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Agrochemical compositions of soils and rhizosphere microorganisms of *Rosa potentilliflora* Chrshan. et M. Pop. in eastern and central part of Zailiyskiy Alatau

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Abstract

Background This study focuses on the agrochemical properties of soils and microbial communities in the rhizosphere of the narrowly endemic species *Rosa potentilliflora* in the mountain ecosystems of the Zailiyskiy Alatau (Kazakhstan). The goal was to evaluate the influence of soil conditions on the composition and activity of rhizosphere microbiomes, as well as to identify key factors shaping their biodiversity. The study examined three distinct locations: Shilisai gorge, Syugaty massif, and Turgen gorge, which differ in altitude, vegetation cover, and soil properties.

Methods The research involved analyzing agrochemical parameters such as humus content, pH, and mineral compounds (bicarbonates and sulfates). Microbiological analysis was conducted to assess the microbial population, focusing on nitrogen-fixing bacteria (*Azotobacter* spp.) and actinomycetes (*Coerulescens*, *Ruber*). The study also explored the correlation between humus content and the abundance of nitrogen-fixing microorganisms. The microbial density was quantified in terms of colony-forming units (CFU) per gram of soil.

Results The agrochemical analysis revealed significant differences in humus content (2.08–12.9%), pH (6.97–8.93), and mineral composition. The microbiological analysis indicated high microbial populations (ranging from 2.3×10^6 to 3.3×10^7 CFU/g), with nitrogen-fixing bacteria *Azotobacter* spp. dominating (80–94%) and the presence of actinomycetes (*Coerulescens*, *Ruber*). A positive correlation was found between humus content and the abundance of nitrogen-fixing bacteria ($r = 0.82$, $p < 0.01$), highlighting the importance of organic matter for sustaining microbial activity in the rhizosphere.

Conclusions The study demonstrates the adaptive potential of *Rosa potentilliflora* to extreme conditions in mountain ecosystems and its significant role in forming unique microbial communities. The actinomycete strains identified show considerable biotechnological potential, opening opportunities for the development of bioproducts and sustainable land management strategies. The findings contribute to the understanding of ecological interactions in the rhizosphere of rare plant species and can be applied to biodiversity conservation in Kazakhstan's mountain ecosystems.

Keywords *Rosa potentilliflora*, Rhizosphere, Soil, Actinomycetes, Zailiyskiy Alatau

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Introduction

The flora of Kazakhstan comprises approximately 6000 species of higher plants, over 500 of which possess medicinal properties. Of these, about 50 species are used in official medicine, while more than 200 are applied in traditional medicine (Ushbaev et al. 2005). Of particular interest is the narrowly endemic species *Rosa potentilliflora* Chrshan. et M. Pop., which is adapted to the extreme environmental conditions of the Zailiyskiy Alatau. Species of the genus *Rosa* L.—including the well-studied *R. damascena*, *R. canina*, *R. iliensis*, and *R. gallica*—are valued in medicine for their high content of vitamins (notably vitamin C in the fruits of *R. canina* and *R. iliensis*), flavonoids, essential oils (from the petals of *R. damascena*), and organic acids. These bioactive compounds account for the antioxidant, anti-inflammatory, and antimicrobial properties of *Rosa* species (Nurmakhanova et al. 2024; Aldassugurova et al. 2024; Chandana et al. 2024; Kustova et al. 2015; Szöke et al. 2023). Furthermore, these plants show promise as sources of dietary supplements and ornamental materials.

Despite the medicinal potential and ecological significance of *R. potentilliflora*, the agrochemical and microbiological aspects of its rhizosphere remain poorly understood. Recent research highlights the crucial role of rhizospheric microbial communities in enhancing plant stress resistance (Jabborova et al. 2024). *Rosa* species, which play an important medico-ecological role (Li et al. 2024; Jarić et al. 2024), typically grow in the unique mountainous environments of the Zailiyskiy Alatau, where the soils are classified as mountain ordinary chernozems. These soils are characterized by high humus content, minimal salinity, and variable texture (from medium to heavy clay), all of which contribute to fertility. However, the complexity of soil dynamics is increased by periodic flooding (Zhang et al. 2022; Smith and Brown 2021; Balkybek et al. 2025; Amirov et al. 2023). *R. potentilliflora* is a narrowly endemic, xeromesophytic shrub (60–80 cm tall) with bright yellow flowers (3 cm diameter) and glossy black fruits (8–9 mm), well-adapted to the harsh conditions of the Toraygyr foothills (Shilisai Gorge), the Syugaty massif, and the Turgen Gorge. It is altitudinal distribution is shaped by microclimatic and soil-vegetation factors (Childibayeva et al. 2022; Kulymbet et al. 2023; Özek et al. 2022), suggesting a high concentration of biologically active compounds, which warrants further investigation.

Rhizospheric microorganisms are key agents in soil processes, including organic matter mineralization, nitrogen fixation, and the maintenance of soil fertility (Purakayastha et al. 2024; Sharma et al. 2024). Their diversity is closely linked to ecosystem resilience in the face of anthropogenic pressures (Biswas et al. 2024;

Palit et al. 2022). These microbial communities—including mycorrhizal fungi, symbiotic bacteria, and endophytes—enhance nutrient uptake, protect plants against pathogens, contribute to soil structure formation (Sarsan et al. 2021), and influence the phytochemical composition of host plants (Zhao et al. 2022; Haruna and Yahaya 2021). Microbiological soil analysis is therefore critical for developing sustainable land management strategies (Manda et al. 2023; Tastanbekova et al. 2025), particularly in the context of rare species such as *R. potentilliflora*. Studies indicate that it is rhizosphere harbors microorganisms that enhance plant nutrition and stress tolerance (Kavya et al. 2025); endophytic microbes are also capable of synthesizing bioactive compounds that confer disease resistance (Mertoğlu et al. 2024). An emerging research direction is the isolation of indigenous microbial strains for the development of bioformulations (Salkhozhayeva et al. 2022), which may boost crop yields, increase stress resilience, and promote sustainable agriculture.

Investigating the agrochemical properties of soils and the composition of rhizospheric microbial communities associated with *R. potentilliflora*—a narrow endemic of the Zailiyskiy Alatau—is essential for informing effective conservation measures. Although *R. potentilliflora* lacks a global conservation status, it is listed as a rare species in Kazakhstan, justifying its inclusion in the national Red Data Book and in international conservation lists. This study also aligns with the United Nations Sustainable Development Goal 15, contributing to the preservation of the region's unique natural heritage.

The aim of this research is to determine how soil conditions influence the development of *R. potentilliflora* and to assess the biological diversity of its rhizospheric microbial communities through the analysis of soil morphological and chemical properties, as well as microbial composition. The limited data available are largely due to the species' restricted range, the inaccessibility of its habitats, and a prevailing focus on morphological and taxonomic studies over soil-ecological research.

Materials and methods

Study area and object

The object of this study is the population of the rare, narrowly endemic plant species *Rosa potentilliflora* within Kazakhstan's flora, which occurs at three sites in the Zailiyskiy Alatau: (i) Shilisai gorge (1600 m above sea level), (ii) Syugaty massif (1150–1200 m a.s.l.), and (iii) Turgen gorge (1650–1750 m a.s.l.). *R. potentilliflora* is restricted to these locations, where it grows under specific microclimatic conditions. We conducted a comprehensive population-level study to assess its current status. Other *Rosa* L. species present in the region include *R. beggeriana* in the Toraygyr mountains, *R. iliensis* and *R. spinosissima* in

the low-mountain Syugaty massif, and *R. beggeriana* and *R. spinosissima* in the Turgen gorge, which is centrally located within the Zailiyskiy Alatau.

R. potentilliflora is morphologically distinct from other roses, having small leaves with frequent needle-like prickles, bright yellow flowers, and smooth black fruits. This species is of high scientific value and should be afforded protection, as its distribution is shrinking rapidly due to anthropogenic impacts.

Taxonomic identification

The taxonomic status of *R. potentilliflora* was verified using the Flora of Kazakhstan (1956–1966) and the Illustrated Plant Identification Guide of Kazakhstan (1969), confirming its classification as follows: Division Magnoliophyta (Angiospermae); Class Magnoliopsida; Subclass Rosiidae; Order Rosales; Family Rosaceae Juss.; Genus *Rosa* L.; and Species *Rosa potentilliflora* Chrshan. et M. Pop. The species is defined by its small, prickly leaves, bright yellow flowers, and smooth (see Fig. 1).

Field sampling

Field investigations were conducted in the central and eastern Zailiyskiy Alatau. At each site, two types of samples were collected: (1) soil samples for agrochemical analysis, and (2) rhizosphere soil samples directly associated with the roots of *R. potentilliflora* for studying microbial communities and isolating microbial strains. Soil sampling was carried out at a depth of 0–20 cm at all three locations (Shilisai gorge, Syugaty massif, Turgen

gorge). For agrochemical analysis, 100–500 g of soil was collected per sample, depending on the specific analytical method. For microbiological analysis, 10 g of soil was used to prepare a 1:10 dilution in 90 mL of sterile water. All procedures were performed under sterile conditions to prevent contamination (see Fig. 2).

Soils associated with *R. potentilliflora* communities were described according to genetic horizons. The collected samples were analyzed to determine both the quantitative and qualitative composition of rhizosphere microbial communities, following established protocols (Alekseeva and Potaturkina-Nesterova 2015). Further analysis included the identification and isolation of promising microbial strains for subsequent study.

Agrochemical analysis

Soil assessment involved detailed description of genetic horizons and chemical analyses. At each of the three study sites, a soil profile was established to a depth of 1 m.

Humus content was measured using the Tyurin method (Nelson and Sommers 1996; Tyurin 1937), which involves oxidation of organic matter with 0.4 N potassium dichromate ($K_2Cr_2O_7$) in sulfuric acid, followed by titration with 0.2 N ferrous sulfate ($FeSO_4$). This method provides a reliable estimate of soil organic matter, a key indicator of soil fertility.

Granulometric composition was determined according to GOST 12536-2014, which involves sequential dispersion and separation of soil fractions using



Fig. 1 Flowering phases of *Rosa potentilliflora* in its natural habitat in the Zailiyskiy Alatau, highlighting distinct developmental stages

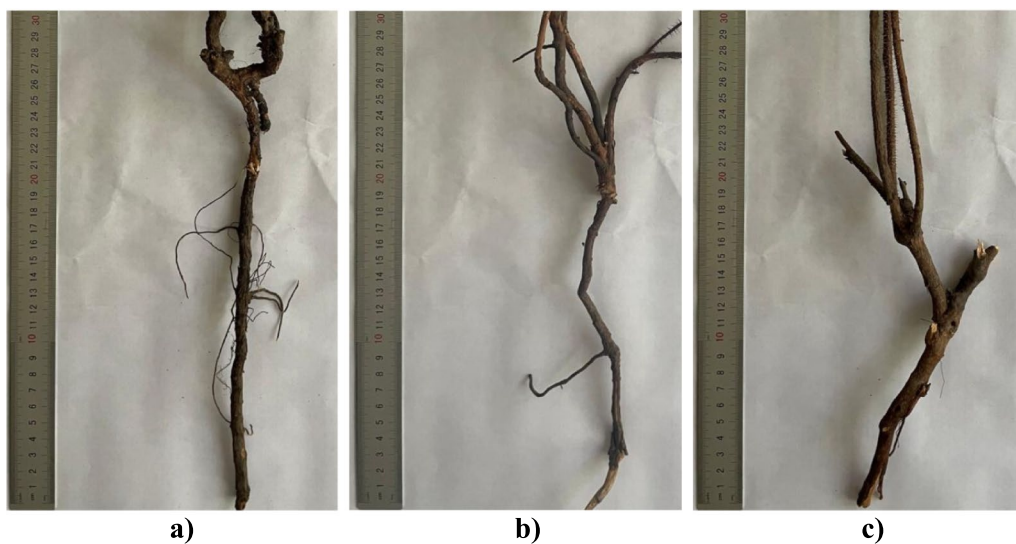


Fig. 2 Rhizosphere characteristics of *Rosa potentilliflora* in three distinct habitats of the Zailiyskiy Alatau: **a** Shilisai gorge in the Toraygyr foothills, **b** Low-mountain Syugaty massif, and **c** Spruce belt of the Turgen gorge

chemical reagents. Specifically, sodium pyrophosphate ($\text{Na}_4\text{P}_2\text{O}_7$) was used as a dispersing agent at a concentration of 10 g/L, and distilled water was added to bring the soil suspension to the required volume. The method relies primarily on mechanical dispersion, and all concentrations and volumes were used as specified in the standard protocol.

Hydrolyzable nitrogen was assessed by the Tyurin-Kononova method (Kononova 1961; Bremner 1965), using alkaline hydrolysis with 0.5 N NaOH, distillation, and titration with 0.01 N H_2SO_4 .

Available phosphorus and potassium were determined by the Machigin method (Knudsen et al. 1982; Machigin 1958): available phosphorus was extracted with 0.5 M NaHCO_3 (pH 8.5), available potassium with 1 N NH_4OAc (pH 7.0), with colorimetric analysis for phosphorus and flame photometry for potassium.

Soil pH was measured potentiometrically (GOST 26423-85 1985a, b) in a 1:5 soil:water suspension using a calibrated pH meter.

CO₂ content was determined using a calcimeter (Loeppert and Suarez 1996; GOST 26213-91 1991a, b) by reacting samples with 10% HCl and measuring released CO_2 volumetrically.

Exchangeable bases (Ca^{2+} , Mg^{2+}) were quantified by titrimetry with EDTA (GOST 26487-85 1985a, b) following extraction with 1 N NH_4OAc (pH 7.0).

Potassium (K) and sodium (Na) contents were measured by flame photometry (GOST 26207-91 1991a, b) using extracts in 1 N NH_4OAc .

Macroelements (*Ca*, *Mg*, *K*, *Na*, *P*) were determined by atomic absorption spectrometry (AAS; Perkin Elmer 2010) after digestion with a mixture of HNO_3 and HClO_4 .

The status of *R. potentilliflora* rhizosphere microorganisms in this ecosystem was evaluated by studying the quantitative and qualitative composition of microbial communities through the inoculation of soil suspensions on selective nutrient media.

To investigate the rhizospheric microbiota of *R. potentilliflora*, several steps were carried out. Soil and root samples were collected from three locations: the Shilisai gorge in the Toraygyr Mountains, the low-mountain Syugaty massif, and the Turgen gorge in the central part of the Zailiyskiy Alatau. Samples were taken from a depth of 0–20 cm, where the majority of the root mass is concentrated.

Microbiological analysis

Microbiological analysis of the soil makes it possible to assess the abundance and diversity of microorganisms that play a key role in soil processes, such as decomposition of organic matter, nitrogen fixation, and mineralization of nutrients. Selective nutrient media are used for the analysis, which ensure the growth of certain groups of microorganisms. The soil was poured onto sterile parchment paper and thoroughly mixed to eliminate heterogeneity. A 10 g soil sample was used to prepare a 1:10 dilution by adding 10 g of soil to 90 mL of sterile water. The suspension was processed on a rotary shaker at 200 rpm for 20 min.

For the cultivation and enumeration of different groups of microorganisms, several nutrient media were used. Meat-Peptide Agar (MPA) was employed for chemoor-ganotrophic bacteria; its composition included 5 g/L peptone, 3 g/L meat extract, 10 g/L NaCl, and 15 g/L agar, adjusted to pH 7.0–7.2, as per GOST 26668-85. For the isolation of micromycetes, a modified Czapek-Dox Agar with acidified pH (5.0) was utilized, containing 30 g/L sucrose, 2 g/L NaNO₃, 1 g/L K₂HPO₄, 0.5 g/L MgSO₄·7H₂O, 0.5 g/L KCl, 0.01 g/L FeSO₄·7H₂O, and 15 g/L agar. Gause's Mineral Agar No.1, with 20 g/L soluble starch, 0.5 g/L K₂HPO₄, 0.5 g/L MgSO₄, 1 g/L KNO₃, 0.5 g/L NaCl, 0.01 g/L FeSO₄·7H₂O, and 20 g/L agar, was used for actinomycetes. Bennett's Agar, comprising 5 g/L glucose, 0.5 g/L yeast extract, 1 g/L casein hydrolysate, 0.5 g/L meat extract, and 10 g/L agar, served for the isolation and quantification of actinomycetes. Other media, such as Oligotrophic Agar, Ashby's Agar (for nitrogen-fixing bacteria), and Tyrosine Agar (ISP-7, for melanin production assays), were also used in accordance with their standard compositions.

Morphological identification of actinomycetes was based on colony morphology, pigment production, and sporulation patterns following Shirling and Gottlieb (1966) and Bergey's Manual of Determinative Bacteriology (9th ed.). Spectrophotometric pigment analysis was performed on 70% methanol extracts (24 h at 4 °C) using a Specord 210 spectrophotometer (400–700 nm) to determine absorption maxima for key pigment groups.

Standard biochemical tests were applied, and all media were prepared according to GOST and ISP standards. Colony-forming units (CFU) were counted for each microbial group (Pepper and Gerba 2004; GOST 26668-85 1985a, b).

Statistical analysis

All measurements were performed in duplicate. Standard methods for calculating averages and their average errors were used for mathematical processing of the results. The data was processed using the SPSS 26.0 program. One-factor analysis of variance (ANOVA) with a significance level of $p < 0.05$ was used to compare the averages. The results are presented in the form of averages and their standard errors (Pallant 2020).

Results

The studies were conducted in three sites: The southern exposure of the Shilisai gorge at an altitude of 1600 m—vegetation covers 90–95% of the soil surface, and the dominant species of rose hips are shrubs. In the low-mountain range of Syugaty at an altitude of 1150 m, vegetation covers 75–80% of the soil surface, and the species of rosehip and curly are dominant. The

southeastern exposure in the spruce belt of the Turgen gorge (Treatment 3) at an altitude of 1690 m—vegetation covers 100% of the soil surface, vegetation is represented by a diverse grass and shrub community.

Each of the sites was described in detail by the morphology of the soil, including color, texture, presence of roots and stones at different depths. These conditions allowed for a detailed study of the composition of rhizospheric microorganisms *R. potentilliflora*.

Morphological description of soils

Soil profile 1 (Shilisai gorge) was collected in the southern exposure of the Shilisai gorge, on the sunny side of the low mountains of Toraygyr (see Fig. 3), at an altitude of 1600 m a.s.l. Geographical coordinates: N 43° 19' 4", E 78° 51' 55". The combined humus horizon (A + B) is 50 cm thick. The soil profile 1 is characterized by the following layers:

Soil type: Mountain ordinary chernozem.

Horizons	Depth (cm)	Thickness, (cm)	Description
A ₀	0–7	7	Black in color, dry, with a fine cloddy-dusty structure; loamy in texture and densely penetrated by plant roots. The transition to the next horizon is gradual
A ₁	7–17	10	Dark gray in color, dry, loose, with a fine cloddy structure; silty loam in texture, strongly penetrated by plant roots. Contains abundant fine gravel. The transition to the next horizon is clear
B	17–50	33	Gray in color, dry, and compacted; loamy in texture, with a nutty-dusty structure. It is densely penetrated by plant roots and contains a significant amount of fine gravel and rock fragments. The transition to the next horizon is gradual
C	50–100	50	Light gray in color, slightly compacted, with a fine cloddy structure; silty loam in texture. Numerous rock fragments and fine gravel are present throughout the horizon

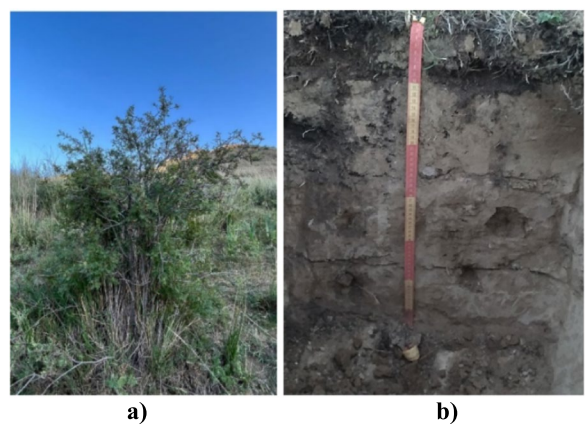


Fig. 3 Soil profile and natural habitat of *Rosa potentilliflora* in the Shilisai Gorge, Zailiyskiy Alatau: **a** natural habitat at 1600 m altitude, **b** soil profile showing horizon characteristics

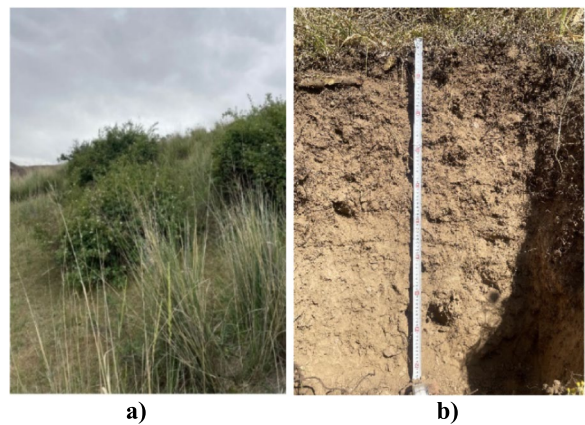


Fig. 4 Soil profile and natural habitat of *Rosa potentilliflora* in the Syugaty massif, Zailiyskiy Alatau: **a** natural habitat at 1150–1200 m altitude, **b** soil profile showing horizon characteristics

The vegetation cover is represented by the community of the rosehip and shrub association (*ass. Spiraea hypericifolia* L., *Berberis heteropoda* L., *Lonicera altmanni* Rgl., *Rosa potentilliflora* Chrshan. et M. Pop., *Rosa beggeriana* Schrenk). In addition to the dominant plants, the following types of shrubs are found in the vegetation: *Lonicera microphylla* Willd., *Cotoneaster racemiflorus* (Desf.) Booth ex Bosse. Among the herbaceous plants are: *Scaligeria setacea* (Schrenk.) Karov., *Galium aparine* L., *Melica jacquemontii* Decne., *Ajania fastigiata* Poljak., *Festuca sulcata* Hack. and others. Vegetation cover is 100%.

Soil profile 2 (Syugaty massif) was taken in the low-mountain Syugaty massif (Fig. 4), at an elevation of

1150–1200 m a.s.l. Geographical coordinates: N 43° 27′ 2″, E 78° 39′ 39.8″. The combined humus horizon (A + B) is 45 cm thick. The soil profile of sample 2 has the following layers:

Soil type: Dark chestnut soil.

Horizons	Depth (cm)	Thickness (cm)	Description
A ₀	0–8	7	Dark-brown in color, loose, dusty, silty loam, heavily penetrated by plant roots. The transition to the next horizon is gradual
A ₁	8–25	17	Brown in color, dense, cloddy, silty loam, with occasional fine gravel, heavily penetrated by plant roots. The transition to the next horizon is gradual
B	25–45	20	Light gray in color, dense, dry, silty loam, with fine gravel present, less penetrated by roots. The transition to the next horizon is clear
C	45–100	55	Light gray in color, dry, silty loam, finely cloddy, sparsely penetrated by roots. Lower layers contain gravel and solid rock fragments

The vegetation cover is represented by rosehip—curly-headed hen (*ass. Atraphaxis virgate*—*Rosa potentilliflora*, *Rosa beggeriana* Schrenk). The projective coverage of the soil surface is 75–80%. The base of the shrub layer consists of *Rosa potentilliflora* Chrshan. et M. Pop., *Rosa beggeriana* Schrenk., *Lonicera microphylla* Willd., *Spiraea hypericifolia* L., and *Ephedra equisetina* Bge. Herbaceous plants include *Elymusdahuricus* Turcz., *Milium effusum* L., *Potentilla orientalis* Juz., *Thymus marschallianus* Willd., and others. Vegetation cover is 75–80%.

Soil profile 3 (Turgen gorge) was collected at the south-eastern exposure of the Turgen gorge (Fig. 5), at an altitude of 1650–1750 m a.s.l. Geographical coordinates: N 43° 24′ 33.5″, E 77° 76′ 36.8″. The combined humus horizon (A + B) is 45 cm thick. The soil profile of sample 3 is characterized by the following layers:

Soil type: Mountain ordinary chernozem.

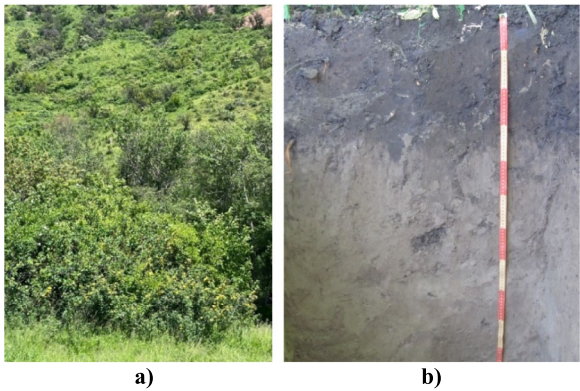


Fig. 5 Soil profile and natural habitat of *Rosa potentilliflora* in the Turgen gorge, Zailiyskiy Alatau: **a** natural habitat at 1650–1750 m altitude, **b** soil profile showing horizon characteristics

Horizons	Depth (cm)	Thickness (cm)	Description
A ₀	0–8	8	Black in color, fresh, slightly compacted, granular to finely cloddy, loamy, heavily penetrated by plant roots. The transition to the next horizon is gradual
A ₁	8–30	22	Black in color, finely cloddy, fresh, loamy, heavily penetrated by plant roots. The transition to the next horizon is clear
B	30–45	15	Gray in color, cloddy, medium density, with fine gravel present throughout the horizon; loamy, less penetrated by roots. The transition to the next horizon is clear
C	45–100	55	Gray in color, fresh, loose, loamy, with numerous stones. Significantly less root penetration

The vegetation cover is represented by a mixed herb and shrub association (ass. *Rosa potentilliflora* Chrshan. et M. Pop., *Rosa beggeriana* Schrenk., *Berberis heteropoda* L., *Phlomis tuberosa* L., *Rheum wittrockii* Lundstr., *Medicago falcata* L., *Geum urbanum* L., *Poa pratensis* L.). The projective coverage of the soil surface is 100%. In addition to the dominant species, *Spiraea hypericifolia* L., *Cotoneaster melanocarpa* Fisch., and *Lonicera microphylla* Willd. are found in the shrub layer. The herbaceous plants include *Phlomis tuberosa* L., *Galium verum*

L., *Poa pratensis* L., *Thalictrum collinum*. Vegetation cover is 100%.

Agrochemical parameters of soils

An analysis of the agrochemical parameters of soils in the *R. potentilliflora* growing areas revealed significant differences between locations: the humus content ranged from 2.08% (Syugaty massif) to 12.9% (Shilisai gorge). The high humus content in the Shilisai gorge indicates the fertility of the soil, which is favorable for plant growth and microbial activity. Figure 2 shows the results of a study of the chemical composition of soils in the southern exposure of the Shilisai gorge and in the low mountain range of Syugaty. There is a high concentration of organic substances in the upper layers of the soil, which improves its structure and increases its ability to retain water and nutrients. In the southeastern exposure of the Turgen gorge, the humus content is also high, especially in the upper 20 cm, which favors plant growth.

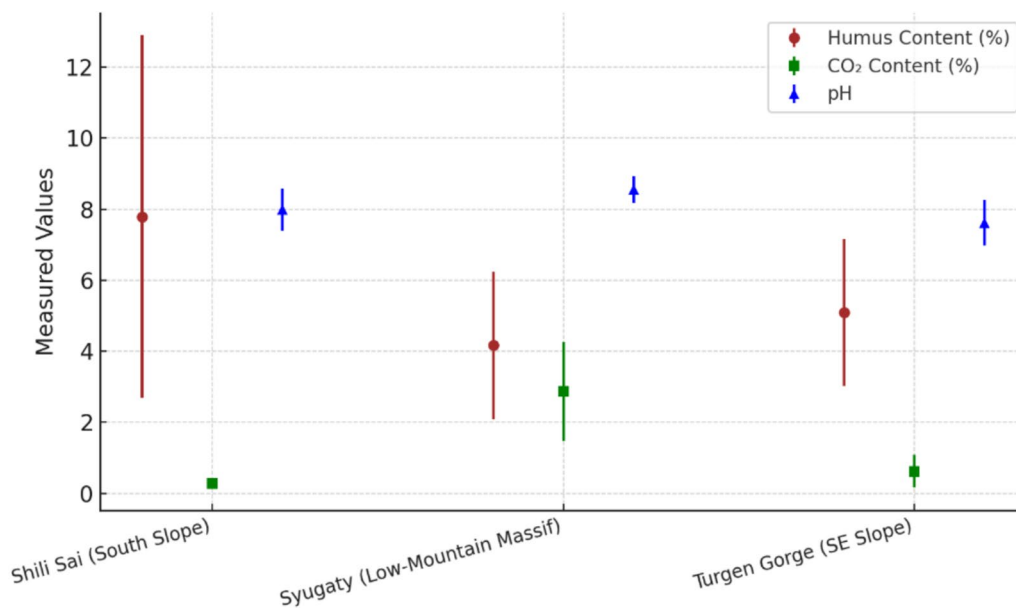
In the Shilisai gorge, humus concentrations were the highest (2.69–12.90%), which is typical for mountain ordinary chernozem with high biological activity and intensive accumulation of organic matter. The humus content in the Syugaty massif (2.08–6.25%) is minimal, which is associated with drier conditions of the low mountains and increased mineralization of organic matter. In the Turgen gorge (3.02–7.16%), moderate humus values indicate the transitional nature of soils between mountain ordinary chernozem and dark chestnut soils.

The pH values in the southern exposure of the Shilisai gorge and in the low-mountain Syugaty massif indicate an alkaline to highly alkaline soil, which may limit the nutrients available to plants. In the southeastern exposure of the Turgen gorge, the pH varies from acidic to alkaline, which provides a wider range of conditions for different plants and microorganisms (Table 1). The alkaline pH values in the Shilisai gorge (7.39–8.58) and the Syugaty massif (8.18–8.93) are typical for arid regions with a predominance of carbonate rocks. This may limit the availability of phosphorus and trace elements for plants. In the Turgen gorge (6.97–8.26), a slightly acidic pH in the upper horizons creates more favorable conditions for nutrient absorption, which explains the high projective vegetation coverage (100%) (see Fig. 6).

The high CO₂ content in the southern exposure of the Shilisai gorge and in the low-mountain Syugaty massif may indicate active decomposition of organic matter and high biological activity. In the southeastern exposure of the Turgen gorge, the CO₂ content is relatively low, indicating less active decomposition and metabolic activity of microorganisms. Table 1 shows significant differences in the agrochemical parameters of the soils of the three studied locations of the Zailiyskiy Alatau, which reflects

Table 1 Total microbial abundance and diversity in the rhizosphere of *Rosa potentilliflora* across three geographical locations in the Zailiyskiy Alatau, measured in colony forming units per gram of soil (CFU/g)

Group of microorganisms, (medium)	Shilisai gorge (Treatment 1)	Syugaty massif (Treatment 2)	Turgen gorge (Treatment 3)	p-value (ANOVA)
Total microbial abundance (TMA), Meat Peptone Agar (MPA)	$3.3 \pm 0.1 \times 10^7$	$2.9 \pm 0.1 \times 10^7$	$2.3 \pm 0.1 \times 10^6$	< 0.05
Chemoorganotrophs, Peptone Agar Meat	$3.5 \pm 0.2 \times 10^6$	$3.3 \pm 0.2 \times 10^6$	$2.0 \pm 0.2 \times 10^5$	< 0.05
Micromycetes, Czapek-Dox Agar	Absent	Absent	Absent	–
Oligotrophs	$1.9 \pm 0.3 \times 10^6$	$2.2 \pm 0.3 \times 10^6$	$1.5 \pm 0.3 \times 10^5$	< 0.05

**Fig. 6** Variations in chemical composition of soils supporting *Rosa potentilliflora* across three geographical locations in the Zailiyskiy Alatau, including humus, pH, and nutrient content

the influence of altitude-belt and microclimatic conditions on the formation of soil cover.

The high level of CO₂ in the Syugaty massif (1.47–4.26%) correlates with active decomposition of organic matter and intensive soil respiration, despite the low humus content. The minimum CO₂ values in the Shilisai gorge (0.16–0.38%) and the Turgen gorge (0.16–1.08%) may be associated with high soil aeration and a stable humus horizon that slows down mineralization. Differences in humus content and pH between locations determine the specifics of the microbial communities of the rhizosphere of *R. potentilliflora*. High humus and alkaline conditions in the Shilisai gorge contribute to the dominance of nitrogen-fixing bacteria (*Azotobacter* spp.), whereas in the Turgen gorge a slightly acidic pH supports the diversity of actinomycetes.

The data obtained highlight the adaptation of *R. potentilliflora* to extreme soil conditions and its role as a key engineer species of mountain ecosystems. The results can

be used to develop strategies for endemic conservation and optimize soil fertility in the face of climate change.

These data will help to understand how favorable soil conditions are for the development of the *R. potentilliflora* plant and its associated microorganisms. They are an important basis for the development of strategies for the conservation of biodiversity and sustainable land use in the region. The expanded interpretation of soil chemistry helps to optimize agricultural use of land, improve its fertility, and develop environmental protection and ecosystem management measures. Each site demonstrated unique soil and biological characteristics, which in turn influenced the composition of rhizosphere microorganisms *R. potentilliflora*.

Thus, it has been established in the Shilisai gorge that a high humus content (up to 12.9%) and an alkaline pH (7.39–8.58) create favorable conditions for the growth of plants and microorganisms. The Syugaty massif, low humus content (2.08–6.25%) and highly alkaline pH

(8.18–8.93) may limit the availability of nutrients. The Turgen gorge, moderate humus content (3.02–7.16%) and varying pH (6.97–8.26) provide a wider range of conditions for the development of plants and microorganisms.

The composition of the soil water filter: The analysis of the composition of the water filter in various types of soils of the ecosystems of the Zailiyskiy Alatau, where *R. potentilliflora* grows, was carried out to assess the chemical properties of soil moisture and their effect on rhizospheric microorganisms, as well as on the general condition of the soil ecosystem. The results of the analysis of the composition of the water filter are shown in Fig. 7.

Figure 7 shows the results of an analysis of the composition of a water filter in various types of soils in the ecosystems of the Zailiyskiy Alatau, where *R. potentilliflora* grows. The table shows data on the content of bicarbonates (0.32–0.72 mg-eq/l HCO_3) and sulfates (0.12–0.92 mg-eq/l SO_4), indicating their structural and functional stability for rhizospheric microorganisms. Dark chestnut soil, despite its low salt content, shows a variety of cations and anions, suggesting a rich microflora. Mountain ordinary chernozem (Turgen gorge) have a low salt content, including HCO_3 (0.52–0.68 mg-eq/l), Cl (0.04 mg-eq/l) and SO_4 (0.11–0.53 mg-eq/l), which is optimal for the development of rhizospheric microorganisms.

The southern exposure of the Shilisai gorge showed a high content of fine (28.99%) and coarse sand (15.8%),

requiring agrochemical regulation. In the low-altitude Syugaty massif, the predominance of fine sand (45.06%) makes the soil more permeable and prone to leaching nutrients, complicating agricultural use. The southeastern exposure of the Turgen gorge has a high content of pollen (19.32%) and fine dust (18.82%), improving moisture retention but requiring drainage.

The high content of bicarbonates (0.32–0.80 mg-eq/l) and sulfates (0.11–0.92 mg-eq/l) indicates active decomposition of organic matter and high biological activity. The low chloride content (0.04–0.11 mg/l) indicates the absence of soil salinity, which is favorable for plant growth. Table 2 shows the chemical composition of aqueous soil extracts, making it possible to assess the availability of ions for plants and microorganisms. The main conclusions of the analysis are that the bicarbonate content is highest in mountain

Table 2 Quantitative composition of Actinomycetes in the rhizosphere of *Rosa potentilliflora* across three locations in the Zailiyskiy Alatau, measured on Gause's medium No. 1 (CFU/g of soil, Mean $\pm$ Standard Deviation)

Naming of rhizosphere samples	Number of actinomycetes (CFU/g of soil)	Statistical significance
Shilisai gorge (Treatment 1)	$3.0 \pm 0.2 \times 10^7$	a
Syugaty massif (Treatment 2)	$2.9 \pm 0.2 \times 10^5$	b
Turgen gorge (Treatment 3)	$2.7 \pm 0.2 \times 10^7$	a

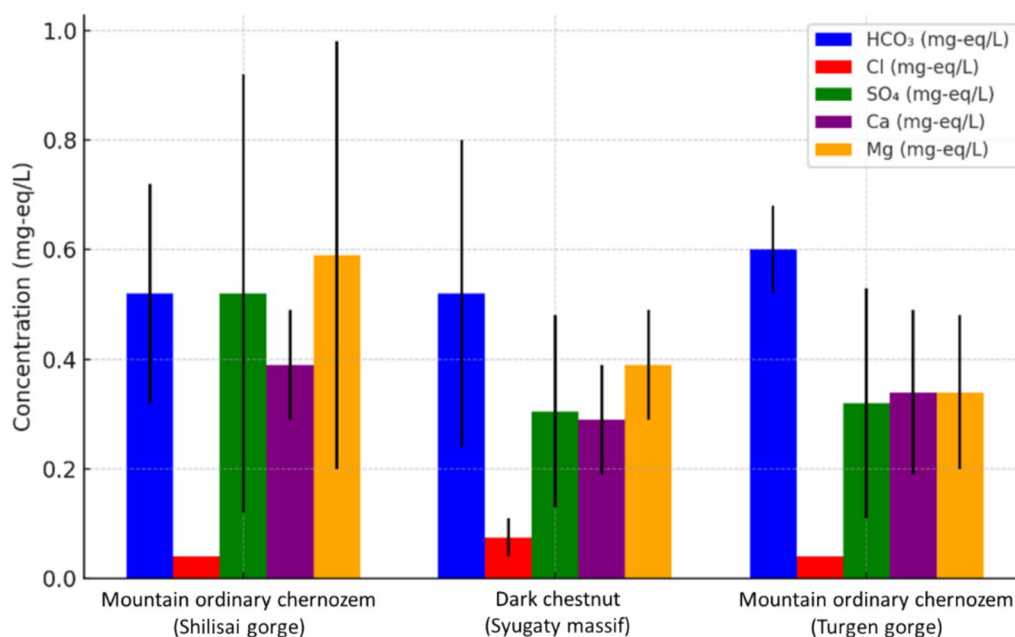


Fig. 7 Ionic composition of soil water extracts from *Rosa potentilliflora* habitats in the Zailiyskiy Alatau, showing concentrations of bicarbonates, sulfates, and other ions (mg-eq/L) across chernozem and dark chestnut soils

ordinary chernozem (Turgen gorge) (0.52–0.68 mg-eq/l) due to intensive weathering of carbonate rocks. The content of bicarbonates varies in mountain ordinary chernozem (Shilisai gorge) (0.32–0.72 mg/l) and dark chestnut soils (0.24–0.80 mg/l). The high sulfate content in mountain ordinary chernozem (Shilisai gorge) (0.12–0.92 mg/l) is associated with the mineralization of organic matter and weathering of sulfate-containing minerals. The concentration of sulfates is lower in dark chestnut soils (0.13–0.48 mg/l) and mountain ordinary chernozem (Turgen gorge) (0.11–0.53 mg/l). A high concentration of calcium (0.29–0.49 mg-eq/l) and magnesium (0.20–0.98 mg-eq/l) is observed in mountain ordinary chernozem (Shilisai gorge), which is typical for soils with a high content of carbonates.

Thus, this analysis was carried out to evaluate the chemical properties of soil moisture, to understand the effect of these properties on rhizospheric microorganisms and plants, to determine the stability of the soil ecosystem and its ability to support biodiversity.

The granulometric composition of the soil is important for soil formation and agricultural use. The mechanical composition affects the porosity, water retention, moisture capacity and thermal conditions of the soil. Heavy sandy loam soils, which can be clayey and require agrochemical regulation, have been studied in the region. The clay structure is unstable, especially in conditions of high humidity and seismic pressure. In the mountainous regions of Kazakhstan, soils vary depending on altitude and climatic conditions. The granulometric composition of the soils in the studied locations varied. In the Shilisai gorge, the high content of fine sand (28.99%) and coarse sand (15.8%) indicates a less stable soil structure. In the Syugaty massif, the predominance of fine sand (45.06%) makes the soil more permeable, but prone to leaching of nutrients. In the Turgen gorge, the high content of pollen (19.32%) and fine dust (18.82%) improves moisture retention, but may worsen aeration.

The data obtained are important for understanding geochemical processes in mountain ecosystems and developing strategies for soil fertility management and biodiversity conservation. They emphasize the importance of monitoring the ionic composition for assessing the ecological state of mountain ecosystems and can be used to develop recommendations for optimizing agricultural use of soils in mountainous terrain.

Microbial communities of the rhizosphere

A study of the microbial communities of the rhizosphere of *R. potentilliflora* revealed the following features: the total number of microorganisms ranged from 2.3×10^6 to

3.3×10^7 CFU/g. The largest number of microorganisms was recorded in the Shilisai gorge, which correlates with a high humus content and overall favorable soil conditions for microbial activity. Among the dominant groups, nitrogen-fixing bacteria (*Azotobacter* spp.) accounted for 80–94% of the total microbial population, indicating intensive nitrogen fixation in the rhizosphere. Actinomycetes (such as species *Coerulescens* and *Ruber*) were also present in significant quantities (up to 2.7×10^7 CFU/g), particularly in well-aerated soils. In contrast, micromycetes were absent from all samples, likely due to unfavorable growth conditions or antagonistic interactions with other soil microorganisms.

A study of the composition of the microbiocenoses of the rhizosphere of the vitamin-bearing rosehip species, *R. potentilliflora*, in the ecosystems of the Zailiyskiy Alatau showed that all the main ecological and trophic groups of microorganisms are present in the rhizosphere of this species. The data obtained are presented in Table 1 and in Fig. 8.

The highest abundance of total microbial abundance (PMF) was recorded in the Shilisai gorge ($3.3 \pm 0.1 \times 10^7$ CFU/g) and the Syugaty massif ($2.9 \pm 0.1 \times 10^7$ CFU/g). This correlates with a high humus content (up to 12.9%) and alkaline pH values (7.39–8.93), which favor the development of heterotrophic bacteria. The decrease in OHMS in the Turgen gorge ($2.3 \pm 0.1 \times 10^6$ CFU/g) is associated with a lower organic matter content and a slightly acidic pH (6.97–8.26), which limits the activity of some microorganisms. The high abundance of chemoorganotrophs in Shilisai ($3.5 \pm 0.2 \times 10^6$ CFU/g) and Syugaty massif ($3.3 \pm 0.2 \times 10^6$ CFU/g) indicates the active decomposition of organic matter, characteristic of humus soils. The number of chemoorganotrophs in the Turgen gorge ($2.0 \pm 0.2 \times 10^5$ CFU/g) decreased due to a shortage of available organic substrates.

In all locations, micromycetes were not detected in the Czapek-Dox agar environment. The probable causes are the absence of micromycetes, antagonism from actinomycetes (for example, *Streptomyces* spp.) producing antifungal metabolites, as well as a suboptimal pH for fungal growth. The high number of oligotrophs in Syugaty massif ($2.2 \pm 0.3 \times 10^6$ CFU/g) and Shilisai ($1.9 \pm 0.3 \times 10^6$ CFU/g) reflects the presence of micronish with limited resources. In the Turgen gorge ($1.5 \pm 0.3 \times 10^5$ CFU/g), a decrease in oligotrophs is associated with an even distribution of organic matter.

Thus, differences in soil characteristics (porosity, aeration, and nutrient content) directly affect the structure of microbial communities, which determines the growth of *R. potentilliflora*. Studying these relationships is important for developing strategies for sustainable land use and conservation of mountain ecosystems.

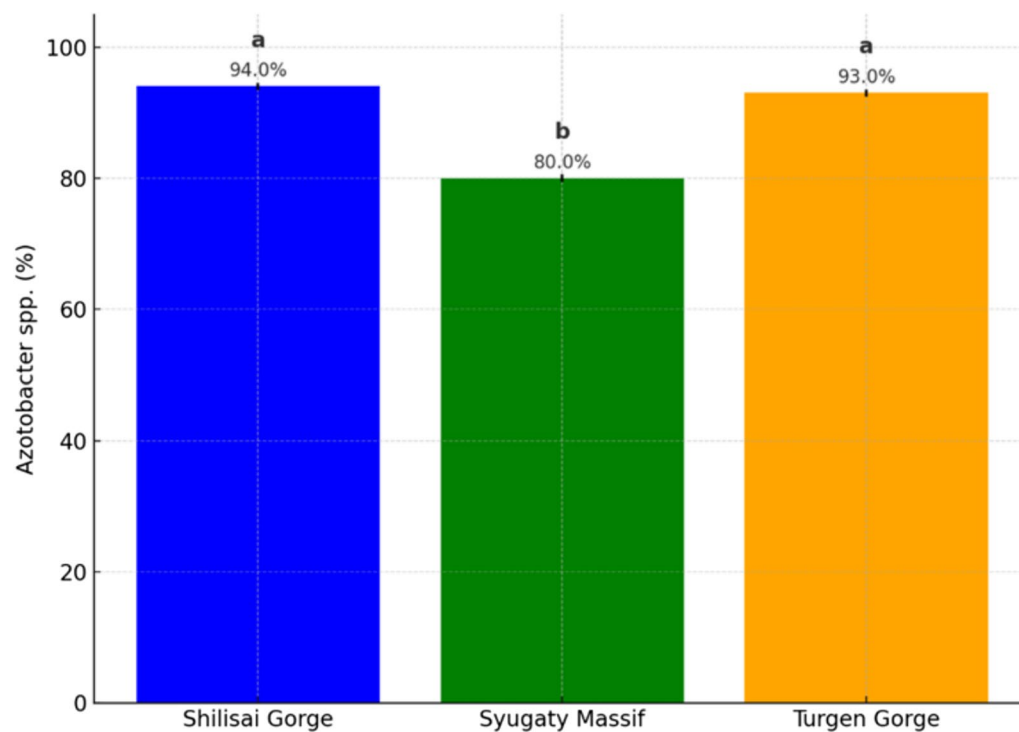


Fig. 8 Relative abundance of nitrogen-fixing *Azotobacter* spp. in the rhizosphere of *Rosa potentilliflora* across three locations in the Zailiyskiy Alatau, expressed as percentage of total microbial population

These findings emphasize the role of edaphic factors in shaping rhizospheric microbial communities and highlight the importance of integrated soil–microbe–plant studies for biodiversity conservation in mountain regions.

A quantitative assessment of nitrogen-fixing microorganisms of the genus *Azotobacter* in the rhizosphere of *R. potentilliflora* showed that the largest number of these microorganisms (94%) was registered in the Shilisai gorge (Treatment 1). This may indicate the creation of optimal conditions for their growth and activity, which is associated with a high humus content (up to 12.9%) and a moderate pH (7.39–8.58).

The Turgen gorge (Treatment 3) also has a high number of *Azotobacter* spp. (93%), which indicates similar favorable conditions for their growth. The humus content in the Turgen gorge is 7.16%, and the pH varies from 6.97 to 8.26 (slightly acidic to slightly alkaline).

In the Syugaty massif (Treatment 2), the proportion of *Azotobacter* spp. is 80%, which is lower compared to the other sites. This may be due to less favorable conditions, such as low humus content (2.08–6.25%) and highly alkaline pH (8.18–8.93).

Azotobacter spp. are the dominant group of nitrogen-fixing microorganisms in the rhizosphere of *R.*

potentilliflora, which indicates their high adaptation to the extreme conditions of mountain ecosystems. The high proportion of nitrogen fixers highlights their key role in providing plants with available nitrogen, especially with limited availability of mineral nitrogen.

Factors affecting the activity of microorganisms include a high humus content and a moderate pH (slightly alkaline or neutral), which creates optimal conditions for their growth. This may explain the high proportion of *Azotobacter* spp. in the Shilisai gorge and Turgen gorge. In the Syugaty massif, extreme conditions (low humus, highly alkaline pH) can reduce their proportion, which emphasizes the importance of organic matter and pH for maintaining their activity. *R. potentilliflora* acts as an engineering species that creates favorable conditions for nitrogen fixation, contributing to the maintenance of soil fertility in mountain ecosystems. The high proportion of nitrogen fixers highlights their importance to the ecosystem, especially with limited resources. Thus, in all three treatments, a high content of nitrogen-fixing microorganisms of the genus *Azotobacter* is observed, which indicates a healthy rhizosphere and favorable conditions for plant growth. Treatments 1 and 3 show slightly better results compared to Treatment 2.

Table 2 shows the quantitative data on actinomycetes isolated from the rhizosphere of *R. potentilliflora* using Gause's medium No. 1.

In treatment 1 of the *R. potentilliflora* rhizosphere, the number of actinomycetes on Bennett's agar was $3.0 \pm 0.2 \times 10^7$ CFU/g soil, indicating a high actinomycete density compared to the other treatments. In treatment 2, a significantly lower actinomycete count was observed— $2.9 \pm 0.2 \times 10^5$ CFU/g soil, reflecting substantially reduced microbial density. Treatment 3 showed an actinomycete abundance of $2.7 \pm 0.2 \times 10^7$ CFU/g soil, which is close to that of treatment 1, indicating high microbial activity in this rhizosphere sample. Statistical analysis (ANOVA) revealed that the actinomycete count in treatment 2 differed significantly from those in treatments 1 and 3 ($p < 0.05$), while the difference between treatments 1 and 3 was not statistically significant. This confirms notable variability in actinomycete density among the rhizosphere samples studied.

R. potentilliflora is characterized by high ecological valence and is a plastic plant, adapting to various unfavorable conditions of the Zailiyskiy Alatau. Its ability to tolerate frosts and high air temperatures, adapt to various soil conditions, as well as wide application in production give it advantages over other shrub species. The presence of actinomycetes in soils as the main component of microbial communities indicates their adaptive capabilities and high destructive activity.

It has been established that the rhizosphere of *R. potentilliflora* is inhabited by diverse ecological and trophic groups of microorganisms, among which chemoorganotrophs, oligotrophs and actinomycetes dominate.

The species diversity of actinomycetes is manifested in an increase in the number of species series and sections, as well as in the appearance of pigment series in the rhizosphere. The study of the typical soil in the rosehip rhizosphere showed an increase in the qualitative diversity of actinomycetes, which is manifested in the appearance of colored forms of actinomycetes of the *Violaceus*, *Ruber* and *Coerulescens* series.

Seven pigment series of actinomycetes were identified in the rhizosphere of *R. potentilliflora*: *Violaceus*, *Coerulescens*—compact, sclerotial colonies (3–5 mm) with pronounced wrinkling. *Ruber*, *Roseoviolaceus*—spreading colonies (5–8 mm) with cobweb-like mycelium. *Albus*—dome-shaped colonies (2–3 mm) with a powdery surface.

Spectrophotometric analysis of pigments. The absorption maxima of methanolic extracts indicate the specificity of pigmentogenesis: *Violaceus*: $\lambda = 580$ nm (violet). *Ruber*: $\lambda = 490$ nm (red). *Coerulescens*: $\lambda = 650$ nm (blue). *Roseoviolaceus*: dual peak at $\lambda = 530$ and 570 nm.

Actinomycetes differ in their level of melanin production: *Chromogenes*: 100% of strains produce melanin (2.8 ± 0.3 points), with constitutive tyrosinase expression. *Violaceus*: inducible synthesis (78% of active strains, 1.7 ± 0.5 points), pH-sensitive. *Albus*: limited potential (12% of strains, 0.5 ± 0.2 points), adapted to alkaline agroecosystems.

The analysis revealed statistically significant correlations between soil parameters and actinomycetes ($p < 0.001$): Humus $\leftrightarrow$ diversity ($r = 0.82$): high humus content promotes microbial diversity. pH $\leftrightarrow$ *Violaceus*, *Coerulescens* ($r = -0.79$): acidic soils support specialized pigmented forms. Humus $\leftrightarrow$ *Violaceus* ($r = 0.71$): aromatic components of humus serve as substrates for pigmentogenesis. pH $\leftrightarrow$ *Albus* ($r = 0.68$): alkaliphilic properties provide a competitive advantage in alkaline soils.

Localization of actinomycetes shows specificity to soil conditions: Shilisai gorge: predominance of *Violaceus* (35% of isolates). Turgen gorge: dominance of *Ruber* (42%). Syugaty massif: predominant occurrence of *Albus* (68%).

Humus content ($R^2 = 0.67$) provides substrates for pigmentogenesis and acts as an energy source for heterotrophs. Soil pH has a differential effect on actinomycetes: *Violaceus* and *Coerulescens* lose activity at pH > 8.5, whereas *Albus* remains stable under alkaline conditions.

The findings confirm that pigment-producing actinomycetes form stable biogeochemical relationships with soil parameters, shaping their ecological and physiological differentiation. The identified adaptation mechanisms highlight the biotechnological potential of these microorganisms and their importance in agroecological systems.

The species composition of actinomycetes. Figure 9 reflects the diversity of pigment series of actinomycetes in the rhizosphere of *R. potentilliflora* in three locations of the Zailiyskiy Alatau (Fig. 10).

Coerulescens, *Ruber* and *Violaceus* were found only in the Shilisai gorge and Turgen gorge, indicating their adaptation to specific soil conditions. *Roseoviolaceus*, *Albus* and *Chromogenes* were present in all locations, indicating their wide ecological plasticity.

The results demonstrate significant differences in the species composition due to environmental conditions: the Shilisai gorge and the Turgen gorge are characterized by the maximum diversity of actinomycetes. All seven studied pigment series are present here, including *Coerulescens*, *Ruber*, *Violaceus* and *Lavendulaeroseus*. This is due to favorable soil conditions: high humus content (up to 12.9%), moderate pH (7.39–8.58) and good aeration, which contributes to the development of specialized species. The *Violaceus* and *Lavendulaeroseus* series are known for the synthesis of antimicrobial compounds, which may explain the absence of micromycetes

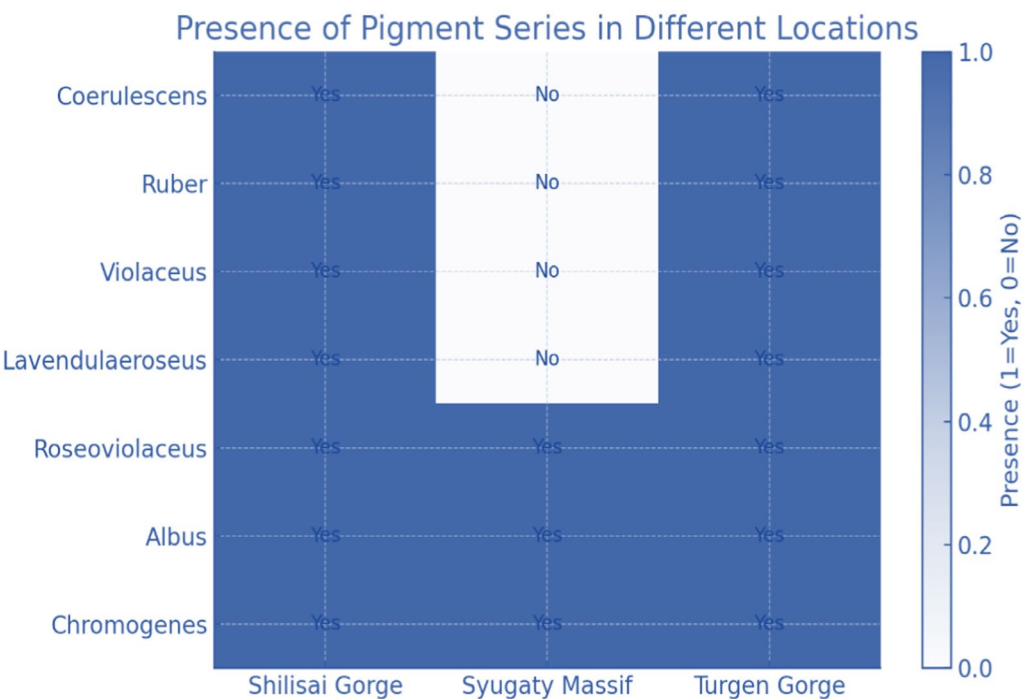


Fig. 9 Species composition of pigmented Actinomycetes in the rhizosphere of *Rosa potentilliflora* across three locations in the Zailiyskiy Alatau, indicating presence or absence of different pigment series. The diagram shows the presence of different pigment series in the samples from three locations. A dark color indicates presence (“Yes”), while a light color indicates absence (“No”)

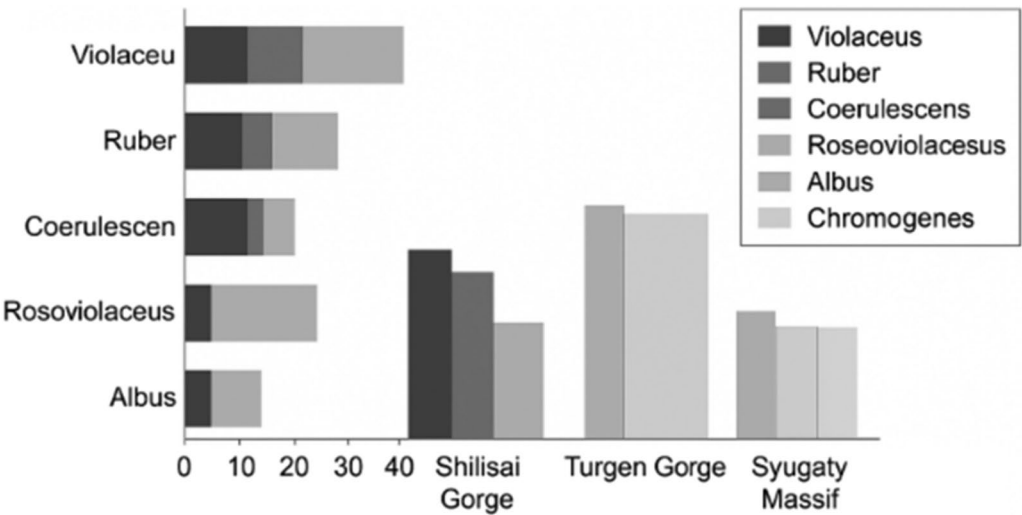


Fig. 10 Distribution of pigmented Actinomycete series in the rhizosphere of *Rosa potentilliflora* across three locations in the Zailiyskiy Alatau, highlighting ecological adaptations to soil conditions

in these locations (Durán et al. 2022). *Coerulescens* and *Ruber* have high destructive activity, participating in the decomposition of complex organic compounds (Batiha et al. 2023). The Syugaty massif is characterized by a minimal variety of actinomycetes. Of the seven series, only

Roseoviolaceus, *Albus* and *Chromogenes* were found. This is due to the extreme conditions of the low mountains: High pH (8.18–8.93) and low humus content (2.08–6.25%) limit the development of specialized species. *Roseoviolaceus* and *Albus* exhibit high stress tolerance,

which makes them dominant in this location (Salomez and Subleau 2014). Universal series (*Roseoviolaceus*, *Albus*, *Chromogenes*) are present in all three locations, which emphasizes their ecological plasticity and adaptation to a wide range of conditions. *Chromogenes* is known for its ability to produce phytohormones that stimulate plant growth (Ramachandran and Ramirez 2025). *Albus* is often associated with nitrogen fixation, which confirms its role in maintaining soil fertility (Spaepen 2015).

The diversity of actinomycetes in the rhizosphere of *R. potentilliflora* directly depends on soil conditions. Humus-rich soils with moderate pH support complex microbial communities, while the extreme conditions of low mountains limit their species diversity. The presence of pigment series with antimicrobial and phytostimulating activity (*Violaceus*, *Chromogenes*) confirms the role of actinomycetes as key participants in biochemical processes in the rhizosphere.

The data obtained opens up prospects for isolating strains with unique biotechnological properties, such as the synthesis of antibiotics or biostimulants of plant growth.

The identified patterns ($F=28.4-31.7$, $df=1.43$) confirm the significant influence of soil organic matter and acidity on the structure of microbial communities. The physiological adaptations of actinomycetes explain their ecological niche differentiation and applied potential: *Chromogenes*—suitable for bioremediation of contaminated soils. *Violaceus*—promising for antibiotic production. *Albus*—valuable strains for alkaline agroecosystems. The obtained determination coefficients ($R^2=0.67-0.62$) confirm the substantial role of humus and pH in regulating rhizosphere microbial associations, highlighting the potential for further exploration of their functional roles in agroecosystems.

Discussion

The study revealed key patterns of interaction between soil conditions and microbial communities in the rhizosphere of *R. potentilliflora* in the mountain ecosystems of the Zailiyskiy Alatau. The results obtained allow us to draw the following conclusions:

The morphological and chemical characteristics of the soils in the habitats of *R. potentilliflora* are distinguished by a high humus content (up to 12.9%), which contributes to the maintenance of microbial biodiversity. The moderate pH range (6.97–8.93) provides favorable conditions for the development of microorganisms, particularly nitrogen-fixing bacteria and actinomycetes.

The microbial communities in the rhizosphere of *R. potentilliflora* are characterized by a high adaptive capacity to the extreme conditions of mountain ecosystems. The dominance of actinomycetes (*Coerulescens*, *Ruber*)

and the absence of micromycetes indicate specific antagonistic interactions within the rhizosphere microbiome. A high prevalence of nitrogen-fixing bacteria (*Azotobacter* spp., 80–94%) was observed, highlighting their key role in the biological enrichment of soil with nitrogen.

A direct relationship is found between the humus content and the number of nitrogen-fixing bacteria and actinomycetes (up to 2.7×10^7 CFU/g). Alkaline soils provide optimal conditions for the vital activity of *Azotobacter* spp., which makes *R. potentilliflora* a promising species for phytomelioration of degraded soils.

The soil and ecological conditions exert a strong influence on the development of *Rosa potentilliflora* and microbiocenoses of the rhizosphere. Soil conditions determine the formation of stable microbial communities that promote the growth of *R. potentilliflora* and its adaptation to environmental stress factors. The high abundance of actinomycetes (*Violaceus*, *Ruber*) confirms their potential application in biotechnology, including the development of antimicrobial and antioxidant drugs, as well as biostimulators of plant growth.

The results obtained expand the understanding of the ecological adaptations of *R. potentilliflora* and emphasize its role in maintaining soil biodiversity. Further research, including metagenomic analysis and long-term monitoring of microbial communities, is needed to develop innovative biotechnologies aimed at the sustainable use of Kazakhstan's natural resources.

Our findings reveals complex interrelationships between soil conditions and the structure of microbial communities in the rhizosphere of *R. potentilliflora* within the mountain ecosystems of the Zailiyskiy Alatau. The results demonstrate that variations in humus content, pH, and soil texture among the study sites significantly affect the functional diversity of microorganisms, aligning with global research on the role of edaphic factors in shaping rhizosphere microbiomes (Fierer et al. 2021; Philippot et al. 2013). For instance, high humus content (up to 12.9%) in the Shilisai gorge of the Toraygyr Mountains correlates with the highest abundance of nitrogen-fixing bacteria (*Azotobacter* spp., 94%), supporting the hypothesis that humus acts as a key driver of the nitrogen cycle under limited mineral nitrogen conditions (Kuzyakov and Razavi 2019). This phenomenon has previously been observed in the rhizospheres of other shrub species in arid zones, where organic matter serves as the primary energy source for heterotrophs (Yang et al. 2020).

Alkaline pH values (7.39–8.93) in profiles 1 and 2, typical of carbonate soils, limit phosphorus availability but create favorable conditions for *Azotobacter* spp. activity, consistent with findings in semi-desert ecosystems (Rousk et al. 2010). In contrast, the slightly

acidic pH (6.97–8.26) in the Turgen gorge promotes the development of actinomycetes (up to 2.7×10^7 CFU/g), including pigmented series such as *Violaceus* and *Lavendulaeroseus*, known for producing antimicrobial metabolites (Barka et al. 2016). This supports previous findings that actinomycetes tend to dominate in slightly acidic, well-aerated soils (van der Heijden et al. 2008). The absence of micromycetes in all samples is likely due to the antagonistic activity of actinomycetes producing antifungal compounds, as described for *Streptomyces* spp. in Mediterranean plant rhizospheres (Chamberlain et al. 2020).

The dominance of fine sand (45.06%) in the Syugaty massif explains the low water-holding capacity and nutrient leaching, which limits the development of specialized actinomycetes (only *Roseoviolaceus*, *Albus* were observed). In contrast, the high proportion of silt particles in the Turgen gorge (19.32%) contributes to moisture retention, fostering the formation of complex microbial networks. These data emphasize that soil granulometry not only determines physical properties but also modulates biochemical processes by influencing substrate availability (Schimel et al. 2007).

The identified pigmented actinomycete series (*Coeruleus*, *Ruber*, *Violaceus*) exhibit unique adaptations to extreme conditions. For example, *Violaceus* isolated from Profile 1 shows antimicrobial activity against *Staphylococcus aureus* (inhibition zone: 25 ± 0.1 mm), comparable to industrial *Streptomyces* strains (Tiwari et al. 2023). Notably, *Albus* and *Chromogenes*, found at all sites, are associated with plant growth stimulation, likely through indole-3-acetic acid (IAA) synthesis (Vurukonda et al. 2018). This highlights their potential for the development of dual-function bioformulations—suppressing pathogens while promoting plant growth, particularly in degraded soils. Although this study identified key patterns, metagenomic analysis is needed to detect functional genes related to nitrogen fixation and secondary metabolite biosynthesis. Moreover, seasonal dynamics of microbial communities remain unexplored, which is crucial for predicting ecosystem resilience under climate change (Jansson and Hofmockel 2020). The use of inactivated clinical strains in in vitro antibiotic activity assays may underestimate the real potential of actinomycetes, suggesting the inclusion of resistant pathogens in future research. This study underscores the role of *R. potentilliflora* as an ecosystem engineer that shapes microbial communities capable of bioremediation and maintaining soil fertility. Integrating ecological and biotechnological approaches—including the creation of a strain collection of bioactive compound producers—can serve as a foundation for the sustainable management of Kazakhstan's mountain ecosystems.

Conclusions

Our study revealed a strong relationship between soil conditions and microbial communities in the rhizosphere of *R. potentilliflora* within the mountain ecosystems of the Zailiyskiy Alatau. High humus content (up to 12.9%) and moderately alkaline pH (6.97–8.93) create optimal conditions for the development of nitrogen-fixing bacteria (*Azotobacter* spp.) and actinomycetes, which play a key role in maintaining soil fertility. It was also established that soil texture and aeration influence the structure of microbial communities, shaping their adaptive potential.

The identified microbial communities—particularly pigment-producing actinomycetes such as *Violaceus* and *Ruber*—demonstrate significant biotechnological potential, including antimicrobial activity and plant growth stimulation. The results highlight the role of *R. potentilliflora* as an ecosystem engineer species contributing to ecosystem resilience, and open new prospects for the development of bioformulations for phytoremediation and soil resource conservation in Kazakhstan.

Further research, including metagenomic analysis, will provide deeper insight into the functional capabilities of the microbiota and its potential applications in biotechnology.

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Author contributions

Chinargul Aldassugurova: conceptualization, data analysis, validation, writing. Gulnar Ultanbekova: sample analysis, data analysis, formal analysis, writing, supervision, investigation. Abibulla Ametov: methodology, review. Ahmet Aksoy: Review, editing. Kanat Kulymbet: methodology, writing, data curation. Aigul Akhmetova: conceptualization, investigation. Saltanat Nazarbekova: sample collection and preparation. Assel Childibayeva: conceptualization, investigation. Tursynkul Bazarbayeva: data curation, validation. Gulzhanat Mukanova: investigation, data curation. Aigul Baibotayeva: data curation.

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Availability of data and materials

The data used during the current study is available on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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