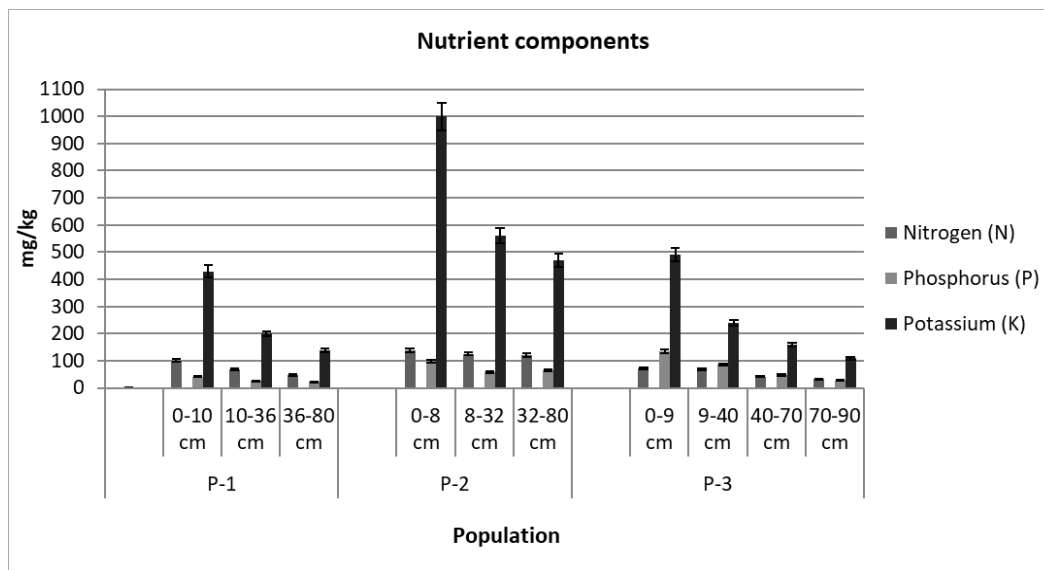


Fig. 11 Indicators of mobile NPK in the soil of the study area, mg/kg.

The granulometric composition of soils in the studied populations reveals significant variation across the gorges, reflecting the influence of local geological and hydrological factors on soil formation and structure. The predominance of specific fractions in each population provides insight into soil texture, which directly impacts water retention, aeration, and nutrient availability—key factors for plant growth and survival (Fig. 11).

In Population 1 (Kimasar gorge), the predominance of the coarse dust fraction (35.9%) and coarse sand (23.07%) within the light loamy soil profile indicates a relatively balanced texture. This composition suggests moderate water retention and aeration, which are essential for supporting the growth of *G. tianschanica* in this region. The fine fractions (fine dust and silt) are limited, reducing the soil's capacity to retain moisture during dry periods.

Population 2 (Big Almaty gorge) is characterized by a high proportion of coarse dust (46.78%) and coarse sand (22.65%),

with a similar light loamy texture. The dominance of coarse dust indicates higher porosity and potentially better drainage compared to Population 1. This could explain the higher nutrient content observed in this population's soil, as adequate drainage prevents nutrient leaching while maintaining aeration for root development.

In contrast, Population 3 (Kaskelen Gorge) exhibits a predominance of coarse sand (49.21%) and fine sand (25.32%), resulting in a significantly coarser soil texture. While the light loamy classification persists, the increased proportion of sandy fractions suggests reduced water retention and lower nutrient availability. Such conditions indicate that *G. tianschanica* in this population may have developed specific adaptations to cope with these challenges, such as efficient water-use mechanisms or deeper root systems.

These differences in granulometric composition highlight the diverse soil environments across the studied gorges, which influence the ecological niches and adaptive strategies of *G.*

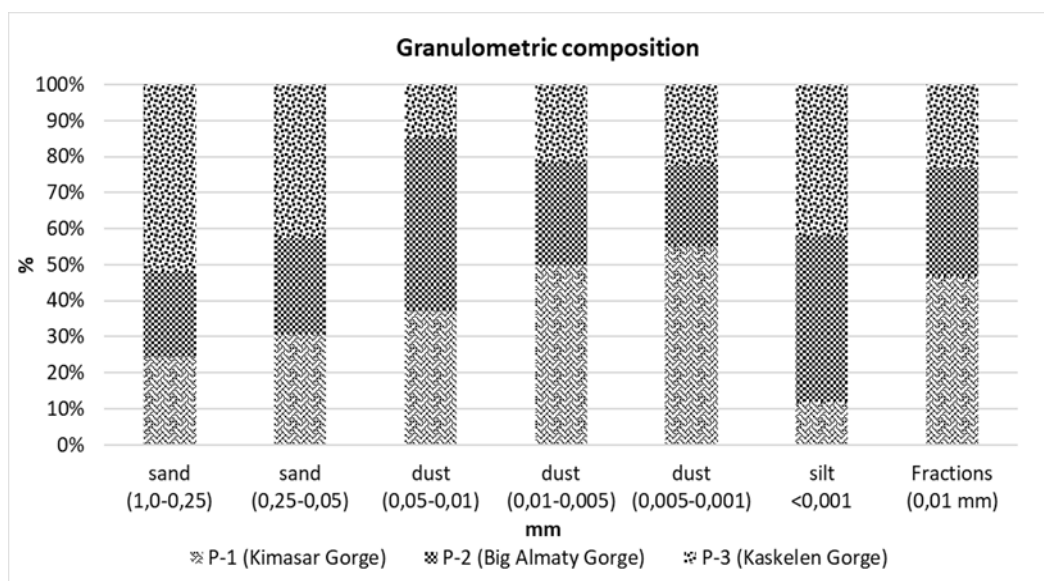


Fig. 12 Granulometric compositions of soils in the study area, %.

tianschanica. The dominance of coarse fractions across all populations underscores the importance of physical soil structure in supporting this species, particularly in mountainous regions with variable climatic conditions.

Future research should explore the relationship between soil texture and plant physiology, focusing on how granulometric composition affects root structure, water uptake, and nutrient absorption. Understanding these interactions is crucial for the conservation of *G. tianschanica* and the management of its habitats under the pressure of climate change and anthropogenic activities.

The granulometric composition of the soil and its porosity are closely associated with properties such as water retention, moisture permeability, moisture capacity, the capacity to accumulate organic substances, and air-thermal regimes (Fig. 12).

The analysis of absorbed bases in the soils of *G. tianschanica* populations reveals notable variability across the studied locations. The predominance of absorbed calcium across all populations aligns with the known role of calcium in maintaining soil structure, fertility, and plant health. However, the variations in total absorbed bases and their distribution reflect the influence of local environmental and geological conditions.

In Population 1, the relatively low total content of absorbed bases within the 0–80 cm soil layer, along with a consistent

calcium concentration (20.8–23.76 mg-eq per 100 g), suggests limited nutrient availability, potentially constraining plant growth. Despite this, the dominance of calcium indicates a favorable condition for root development and nutrient uptake, critical for sustaining endemic plant species like *G. tianschanica*.

Population 2 displayed a broader range of absorbed bases (19.8–38.61 mg-eq per 100 g of soil), with magnesium playing a secondary role after calcium. This variation may be attributed to differences in soil texture or the degree of weathering. The higher levels of absorbed bases in this population's soil profile may contribute to the observed diversity and density of plant communities in this area, highlighting its ecological importance (Fig. 13).

Interestingly, Population 3 exhibited a markedly lower total content of absorbed bases (0.22–0.40 mg-eq per 100 g), with absorbed calcium still remaining the predominant ion. However, magnesium showed a relatively higher range (2.48–11.39 mg-eq), indicating that while calcium dominates, magnesium may also significantly influence soil and plant interactions in this site. Such low nutrient levels suggest that this population thrives in relatively poor soils, which may point to adaptive mechanisms of *G. tianschanica* to nutrient-limited environments.

These findings highlight the variability in soil chemical properties across the studied populations and their potential

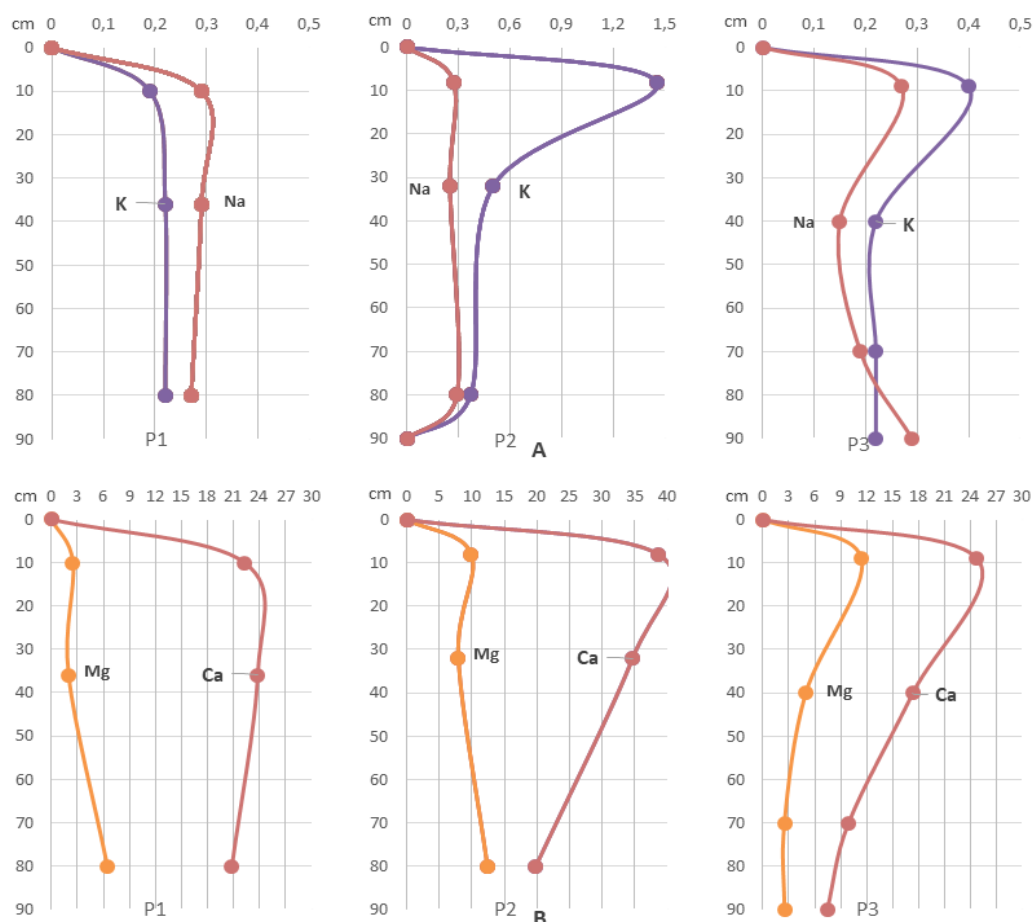


Fig. 13 The amount of absorbed soil bases in the study area, mg-eq (A) – Na, K and (B) – Ca, Mg.

ecological implications. The predominance of absorbed calcium across all populations emphasizes its critical role in the soil-plant system, particularly in supporting endemic and medicinally valuable species. Future studies should investigate the physiological adaptations of *G. tianschanica* to these soil conditions and explore seasonal and anthropogenic influences on soil chemistry. Such research is essential for devising conservation strategies to protect both the species and its unique habitat.

The analysis of salt content in different types of soils from three gorges—Kimasar, Big Almaty, and Kaskelen—provides valuable insights into the chemical characteristics and potential environmental conditions of these regions. The observed variations in ion concentrations and total salt content suggest differences in soil formation processes, water availability, and the influence of local vegetation and climate. Absence of Carbonates (CO_3^{2-}). In all three soil types, carbonate ions (CO_3^{2-}) were either undetected or present in trace amounts (e.g., 0.001% in Kaskelen). This absence might indicate the soils are not strongly alkaline and are instead neutral to slightly acidic. This finding is consistent with soils found in regions with moderate precipitation, which tends to leach out carbonates over time. Bicarbonates (HCO_3^-) in chestnut soils of Kimasar, bicarbonates were relatively low (0.08–0.12%), indicating lower buffering capacity against acidification. In dark chestnut soils of Big Almaty, the bicarbonate concentration was significantly higher (0.20–0.40%), reflecting better buffering properties and perhaps higher biological activity or carbonate weathering in this region (Fig. 5). In Kaskelen, the bicarbonate levels (0.12–0.28%) were intermediate, suggesting moderate environmental conditions between those of Kimasar and Big Almaty. Chlorides (Cl^-) on concentrations were similar across the gorges (0.04–0.07%), except for a slightly higher range in Kaskelen (up to 0.15%). Chlorides often reflect soil salinity levels and water movement. Higher Cl^- levels in Kaskelen could indicate periodic irrigation or water stagnation, leading to salt accumulation. Kimasar soils had moderate sulfate levels (0.29–0.61%), suggesting some input from mineral weathering or local vegetation. Big Almaty soils had the highest sulfate concentrations (0.63–0.84%), which may indicate higher levels of gypsum or other sulfate minerals in the parent material or greater influence of external inputs like runoff. In Kaskelen, sulfates showed the broadest range (0.09–0.46%), implying variable conditions, such as alternating wet and dry periods that could influence sulfate leaching. Big Almaty soils had the highest Ca^{2+} content (0.19–0.29%), suggesting better nutrient availability or higher calcareous material. Kimasar and Kaskelen soils showed lower and similar Ca^{2+} levels (~0.10–0.19%), indicating potential nutrient limitations in these areas. Mg^{2+} levels varied widely, with Kimasar showing the broadest range (0.19–0.48%) and Big Almaty recording a fixed value of 0.48%. Magnesium plays a crucial role in plant metabolism, and its high availability in Big Almaty soils may support richer vegetation. Na^+ content

ranged more widely in Kimasar (0.04–0.19%), suggesting potential salinity issues. Big Almaty and Kaskelen soils showed narrower ranges (0.10–0.16%), indicative of more stable conditions. Potassium levels varied significantly across regions, with Big Almaty showing the highest range (0.09–0.41%), reflecting better soil fertility. In contrast, Kimasar and Kaskelen had lower and narrower ranges (0.02–0.15%), potentially limiting plant growth.

Soils from Big Almaty gorge had the highest total salt content (0.059–0.098%), indicating a saline tendency. This could impact vegetation composition and soil health, requiring consideration for agricultural or conservation activities.

Kimasar soils showed moderate salinity (0.027–0.054%), suggesting favorable conditions for diverse plant growth without significant salinity stress. Kaskelen soils exhibited the lowest salinity (0.018–0.049%), likely supporting sensitive plant species that cannot tolerate high salt concentrations.

The observed salt content and ionic composition highlight the ecological diversity of the three gorges: Big Almaty gorge soils are richer in salts and nutrients, potentially supporting a diverse and productive ecosystem but with a risk of salinization in agricultural use. Kimasar gorge soils are moderately saline and nutrient-rich, suitable for robust vegetation and agricultural applications with minimal soil management. Kaskelen gorge soils have lower salt content, making them suitable for sensitive crops or natural vegetation adapted to low-salinity environments.

3.5 Main chemical components of *G. tianschanica*

Phenolic compounds in *G. tianschanica* play a crucial role in the plant's defense mechanisms and possess significant pharmacological potential. These compounds are widely distributed in plants and provide protection against pests, diseases, and environmental stressors. In *G. tianschanica*, phenolic compounds such as quercetin, apigenin, chlorogenic acid, and others contribute to the plant's resilience and healing properties.

The graph illustrates the biological properties of different parts (root, stem, leaf) of *G. tianschanica*. The parameters analyzed include total phenolics, total flavonoids, vitamin C, and antioxidant activity, measured in mg per 100 g of sample (Fig. 14).

The leaf contains the highest amount of total phenolics at 9008.20 mg GAE/100 g, significantly surpassing the root, which has 1567.17 mg, and the stem, with 2975.84 mg. Similarly, the leaf demonstrates the highest concentration of total flavonoids at 1358.25 mg CE/100 g, compared to the root with 392.11 mg and the stem with 463.81 mg. The concentration of vitamin C is also highest in the leaf at 244.7 mg/100 g, followed by the stem at 187.0 mg and the root at 37.5 mg. Antioxidant activity is most potent in the leaf at 530.30 mg TE/100 g, with lower values observed in the stem at 228.97 mg and the root at 158.70 mg.

The findings indicate that the leaf of *G. tianschanica* demonstrates superior biological activity across all parameters,

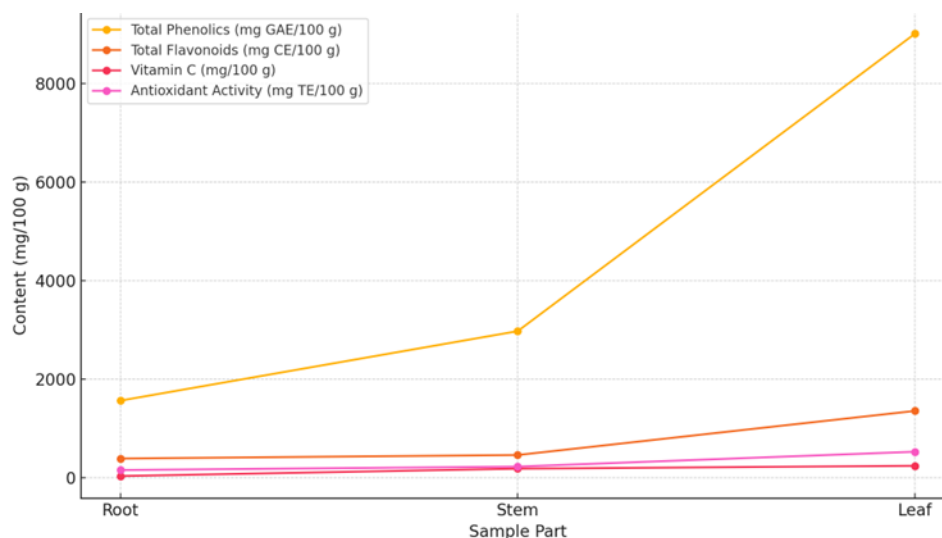


Fig. 14 Biological Properties of *G. tianschanica*.

suggesting its potential as a valuable resource for pharmacological and biomedical applications. These results highlight the importance of leaves for further phytochemical and antioxidant studies.

The antioxidant, anti-inflammatory, and antimicrobial activities of phenolic compounds in *G. tianschanica* help the plant protect itself from oxidative stress, harmful microorganisms, and environmental damage. These properties are also beneficial for humans. For example, quercetin and apigenin are known for their ability to reduce inflammation and protect cells from free radical damage, which is essential for preventing chronic diseases like cancer and cardiovascular conditions. These compounds are actively studied for their potential to develop drugs aimed at boosting immunity and treating chronic inflammation.

Chlorogenic and caffeic acids found in *G. tianschanica* are known for their antimicrobial and antioxidant properties, making them promising for developing products aimed at fighting infections and improving overall health. These compounds protect the organism from oxidative stress, playing a key role in preventing age-related diseases.

Syringic and p-coumaric acids in *G. tianschanica* contribute to strengthening cellular structures and preventing damage caused by toxins and environmental factors. They also have significant antioxidant activity, which makes them valuable in the pharmaceutical and cosmetic industries.

Luteolin and trans-ferulic acid in *G. tianschanica* exhibit strong anti-inflammatory activity, protecting tissues from destruction and aiding in recovery after illnesses. They also positively impact the cardiovascular system by strengthening blood vessel walls and improving elasticity.

Thus, the phenolic compounds found in *G. tianschanica* not only provide the plant with protection but also demonstrate significant potential for pharmaceutical applications, particularly in the areas of anti-inflammatory, antioxidant, and antimicrobial treatments. These compounds hold promise for the development of drugs and health products aimed at

improving human health and preventing various diseases.

Based on the data in the table (Table 9), the following conclusions can be drawn. Quercetin is found in the highest concentration in leaves (317.4 mg/g), while its concentration in the stem and root is 224.5 mg/g and 143.1 mg/g, respectively. This compound has antioxidant, anti-inflammatory, and anticancer properties, making it valuable for inflammation prevention and cancer therapy. Apigenin is found exclusively in leaves at a concentration of 9.3 mg/g. It exhibits antioxidant and anti-inflammatory effects and is promising for treating inflammatory conditions. Chlorogenic Acid is most concentrated in roots (235.0 mg/g), while its levels in the stem and leaves are 113.9 mg/g and 78.8 mg/g, respectively. This compound is effective in combating infections and oxidative stress. Caffeic Acid is most abundant in the stem (43.2 mg/g), while its concentrations in leaves and roots are 21.2 mg/g and 9.0 mg/g, respectively. This compound is valuable for preventing age-related diseases. Syringic Acid is highly concentrated in roots (1685.8 mg/g), with significantly lower levels in the stem (742.0 mg/g) and leaves (682.9 mg/g). It is widely used in cosmetics and pharmaceuticals due to its antioxidant properties. p-Coumaric Acid is found in the highest concentration in leaves (205.6 mg/g), with a concentration of 81.7 mg/g in the stem and none in the roots. This compound is important for cosmetic and pharmaceutical industries. Luteolin is predominantly found in roots (101.8 mg/g), but leaves also contain it at 79.3 mg/g. It supports cardiovascular health through its antioxidant and anti-inflammatory properties. Trans-Ferulic Acid is primarily concentrated in leaves (139.2 mg/g), with a much lower concentration in the stem (9.0 mg/g). This compound is actively used in cardiovascular disease treatment.

Thus, different parts of the plant contain various phenolic compounds in unique concentrations, making them valuable sources of bioactive substances for pharmaceuticals, medicine, and cosmetics.

Table 9. Phenolic compound content in *G. tianschanica* quantity (mg/100g).

Phenolic Compound	Chemical Formula	Biological Activity	Pharmacological Potential	Root	Stem	Leaf
Quercetin	C ₁₇ H ₁₆ O ₇	Anti-inflammatory, antioxidant, protects cells from free radical damage, anticancer	Used for immune system enhancement, treatment of chronic inflammation, cancer prevention and therapy	143.1	224.5	317.4
Apigenin	C ₁₆ H ₁₄ O ₅	Anti-inflammatory, antioxidant, protects cells from damage, anticancer	Potential in cancer treatment, prevention of chronic inflammation, and improving immune function	-	-	9.3
Chlorogenic Acid	C ₁₈ H ₁₈ O ₉	Antimicrobial, antioxidant	Promising for developing treatments against infections, improving overall health, combating oxidative stress	235.0	113.9	78.8
Caffeine Acid	C ₈ H ₈ O ₄	Antimicrobial, antioxidant	Potential in fighting infections, improving health, and preventing age-related diseases caused by oxidative stress	9.0	43.2	21.2
Syringic Acid	C ₈ H ₈ O ₄	Strengthens cell structures, prevents damage from toxins, antioxidant	Valuable for pharmaceutical and cosmetic industries due to its antioxidant properties and environmental protection effects	1685.8	742.0	682.9
p-Coumaric Acid	C ₉ H ₁₀ O ₂	Strengthens cell structures, prevents damage, antioxidant	Important for preventing environmental damage, and used in cosmetics and pharmaceuticals for its antioxidant benefits	-	81.7	205.6
Luteolin	C ₁₆ H ₁₄ O ₄	Anti-inflammatory, antioxidant, cardiovascular protection	Helps in cardiovascular health by improving blood vessel elasticity and protecting against inflammation	101.8	-	79.3
Trans-Ferulic Acid	C ₁₆ H ₁₆ O ₄	Anti-inflammatory, antioxidant, improves blood vessel health, cardiovascular protection	Used in cardiovascular health treatments and inflammation recovery, enhancing vascular function	-	9.0	139.2

Table 9 now includes the chemical formulas and typical quantities of these phenolic compounds in *G. tianschanica*, which highlights their potential for use in health-related products. These compounds are primarily noted for their antioxidant, anti-inflammatory, antimicrobial, and cardiovascular benefits. The listed quantities reflect their concentrations in the plant, which can vary depending on environmental factors and plant processing.

Chromatographic analysis of the roots of *G. tianschanica* confirmed the presence of vitamin C. The study was conducted using high-performance liquid chromatography (HPLC), a method that allows for the precise identification of compounds. The chromatogram presents the results of the analysis of

vitamin C content in the sample. The main peak on the graph confirms the successful detection of vitamin C, with its retention time matching the standard values, ensuring the accuracy of the identification.

Vitamin C is a vital antioxidant that plays a key role in protecting cells from damage caused by oxidative stress. It also contributes to maintaining the immune system and overall metabolic health. The presence of vitamin C in the plant emphasizes the importance of the studied sample as a source of natural antioxidants. The results confirm that the plant under investigation may be a promising candidate for use in medical and pharmacological applications. This opens up opportunities for further study of its biological activity and

potential use in drug development.

The analysis of carbohydrates in the leaves of *G. tianschanica* revealed the presence of various sugars, including glucose, fructose, and sucrose. These compounds provide the plant with energy to maintain vital processes and contribute to its resilience under stress conditions, such as drought or low temperatures. Additionally, carbohydrates play an important role in human metabolic processes, making the plant a potential source of beneficial dietary supplements.

The chromatogram highlights three main peaks corresponding to glucose, fructose, and sucrose. The first peak, appearing earlier than the others, is associated with glucose, which is the most significant sugar in the plant. It plays a key role in energy metabolism, providing the plant with the necessary energy to support growth and development.

The second peak corresponds to fructose, which is present at a slightly lower level than glucose. Fructose serves as an important component of metabolism, providing the plant with an additional source of energy and aiding in osmoregulation, especially under stress conditions.

The third peak on the chromatogram represents sucrose, which is present at a significantly lower level compared to glucose and fructose. Sucrose performs a supporting role, participating in carbohydrate storage and transport to other parts of the plant. It also plays a crucial role in maintaining the energy balance under unfavorable conditions, such as drought or temperature fluctuations.

In summary, the analysis demonstrates that glucose is the primary carbohydrate, fructose complements its functions, and sucrose facilitates the storage and transport of energy. These sugars play a vital role in the plant's adaptation to its environment, contributing to its resilience and overall viability. In addition to vitamin C, *G. tianschanica* contains several other antioxidants that contribute to its overall antioxidant activity. These antioxidants help protect cells from oxidative stress and support overall health. Among them are flavonoids, such as quercetin, apigenin, and luteolin. Flavonoids are powerful antioxidants that neutralize free radicals and reduce oxidative damage to cells. They also possess anti-inflammatory, anti-cancer, and immune-boosting properties. The plant also contains phenolic acids, including chlorogenic acid, caffeic acid, syringic acid, and p-coumaric acid. These compounds have strong antioxidant and anti-inflammatory effects and contribute to the plant's antimicrobial activity. Phenolic acids help protect the plant from environmental stress and may also support human health by preventing oxidative damage and promoting cardiovascular health.

Lignans, which are plant compounds found in *G. tianschanica*, also act as antioxidants. They have been shown to have anti-cancer, anti-inflammatory, and antioxidant properties, further contributing to the plant's overall health benefits.

Although less commonly discussed, some plants in the *Gentiana* genus contain carotenoid compounds such as lutein and beta-carotene. These antioxidants help protect the body

from oxidative stress and support eye health.

Together, these antioxidants, along with vitamin C, enhance the medicinal and health-promoting properties of *G. tianschanica*. The presence of these compounds underscores the plant's potential for use in natural health products, particularly those aimed at reducing inflammation, improving immune function, and preventing chronic diseases associated with oxidative stress.

The results of the study highlight the high ecological importance of *G. tianschanica*. The plant not only plays an important role in the ecosystem by stabilizing soil and supporting biodiversity, but it also possesses unique properties that make it a valuable object for the pharmaceutical industry. The biologically active compounds contained in the plant open up prospects for the creation of drugs with antioxidant, anti-inflammatory, and antimicrobial effects.

The findings also confirm the need to preserve the natural populations of the plant, as its unique properties are directly related to the growing conditions. Further research is recommended to study its biochemical composition and the potential for cultivation for medicinal purposes.

The study identified three populations of *G. tianschanica*, each of which has unique ecological conditions that influence its state and characteristics.

The population in the Kimasar Gorge grows in mountain meadows with a moderate slope and light soils characterized by good aeration and moderate humidity. The plant cover includes herbaceous and shrub species such as *Cotoneaster oliganthus* and *Rosa alberti*, which create diverse microecosystems and protect the soil. The population in this area has a medium plant density, which may be related to relatively dry conditions and limited moisture.^[41]

The population in the Big Almaty Gorge grows in more humid conditions with a rich herbaceous and shrub cover. The vegetation, including *Spiraea lasiocarpa* and *Juniperus sabina*, forms dense thickets that help retain moisture and prevent erosion. These conditions support a high population density, which is associated with better growth conditions, including higher water and nutrient content in the soils.

The population in the Kaskelen Gorge grows in drier, thermic exfoliating conditions with sandy and less fertile soils. The plant cover includes species such as *Spiraea lasiocarpa* and *Artemisia dracunculus*, which are well adapted to harsh conditions. This population has a lower density, which is explained by limited moisture and nutrients in the soils.^[42]

A comparison of these populations shows that soil moisture and nutrient availability play a decisive role in population density and biodiversity. The population in the Big Almaty Gorge has the highest density and species diversity, thanks to better growing conditions. Meanwhile, populations in the Kimasar and Kaskelen Gorges face limited resources, which restrict their growth and development.

The population in the Kimasar Gorge is characterized by relatively low levels of biologically active compounds, such as phenolic compounds and flavonoids. This may be related to

the drier environmental conditions, which slow down the synthesis of these substances.

The population in the Big Almaty Gorge has the highest content of antioxidant compounds, such as quercetin and chlorogenic acid. These substances are more actively synthesized in conditions of increased humidity and higher nutrient levels, which contribute to better plant growth and the accumulation of biologically active compounds.^[43]

The population in the Kaskelen Gorge, despite its lower plant density, has high levels of some phytochemical compounds, such as caffeic and chlorogenic acids. This indicates possible adaptations to environmental stress conditions, such as drought or poor soil quality.

Comparing these populations shows that in conditions of better moisture and nutrient availability, as in the Big Almaty Gorge, plants are able to synthesize more antioxidant substances. In contrast, in drier and poorer soils, as in the Kimasar and Kaskelen Gorges, plants develop mechanisms aimed at survival in stressful conditions, which is reflected in an increase in certain phytochemical compounds.

In the population of the Kimasar Gorge, adult generative individuals dominate, but there is a low number of juvenile and immature plants. This may indicate difficulties in reproduction due to limited moisture, which hinders active reproduction.

The population in the Big Almaty Gorge shows a balanced age structure with a large number of generative and young individuals. This indicates an active reproduction process supported by better ecological conditions.^[44]

The population in the Kaskelen Gorge also has a high number of adult generative individuals, but compared to the population in the Big Almaty Gorge, it has fewer young and juvenile individuals. This may also be due to the limited environmental conditions.

Comparing these populations shows that more favorable conditions in the Big Almaty Gorge promote a higher number of young and juvenile plants, ensuring the stability of the population. Meanwhile, in the Kimasar and Kaskelen Gorges, limited resources hinder reproduction and the growth of new plants.

The populations of *G. tianschanica* are under threat due to anthropogenic factors such as overgrazing, plant collection, and climate change. To effectively preserve this species, the following measures need to be implemented.

The first step is the creation of specially protected natural areas where *G. tianschanica* populations can develop in natural conditions without anthropogenic impacts. These areas should be protected from intensive grazing, plant collection, and other destructive human activities.

An important step is also to monitor grazing and recreational load. In areas with *G. tianschanica* populations, strict grazing norms should be established to prevent soil compaction, vegetation destruction, and ecosystem degradation. Sustainable grazing systems should be introduced, and livestock numbers should be limited in key

zones.^[45]

The rational collection of plants for decorative and pharmaceutical purposes also requires the implementation of sustainable use practices. Quotas for plant collection can be set, and restoration plans for populations should be developed to avoid the risk of extinction.

Regular monitoring of population conditions will help identify changes caused by anthropogenic impact and take measures to restore population numbers. Such measures include planting plants in suitable locations and supporting existing populations.

It is also necessary to protect the ecosystem functions that are supported by *G. tianschanica* plants. Restoring degraded lands and creating buffer zones to protect plants from external impacts will help preserve ecosystems.

G. tianschanica is a valuable source of biologically active compounds, opening up broad prospects for its use in the pharmaceutical industry. One area of application is the development of antioxidant drugs, as the high content of antioxidant compounds, such as quercetin and chlorogenic acid, makes the plant useful for the prevention of diseases related to oxidative stress, such as heart disease, diabetes, and cancer.

Flavonoids and alkaloids contained in the plant have pronounced anti-inflammatory activity. These components can be used to create drugs for the treatment of inflammatory diseases such as arthritis, inflammatory bowel diseases, and respiratory illnesses.

The antimicrobial activity of *G. tianschanica* against various pathogenic microorganisms opens up the possibility of developing new antimicrobial agents that can be used to treat infectious diseases.

Products based on *G. tianschanica* extracts can be used in traditional and alternative medicine to treat various disorders such as digestive problems, infectious diseases, and metabolic disorders.

Extracts of the plant can also be used in the production of functional foods, such as vitamin supplements, energy drinks, and herbal teas, which contribute to the improvement of overall health, the immune system, and digestion.

To ensure a stable supply of raw materials for the pharmaceutical industry, cultivation programs for *G. tianschanica* can be developed under controlled conditions, such as plantations or greenhouses. This would reduce pressure on natural populations and ensure a stable supply of the plant.

The development of biotechnology, such as cell cultures and genetic modification of plants, could increase the concentration of active compounds in the plant and improve its potential for pharmaceutical use.

4. Conclusion

The study of *G. tianschanica* populations in the Ile-Alatau region showed that the species is well adapted to high-altitude conditions, exhibiting various adaptive traits depending on the

ecosystem factors. Populations in wetter and more fertile areas, such as the Big Almaty Gorge, have higher density and a balanced age structure, indicating population stability and active reproduction. In drier and resource-poor areas like the Kimasar and Kaskelen Gorges, populations are less dense but develop protective mechanisms to survive harsh conditions. The study highlights the importance of soil properties in shaping the growth and survival of the plant, as different gorges possess distinct soil types that influence the species' adaptations. These findings emphasize the need for the conservation of *G. tianschanica* from anthropogenic factors such as overgrazing, plant collection, and climate change. Future research should focus on seasonal dynamics, human impact, and adaptive land management strategies to ensure the long-term preservation of the species. In conclusion, the study demonstrates the remarkable ecological and phytochemical adaptations of *Gentiana tianschanica* populations to the diverse environmental conditions of the Ile-Alatau region in Kazakhstan. The species' ability to thrive in varying altitudinal and climatic zones, as evidenced by its adaptation to different soil types and nutrient levels, highlights its resilience to environmental variability. Phytochemical analyses further reveal the plant's significant pharmacological potential, with high concentrations of bioactive compounds offering antioxidant and anti-inflammatory properties. However, the ongoing anthropogenic pressures, such as overgrazing, habitat disturbance, and unsustainable plant collection, pose serious threats to the species' survival and ecological stability. To ensure the long-term conservation of *G. tianschanica* and its valuable ecological role, it is crucial to implement comprehensive conservation strategies. These should include habitat protection, sustainable management practices, and regular monitoring of population dynamics. Ultimately, the findings underscore the need for continued research on the species' ecological adaptability and pharmacological properties, while also emphasizing the importance of safeguarding its natural habitats. Effective conservation and sustainable use of *G. tianschanica* will contribute not only to preserving a rare and endemic species but also to advancing pharmaceutical research and the promotion of biodiversity in Kazakhstan's mountainous ecosystems.

Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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