RESEARCH ARTICLE

SABRAO Journal of Breeding and Genetics
58 (3) 1407-1414, 2026
http://doi.org/10.54910/sabrao2026.58.3.43
http://sabraojournal.org/
pISSN 1029-7073; eISSN 2224-8978

ROCKY SOIL COMPOSITIONS INFLUENCE ON THE MICROORGANISMS AND VEGETATION AT THE SHEKI-ZAGATALA ECONOMIC REGION, AZERBAIJAN

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SUMMARY

The pioneering research comprised modern biogeological studies of the soil. The study based on soil microorganisms and natural vegetation in the mountain cliffs of the Sheki-Zagatala economic region (Sheki Region), Azerbaijan, emerged as innovative in environmental research of the said area. Rocky soil compositions were specific to extreme ecosystems, which contribute to the formation of special communities of microorganisms. With weathering crust of rocks, actinomycetes were considerably less abundant and biomass-rich than other microbial groups. The highest content of prokaryotes in the finer fraction of samples (less than 1 mm) evidently occurred to be closely associated with its mineral composition. The presented research can serve as a modern literary source in the fields of biology and soil science. This innovative research focused on the exploration of microorganisms and vegetation in the extreme ecosystems found in the mountain cliff soils of the Sheki-Zagatala Region, Azerbaijan.

Keywords: Rocky soil compositions, extreme ecosystems, microorganisms, vegetation, biogeological parameters, biomineral complex, phytomass, landscapes

Key findings: The results highlighted the unique microbial communities adapted to rocky soil compositions and extreme environments, which proved to be valuable resources in the fields of biology and soil science. Actinomycetes appeared significantly less abundant and biomass-rich than other microbial groups in the weathering crust of rocks.

Communicating Editor: Prof. Naqib Ullah Khan

Manuscript received: December 03, 2025; Accepted: January 11, 2026.

Citation: Mammadova GI, Salimova ShJ, Jafarov AM, Huseynova SM, Isayeva KK, Isagova VG, Hasanova TA (2026). Rocky soil compositions influence on the microorganisms and vegetation at the Sheki-Zagatala Economic Region, Azerbaijan. *SABRAO J. Breed. Genet. 58 (3) 1407-1414. http://doi.org/10.54910/sabrao2026.58.3.43*.

INTRODUCTION

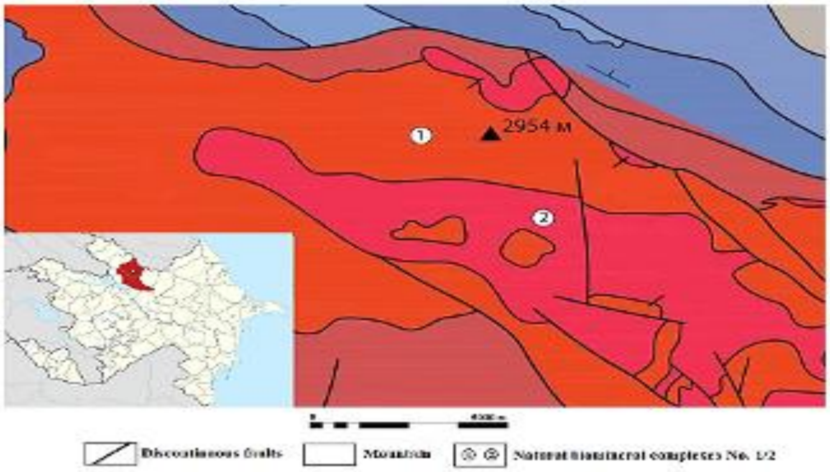
The influence of rocky soil composition of natural biomineral complexes on the microorganisms resulted in their role as a habitat and a source of minerals and nutrients. Similarly, it promotes biological weathering and the formation of favorable conditions for the microbial community. The rocky composition has a significant impact on the structure, functions, and dynamics of microbial communities in natural biomineral complexes and plays a crucial role in geochemical and biogeochemical processes, weathering, and soil formation (Boyd *et al*., 2011; Hasanova *et al*., 2021).

Microorganisms both destroy the rocks and actively participate in forming new minerals by changing the geochemical composition of the environment and influencing the evolution of mineral complexes. Over time, the rock breaks down into smaller mineral particles (Bunyatova *et al*., 2025; Gahramanova *et al*., 2026). However, the rate and type of weathering depend upon the climate, water, and organic matter, which eventually influence the soil mineralogy (Figure 1). Vegetation types can also affect various mineral contents. Nutrients like carbon, nitrogen, phosphorus, potassium, calcium, magnesium, iron, and aluminum (C, N, P, K, Ca, Mg, Fe, and Al, respectively) and heavy metals, with forests often showing higher accumulation than grasslands, and different plants exhibiting varied extraction capacities. Rocky soils are rich in primary minerals like quartz, feldspars (K, Na, and Ca), and micas, alongside iron oxides (hematite, goethite), clay minerals (montmorillonite, illite), and calcium/magnesium carbonates (calcite) (Ibrahimova *et al*., 2025). They reflect their parent rock's composition (granite, basalt, limestone) but also show weathering, adding aluminum (gibbsite) and sulfates (gypsum). Plants can release organic ligands (phenolic acids, amino acids, sugars, organic acids, siderophores, and flavonoids) that influence weathering and mineralization, and these soil minerals, in return, can also manage plant growth and development (Ismayil *et al*., 2025; Ismayilova *et al*., 2025; Mammadova *et al*., 2024).

Minerals' consumption mostly occurs in the same locations, as complemented by the formation of characteristic landscape features, such as natural biomineral (quartz, feldspars, and micas) complexes (NBC) (Kazeev and Kolesnikov, 2012). For the determination of rocks' consumption within these NBC by wild animals on the southern slopes of the Greater Caucasus Mountains, the fieldwork proceeded in 2024–2025, with the different crop plants and rock samples collected. The following research presents and discusses the results of said investigations.

Annual narrow- and broad-leaved weeds are widespread in the area: *Alopecurus myosuroides, Amaranthus albus, Amaranthus retroflexus, Amaranthus viridis, Avena sterilis, Bromus sterilis, Chenopodium album, Chrozophora tinctoria, Daucus carota, Echinochloa colonum, Echinochloa crus-galli, Euphorbia amygdaloides, Brassica napus L., Lathyrus pratensis, Malva neglecta, Medicago polymorpha, Ochthodium aegyptiacum, Phalaris arundinacea* L., *Phalaris aquatica, Portulaca oleracea, Ranunculus arvensis, Senecio vernalis, Setaria viridis, Sinapis arvensis, Stellaria media, Vicia faba, Xanthium spinosum,* and *Xanthium strumarium* (Kazeev and Kolesnikov, 2012; Ma *et al*., 2021; Macnunlu *et al*., 2025).

The perennial narrow- and broad-leaved weeds were also prevalent. *Artemisia vulgaris, Convolvulus arvensis, Cyperus rotundus, Cynodon dactylon, Sorghum halepense, Urtica dioica, Carduus nutans, Centaurea cyanus, Cirsium arvense, Lactuca serriola* L., *Matricaria chamomilla, Senecio vernalis, Sonchus oleraceus, Artemisia arvensis, Chrysanthemum segetum, Lamium amplexicaule, Matricaria recutita, Papaver rhoeas, Polygonum convolvulus, Senecio vulgaris, Stellaria media, Taraxacum officinale, Tussilago farfara, Veronica hederifolia, Triticum aestivum, Hordeum vulgare, Sorghum halepense,* and *Lolium temulentum* (Makki *et al*., 2025; Mammadova *et al*., 2025; Gahramanova *et al*., 2026).



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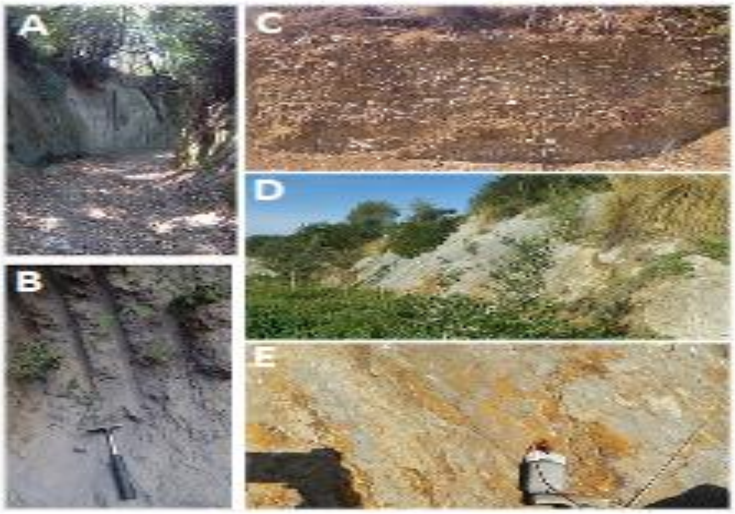

B

Figure 1A. Geological map of the study area—inset shows the location of the study area within the territory; **1B.** Some examples of deposits and faults from the study area. a) Pyroclastic deposits, b) alluvial fan deposits, c) volcanic deposits, d) fault plane from the southern flank of the mountain, and e) oblique striations on the fault surface in panel d.

MATERIALS AND METHODS

Based on the conducted field studies, the rocky composition samples, as collected, came from two natural biomineral complexes (NBC) formed on the slopes of Khan Plateau, Great Caucasus Range, Sheki Region, Azerbaijan. Externally, the complexes were similar and represent a series of almost isometric sites on grassy (wildflowers, shrubs) mountain slopes, cleared of vegetation and soil, and worn out by animal hooves, and connected by animal trails. At NBC No. 1 and No. 2, the collection of two generalized samples of loose rock used the envelope method (Figure 2).

The samples collected came from niches (usually located near the underground roots of grass vegetation) at depths of 0–3 cm and 10–15 cm. The air-dried samples reached sieving through a 1-mm mesh before use for subsequent mineralogical and microbiological analyses (Mammadzada *et al*. 2025; Mirzezadeh *et al*. 2026). Analysis based on the particle size (20–4.5 mm) and mineral composition of the collected rocks continued in the Institute of Geography, Baku, Azerbaijan.

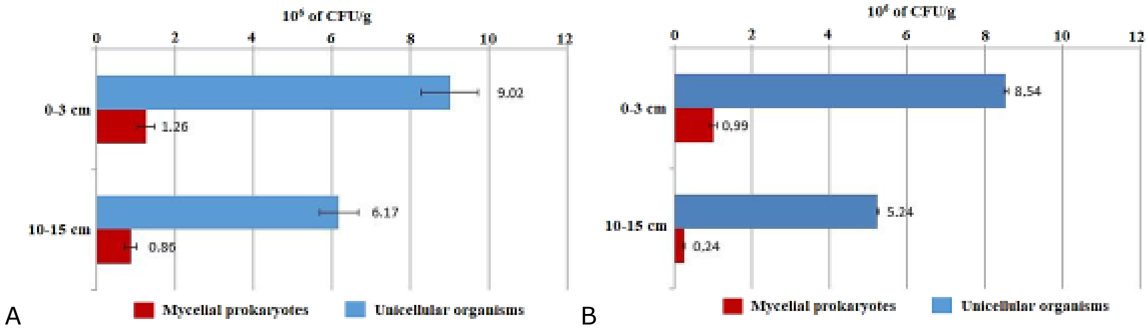

Figure 2. The amount of unicellular organisms and mycelial prokaryotes in the studied samples: NBC No. 1 (A), NBC No. 2 (B).

According to the granulometric composition of the selected rocks, the sieve analysis performed was in accordance with GOST 12536-2016, with the classification of GOST 25100-2011, with a representation of gravel sand (NBC No. 2) and gravel soil with sand filler (NBC No. 1) with an eluvial-deluvial origin (Nasirova *et al*. 2026).

The mineral composition of the clay fraction, when determined, used an Ultima-IV diffractometer. The operating mode was 40 kV at 40 mA, comprising copper radiation, a nickel filter, and a measurement range of 3–55° and 3–65° 2θ, a scanning angle step of 0.02° 2θ, and a fixed focusing slit system. Using a DTex/Ultra semiconductor detector sped up acquisition and improved the quality of experimental data, and the scanning rate was 10° 2θ/min. The abundance and diversity of the actinomycete complexes underwent evaluation by plating aqueous suspensions of samples onto a solid nutrient medium with the following composition (g/L): glucose 10, asparagine 0.5, K_2HPO_4 0.5, and agar 20, adding the nystatin (250 µg/mL) to the agar to control the growth of filamentous fungi. Petri dishes containing the plated samples received incubation at 28 °C for a week, after which counting the colonies ensued, with the clones isolated for further analysis (Nazim *et al*. 2024; Mammadova *et al*. 2026). The isolated cultures entailed storage in test tubes with slanted oatmeal medium at +4 °C. Among all isolated cultures, the screening proceeded for the identification and presence of antibiotic activity in vitro using the well method against test cultures of bacteria: *Staphylococcus aureus* ATCC 29213, *Bacillus cereus* ATCC 10702, and *Escherichia coli* ATCC 25923 (Rowell, 1999; Ma *et al*., 2021; Mammadova *et al*., 2025).

RESULTS AND DISCUSSION

Mineral composition – fractions over 1 mm

According to geological exploration levels of this area, the Khan Plateau consisted of Paleozoic granitoids of the γPZ2b igneous complex and the γPZ3u igneous complex. The soil rocks of the complexes had representations of coarse-grained granodiorites, including porphyritic, and granites, including gneissic types. Past studies enunciated the vein formations of the soil complex, showing characteristics of a pegmatite-aplite composition (Mammadova *et al*., 2024; Makki *et al*., 2025). Granites, including numerous xenoliths of amphibolites, gneisses, and schists, form the large massifs.

In natural biomineral complexes of the Khan Plateau, the fragments of bedrock in thin sections were notable as holocrystalline granites with an uneven medium-coarse-grained structure and a heterogeneous spotted texture, with elongated zones composed exclusively of quartz. The main rock-forming minerals were plagioclase (50%), quartz (35%), potassium feldspar (10%), and biotite (5%). The accessory mineral was zircon (1%). Secondary minerals, sericite and clays, develop primarily after plagioclase. The mineral composition of the collected rock samples, for fractions larger than 1 mm, revealed representations primarily of gravel-sized plagioclase and quartz grains, as also reported in previous studies (Nasirova *et al*. 2026; Sadigov *et al*., 2025).

Mineral composition – fractions smaller than 1 mm

All the collected rocky soil samples displayed characteristics of a predominance of clay minerals (illite with an admixture of smectite and kaolinite), and their content fluctuates between 34% and 47%. The studied rocks also contain numerous quartz crystal fragments (ranging from 14% to 25%), and the rest of them consist of feldspars (making up sand/silt fractions slowly weathering into clays) and chlorites (Figure 2) (Kazeev and Kolesnikov, 2012). Using dry sieving through a 1-mm sieve as a sample preparation method, followed by inoculating aqueous suspension of samples with fractions larger and smaller than 1 mm onto a solid nutrient medium, revealed prokaryotic organisms' associations with the finer fractions. In the weathering crust of rocks, microorganisms reached adsorption due to various physicochemical forces, as well as molecular and biological mechanisms (Rowell, 1999; Kazeev and Kolesnikov, 2012). Furthermore, the interaction of cells with various mineral particles gained significant influences from the chemical composition of the mineral (including the electrical charge of the surface), the organic films on the soil surface, the concentration of cations in the medium, and humidity. Above all, the number of adherent cells was directly proportional to the surface area to which they can attach, so adhesion, when calculated per unit weight of sorbent, was inversely proportional to particle size. This explains why microbiological culture of the fraction retained on the 1-mm sieve, which comprised primarily plagioclase and quartz fragments, revealed an extremely low number of microorganisms on the nutrient medium. In the numbers of prokaryotes, the differences were remarkable when culturing aqueous suspensions from the two size fractions, more than two orders of magnitude (Figure 3).

Sowing suspensions of soil fractions (smaller than 1 mm) revealed a relatively high abundance of actinobacteria, comparable to the abundance of actinomycetes in the humus horizon of gray-brown soils. The abundance of mycelial prokaryotes in the 0–3 cm layer, both NBC complexes amounted to 10^6 CFU/g. The relatively low diversity of the identified actinobacteria morphotypes was evident; in

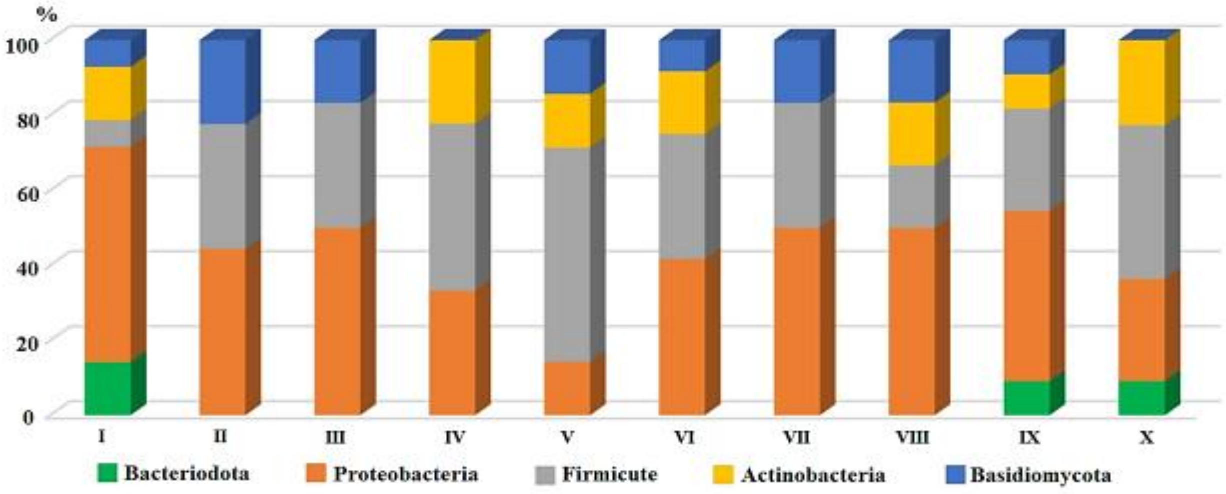

Figure 3. Taxonomic diversity of cultured heterotrophic microorganisms in rocks. Note: I-VI samples from Khan Plateau and VII-X samples from Mount Zandag.

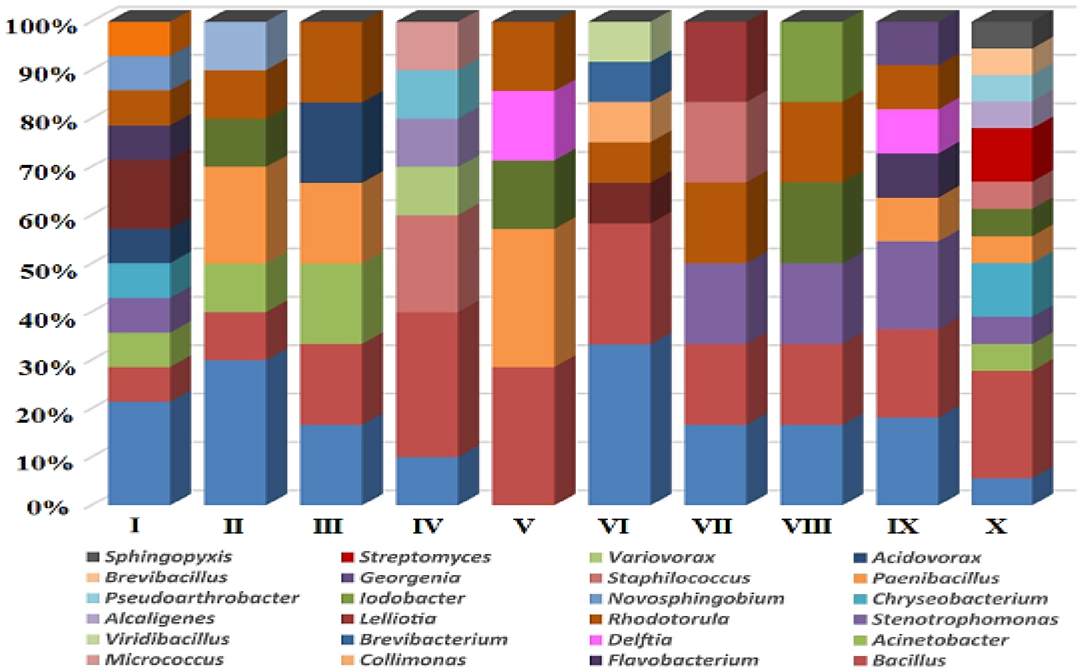

Figure 4. Taxonomic diversity of cultivated heterotrophic microorganisms at the genus level in the rocks of the Khan Plateau. Note: I-VI samples from Khan Plateau and VII-X samples from Mount Zandag.

contrast, it was more typical of low-humus soils with low organic matter content. The vast majority of actinomycetes isolated by culture from rocky soil samples consumed by animals collected within the studied soil horizons belong to the genus *Streptomyces*, a characteristic feature of most soils. The genus *Micromonospora* representatives showed a typical association with crop plants and plant debris and, therefore, achieved recognition as minor components of the complex in mineral soil horizons (Figure 4) (Ma *et al*., 2021; Sadigov *et al*., 2025; Verdiyeva *et al*., 2025).

The antagonistic activity screening among all the isolated actinomycete strains disclosed streptomycetes that inhibit the growth of test organisms, such as *Staphylococcus aureus, Bacillus cereus,* and *Escherichia coli.* These bacterial species are well known for their widespread occurrence in nature and for their ability to cause a wide range of diseases, from toxic infections to septicemia (SP 1.3.2322-08). Antagonism against gram-positive organisms (*S. aureus* and *B. cereus)* was much more common among the actinomycetes than the ability to inhibit the growth of gram-negative bacteria, particularly *E. coli*. The said phenomenon may be due to the structural features of the gram-negative bacteria's cell wall, which prevents the penetration of large biomolecules, and their ability to remove the small foreign molecules from cells through an active transport mechanism (Shukurov *et al*., 2025a, 2025b).

Actinomycete strains capable of producing various substances that limit the growth of gram-negative bacteria hold significant promise for further research and exploration of their properties. In this perspective, the most promising one is *Streptomyces sp*. GA5 strain for further study, which is an active antagonist against aureus. It is also capable of inhibiting the growth of *E. coli*. A phylogenetic study of the most antagonistically active actinobacteria strains, GA2, GA5, and GA7, showed that, based on the analysis of the nucleotide sequences of the 16S rRNA genes, these strains belong to species of the genus *Streptomyces* (Table 1). The study also showed the levels of similarity to the closest type cultures were 98.99%, 100%, and 99.72% (Figure 4) (Ma *et al*., 2021; Kazeev and Kolesnikov, 2012).

The natural distribution of actinomycetes indicated linkage to the wide range of ecological adaptations and possessed the tolerance to low moisture and nutrient levels in the environment and the ability to form the dormant structures. Being slow-growing organisms, they were able to develop in soils representing the weathering crust of rocks only in the late stages of succession, as and when the readily available energy sources had been exhausted (Sadigov *et al*., 2025; Makki *et al*., 2025; Nasirova *et al*., 2026).

According to various studies, in the prokaryotic complexes of most soils, the proportion of mycelial prokaryotes rarely exceeds 20% of the total biomass. Even at relatively low numbers, actinomycetes emerged to be capable of exerting a noticeable regulatory effect on the composition of microbial complexes (bacteria, fungi, algae, and lichens) due to their ability to produce substances with antibiotic properties. The abundant growth of streptomycetes in weathered rocky soil layers can easily be noticeable with animals due to the secretion of geosmin, a substance with a pronounced odor (Shukurov *et al*., 2025; Verdiyeva *et al*., 2025; Ismayilova *et al*., 2025).

CONCLUSIONS

In the weathering crust of rocky soil during the late stages of microbial succession, the conditions proved favorable for the development of actinomycetes, which were usually significantly fewer and lesser in biomass than other microbial groups. The highest prokaryotic abundance in the finer fraction of the samples (less than 1 mm) showed a clear close association with its mineral composition. Clay minerals, which predominantly comprise the studied fine fraction, have significantly higher adsorption capacity, specific surface area, and cation exchange capacity than other weathering crust minerals. During their development, actinomycetes accumulate and release the secondary metabolites into the environment that have antagonistic properties toward other prokaryotes.

ACKNOWLEDGMENTS

This research work received financial support from the authors, with the Institute of Geography Public Legal Entity, and Baku State University providing the equipment. The authors are grateful to all other colleagues at the Lankaran State University and Sumgayit State University, Azerbaijan.

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