ECO-BIOLOGICAL INDICATORS OF MOUNTAIN FOREST SOILS IN THE LANKARAN REGION, AZERBAIJAN

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SUMMARY

The potential study aimed to examine the influence of microorganisms, phytomass (green plants), and invertebrates on the agrophysical, agrochemical, and biological properties of mountain-forest brown soils. Mountain-forest dark brown soils develop in moderately warm and humid climate conditions. These soils have characteristics of air temperature from 6.0 °C to 11.9 °C), a large amount of precipitation (570–950 mm), low evaporation, and a high moisture coefficient (MC = 1.0–1.5). Mountain-forest dark brown soils remain confined to the lower belt of dry forests and shrubs. The total content and reserves of humus, total nitrogen, the composition, exchange cations, acidity, and temperature-humidity indicators entailed a comparative determination. Graphical analysis established the relationships between phytomass, the amount of microorganisms, and humus content. Likewise, the analysis identified the association between the total humus content and the absorption capacity of these soils, which limit the values of hydrothermal indicators of the soil biological activity. The results further revealed that in mountain-forest dark brown soils, the amount of microorganisms was greater than in mountain-forest brown soils, despite the phytomass reserves formation in the latter being 1.5–2.1 times more.

Keywords: Vegetation, microorganisms, agrochemical content, acidity, soil mesofauna, phytomass, bio-ecological indicators

Key findings: This study determined the effect of microorganisms, phytomass, and invertebrates on the agrophysical, agrochemical, and biological properties of mountain-forest brown soils. Sorption interactions, formed between the absorption capacity (cations and clay minerals) and soil humus, resulted in the formation of clay-humus complexes.

INTRODUCTION

Environmental conditions considerably influence the intensity of biological processes occurring in the soils. Similarly, it is particularly necessary to research the interrelation of soil biological activity with hydrothermal and physicochemical indicators (Aliyeva and Mammadova, 2023). Studying the group composition of invertebrates, microorganisms, and phytomass, as well as their positive role in humus formation of mountain-forest brown and mountain-forest dark brown soils, was advantageous. Their development has an important biodiagnostic significance for classifying the regional features of soil formation (Aliyeva, 2022; AzStat, 2024). Numerous investigations have progressed on the physicochemical indicators in mountain-forest brown soil. Several parameters determined, such as humus, carbonate content, and reaction of water solution or $CaCl_2$ instead of water, can provide more consistent results by releasing hydrogen ions into the solution of soil samples selected from natural and cultivated biotopes (Bakshaliyeva *et al.*, 2020; Ghong *et al.*, 2023). The dynamics of variations in these parameters for individual layers of the studied biotopes succeeded in their establishment (Bunyatova *et al.*, 2025). Physicochemical analyses of soil samples obtained from natural and cultivated biotopes (irrigated agrocenoses) of mountain forest dark brown soil revealed variations (Hasanov, 2017; Ikhtiyar, 2024). Such types of studies can be beneficial in a comprehensive ecological assessment of the state of lands, agricultural lands of Azerbaijan, species diversity of populations of living organisms, and for ecological assessment of the environment (Isagaliev *et al.*, 2015; Ismayil *et al.*, 2025).

On the foothills of the Fergana Mountains, similar studies have taken place based on morphological characteristics and physical properties and the soil-forming processes of brown mountain forest soils. These soils' characterization with agrophysical properties has massive lumpy-granular structural elements and water-resistant aggregates, with the lowest density, increased moisture capacity, and better aeration, contributing to a significant increase in natural and effective fertility (Ikhtiyar and Bahram, 2023).

Investigations transpired on the relationship between dehydrogenase activity and the physicochemical properties of mountain soils. Soil samples from the organic horizon involved studies for the determination of pH, organic carbon, nitrogen, base cation content, acidity, and dehydrogenase activity, with the carabid beetles also monitored (Kazakov, 1990; Kacprzyk *et al.*, 2020). In all the tested variants, the activity was higher in soil samples after burning the residues than in the control variants. Likewise, no positive correlation appeared between dehydrogenase activity and the number of carabid specimens. Simultaneously, the soil organic matter content showed a positive correlation to the carabid abundance. The significant impact of forest site conditions and the residues burning on the number of caught specimens achieved confirmation. In contrast, no relationships between the species richness, species diversity, mean individual biomass, and spot burning effect were evident. This research supports the recommendation of spruce fine woody debris utilization by spot burning in mountain regions with rich habitats presenting moderate wet conditions (for creating anaerobic environments) and small landfalls (Mammadova and Mammadova, 2024; Macnunlu *et al.*, 2025).

In soil diagnostics and classification, the dominant plant species and soil biota play an essential role. Studies for specific soil types, as well as for various mountain relief forms, have identified bioindicator plants of biophilic

elemental composition. The migration capacity of biophilic and the biochemical composition in typical soil types (Cu, Zn, and Co) can be effective as a diagnostic biological test. The higher contents of biophilic microelements (Cu, Zn, and Co) and often less (Ni, Cr, and Pb) in plants of brown mountain meadow and mountain forest soils of the western part of the southern slope of the Greater Caucasus can entail further scrutiny. Therefore, in addition to various relief forms, the main soil types determined the bioindicator plants' characteristics of a given region (Manu *et al.*, 2022; Mammadova *et al.*, 2024).

Past studies revealed the main terrestrial soil use categories comprised the forest (mangrove, lowland, montane, and sub-montane), agroforestry, plantations, grassland, settlement, cropland, shrubby savannah, and bare lava (Mammadzade, 2022, 2025). Bulk density showed the highest values in settlement areas, and the lowest values were notable with forest soil-use categories. Soil moisture content exhibited a reverse trend compared with that of soil bulk density. Forest soils were the sandiest, while soils in plantations and the arable lands were the most clayey. The soils were slightly acidic to neutral, while soils from arable lands were becoming more acidic. The soil conversion from forest to other land use classes enhanced the soil degradation, and the soil physico-chemical properties adequately serve as indicators of soil quality.

The soil types achieved determination by landscape forms, their use in agriculture, and the state of erosion, with the signs that manage the fertility indicators of soil types analyzed (Mammadzade, 2024). Moreover, it showed different land uses affect the variation of minerals in its ecological environment to different degrees on both landscapes and soil types. However, this has a serious negative impact on the efficient uses of lands in the environment and the development of a sustainable agricultural system. In eliminating this trend, various agrotechnological measures to reduce the mentioned negative dynamics and anti-erosion measures and improvement of land use conditions enhance the fertility parameters and re-introduction into the agricultural cycle being justified (Nasirova *et al.*, 2022; Mammadov *et al.*, 2024).

The possibility of using an office scanner to obtain digital images of soil samples with their subsequent analysis using the RGB colorimetric system was successful to demonstrate. The main factors determining the intensity of coloration of different types of soil include the content and optical density of humic acids. Increased clay particles and other factors remained constant, which leads to a decrease in the intensity of coloration of specific types of soils (Ikhtiar, 2024; Rzayeva and Mammadzade, 2024).

MATERIALS AND METHODS

The conduct of this research occurred on mountain-forest brown soils in the Masalli Region (39.005561, 48.635483) and mountain-forest dark brown soils in the Yardimli Region (38.904144, 48.248659). Additionally, these locations had ecologically humid conditions of the subtropical zone of natural forest biotopes under woody vegetation and grass cover. The prepared maps of common soils of the Lankaran Region appear in Figure 1. The thematic soil map describes the types of soil covers in a given area, their characteristics, and distribution areas. The main objectives also focused on soil resource assessment to determine the suitability of soils for agriculture, forestry, and land reclamation and environmental protection to identify risks associated with erosion, pollution, and soil degradation. Other objectives looked into urban and infrastructure planning to study soil properties for planning residential and industrial zones and water resources management to analyze the relationship between soil structure and water infiltration capacity. A digital elevation model (DEM) map presents elevation and the relief data of an area in digital form. Its main purposes included topographic analysis to determine the elevation differences and relief features of the area and
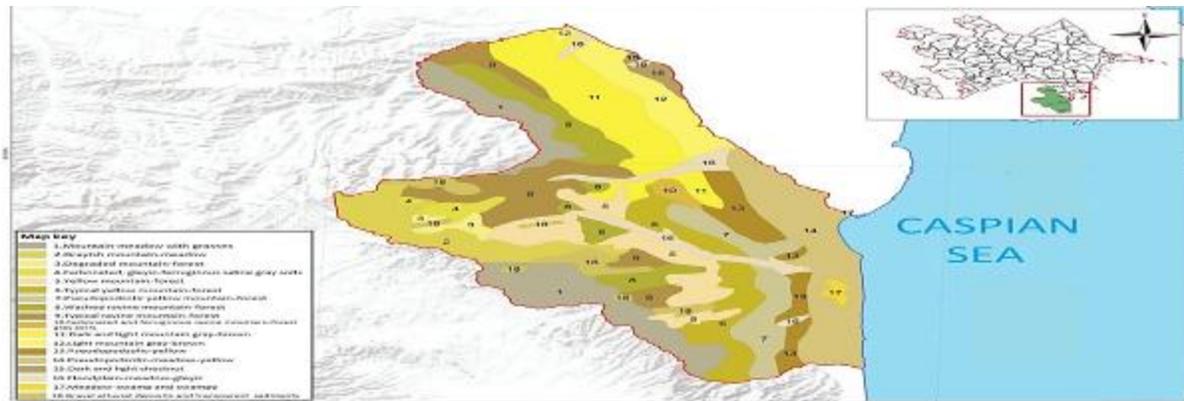
Figure 1. Soil map of the Lankaran District. (Source: By authors in 2024)
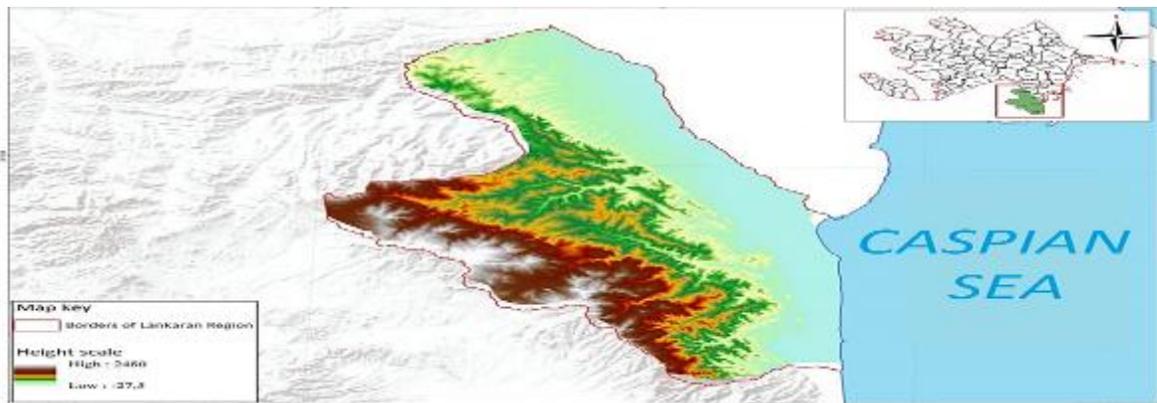

Figure 2. Digital Elevation Model map of Lankaran regions.

geographical analysis for hydrology, geology, urban planning, and environmental monitoring. The DEM also aided simulation and modeling to predict floods, landslides, and other natural phenomena, and engineering and construction to plan roads, reservoirs, tunnels, and other infrastructure projects (Figure 2).

The higher content of silt particles was prevalent in the middle part of the profile in the B horizon. In the upper humus horizon, the base absorption capacity was 31.3–39.7 mg/eq per 100 g of soil. The reaction of the soil solution (pH) was neutral and slightly alkaline (7.0–7.5) (Ikhtiyar, 2024). Mountain-forest brown soils showed characteristics of a noticeable enhancement in silt particles and physical clay in the illuvial-Bt horizon, as expressed by the compaction and clay content of the middle part of the profile. Minerals of the montmorillonite group predominate in the silt fraction composition. In mountain-forest brown soils, the absorption capacity was high (36.9–42.8 mg/eq per 100 g of soil). In addition to clay minerals, the exchange composition revealed a dominance of cations Ca, Mg, and Al. The soil solution (pH) reaction was acidic (5.4 to 6.2). Sorption interactions play an important role in the formation of specific organomineral compounds of the soil solid phase and humus-accumulative horizons, in the stabilization of the characteristic humus profile, and in shaping water-stable aggregates and micro-aggregates. The research also studied the influence of temperature and

humidity parameters on the biological activity of the soils. It found that at low temperatures (5 °C) and high soil moisture (35%), the weak biological activity was evident. A revival of biological activity emerged at a temperature of 5 °C–10 °C and moderate soil moisture of 20%. However, active biological activity was notable at an optimal temperature (10 °C–20 °C) and natural soil moisture (20%–30%) (Samadov, 2024). The entire system showed an inextricable connection among all the soil-biological components of the ecosystem.

Temperature and humidity, biological, and physical and chemical parameters obtained a comprehensive study in the selected biotopes. The phytomass (aboveground) accounting was on an area of 1 m^2 in 5 extreme replications according to the generally accepted method. Soil mesofauna determination was on an area of 0.25 m^2 in 10 extreme replicates. Microbiological analyses proceeded in compliance with the necessary aseptic conditions (Samadov, 2023). Hydrothermal indicators and pH value measurements used the Orion 3-Star Benchtop pH Meters (Thermo Scientific, USA) and Orion 3-Star Benchtop Conductivity Meters (Thermo Scientific, USA).

Absorbed cations' detection took place on a KFK-2-UHL 4.2 device with light-sensitive filters and spectral lengths of 364–980 nm. The use of the electron paramagnetic resonance (EPR) method determined the total humus content in soils and the degree of condensation of its aromatic core, as well as determined the paramagnetic centers of humic substances. The D.G. Zvyaginchev method served to determine the species and the composition of microorganisms and soil fungi (Rzayeva and Mammadzade, 2024).

RESULTS AND DISCUSSION

The humid subtropical soil in the Lankaran Region of Azerbaijan revealed the characteristic types of mountain-forest brown and mountain-forest dark brown soils. Geographically, these soils remained only at the strip of low and medium mountains within the altitudes of 150–350 and 600–900 m.

These soils' distribution was in a single ecological (subtropical) space, and each of them has specific conditions for the development of the soil-forming process with their characteristic physicochemical and biological indicators. Therefore, it seemed appropriate to dwell on some general features of the region (Hasanov, 2017).

The forest-type soil formation was predominant in the foothill zone as well as in the lowland part of the region. The geographic area indicated varied altitudes; from South to North and from East to West, a gradual manifestation of variations resulted in the general climate, which manifested primarily in the contrasting distribution of incoming precipitation (Stork and Eggleton, 1992). For example, for the mountain-forest yellow soils zone, the annual precipitation was 1000–1400 mm; for mountain-forest brown soils, the average annual precipitation decreases to 570–950 mm; and in mountain-forest dark brown soils, the annual precipitation was 350–650 mm (Shukurov *et al.*, 2025).

Significant diversity of relief and warm humid climate contribute to the development of relict Hyrcanian forest flora, especially in yellow soils, which had distinctions of ironwood (*Parrotia persica* C.H.U.), chestnut-leaved oak (*Quercus castaneifolia* C.A.M.), and zelkova (*Zelkova hyrcana* Crosshet. A garm) and Lankaran silk acacia (*Albizia julibrissin* Dur.). Mountain-forest dark brown soils most typically materialized under oak-hornbeam vegetation and xerophilous grass cover. However, the development of mountain-forest brown soils mainly surfaced under oak-hornbeam and often under beech forest soils (38.762979, 48.854859) with weak production of grassy undergrowth (Mammadova *et al.*, 2024).

In soil formation and its fertility, the living organisms play a remarkable role. Green plants, microorganisms, and animals in integration with the soil form the complex ecosystems (biogeocenoses). The ecosystem components show connections not only from the unity of the territory but also in the general flow of energy, exchange of chemical elements, physical and biochemical regimes, and ratio of the living organism population. The forest biogeocenosis' main feature is its long-

term life cycle, participation in the global biological cycle of substances, and the annual loss of the biomass in the form of leaf litter, dead ground, and root remains (Samadov, 2023).

When forest litter (the layer of dead leaves) transformed onto the soil surface and washed out of it chemical and organic decomposition products, the conditions developed for their humification and active interaction with the soil rock by mineral components. As a result, complex organo-mineral compounds emerged (Hasanov, 2017). However, the nature of this interaction mostly depends on regional eco-climatic conditions, hydrothermal, physical, and chemical indicators, the activity of soil fauna and microflora, and soil-forming rocks' composition. Therefore, specific soil type development can occur under different forest ecosystems even within the same region (Samadov, 2024).

Mountain-forest brown soils have a limited range of distribution and developed under moderately warm and humid climate, with an average annual air temperature of 6.0 °C–11.9 °C. With heavy precipitation (570–950 mm) and low evaporation, these soils revealed characteristics of a high moisture coefficient (1.0–1.5). In these soils, the humus content was high, with an average of 6.0%–10%; however, it sharply decreasing with the profile (Mammadova and Mammadova, 2024; Nasirova *et al.*, 2026).

Soil re-salinization and water shortages pose severe threats to the sustainability of the agricultural industry and food security of Azerbaijan and neighboring countries. These factors are also undiscovered disasters for developing countries without reliable, up-to-date, and localized information to assess the impact of climate change. Additional assessment should proceed to identify the effects of climate change more accurately and extensively to ensure food production and sustainability in Azerbaijan and its neighboring countries. Additionally, more efforts should center on developing countries in preparation for the further impact of climate change (Ikhtiyar, 2024; Ismayilova *et al.*, 2025).

Intensive development of the soil-forming process promotes the clay formation due to silt particles and the creation of a large amount of mobile iron. However, these soils mostly develop both on dense rocks (basalt and porphyrite) and on loose eluvial-deluvial and rubble clay products from the weathering of bedrocks. An important diagnostic indicator of mountain-forest brown soils is the distribution nature of silt particles and physical clay along the soil profile. A noticeable increase was evident in the illuvial-Bt horizon, as expressed in the compaction of the profile's middle part. Mountain-forest dark brown soils were widespread and confined to the lower belt of dry forests and shrubs. These forests climate was similar to the Mediterranean climate, with an average annual air temperature (8.4 °C–10.8 °C), precipitation (350–600 mm), and moisture coefficient (0.46–1.1) (Mammadzade *et al.*, 2025). Dark brown soils were distinctive of high humus content (5.4%–6.4%), especially in the upper horizons, which gave an even distribution along the profile, and at the depth of 90–100 cm, the humus content was 0.8%–1.1%. Soil-forming rocks were limestones, carbonate clay shales, and eluvial-deluvial carbonate loams. The release of carbonates occurred mostly in deeper layers. In terms of granulometric composition, the soil profile was well differentiated. The silt particles with a high content were predominant in the middle part of the profile-the B Mountain. An observation was also noteworthy before further analysis of the main biological indicators of mountain-forest brown and mountain-forest dark brown soils. Such observation disclosed that ecological groupings of living organisms have a global biosphere significance and play a vital role in soil formation and its fertility.

As a result of the joint vital activity of the organisms with similar ecological requirements and the entry of their vital attributes into the soil, the most crucial processes in soil formation succeeded. These are the synthesis and destruction of organic matter, the concentration of biologically important elements, mineral destruction and formation, and the migration and accumulation

Table 1. Phytomass reserves in mountain-forest brown and mountain-forest dark brown soils.

Soils of Lankaran Region (Lerik, Yardimli, Astara, Masalli)	Phytomass (g/m^2)		
	Mass	Leaf litter	Litter
Mountain-forest brown	1077	1676	2400
Mountain-forest dark brown	712	792	1990

of substances constituting soil formation and its fertility. In soils, the plants are the primary source of organic residues. Their main function as soil formers requires consideration for the biological cycle of substances, the synthesis of humus compounds, and the process of humification with the active participation of microorganisms and soil saprophages. For the transformation process of humus compounds along the food chain, the released energy is beneficial to the new generations of plants, microorganisms, and soil animals (invertebrates), ensuring their vital activity. In mountain-forest brown and mountain-forest dark brown soils, the phytomass determination varies between 2700 and 1950 g/m^2, respectively (Aliyeva, 2022; Nasirova *et al.*, 2026).

Concerning humus accumulation in the soil, the little falloff and litter play a primary role. In these soils, the reserves of litter and litter vary within the range of 670 and 1750 g/m^2 and 600 and 330 g/m^2, respectively. Based on herbaceous phytomass, leaf litter and litter revealed some quantitative differences between them. In mountain-forest brown soils, the reserves of herbaceous phytomass, leaf litter, and litter varied at 1077, 1676, and 2400 g/m^2, respectively. Accordingly, in mountain-forest dark brown soils, these indicators were 712, 792, and 1990 g/m^2 (Table 1).

Microorganisms with various groups and saprotrophic representatives of soil invertebrates process the phytomass remains reaching the soil surface. Microbiological analysis has established that in mountain-forest dark brown soils, the total number of microbiota in soil layers of 0–10, 10–20, and 20–30 cm varied between 3.26 and 4.4·10^6/g of soil. The microorganisms with quantitative indicators in the same soil layers amounted to a range from 2.52 to 2.95·10^6/g of soil in mountain-forest brown soils. The results

further revealed the number of microorganisms in mountain-forest dark brown soils was greater than in the mountain-forest brown soils, despite the fact the reserve formation of phytomass in the latter was 1.5–2.1 times more.

Apparently, the acidic products of decaying plant residues negatively affect the microbiological activity of saprophytic bacterial flora, limiting the rate of decomposition and humification of wood, leaf litter, and litter. Observations on the differences of quantitative indicators of invertebrates also ensued. If in mountain-forest brown soils, the total number of mesofauna was 19.1 specimens/m^2, then in mountain-forest dark brown soils, the same increases to 61.4 specimens/m^2. Accordingly, the total energy accumulated in their biomass (1.3515 and 2.1660 g/m^2) changes from 6.7565 to 15.9420 kcal/m^2 (Figure 3). Compared with microbiota, mesofauna was more selective in its approach to food resources, which allows it to more actively develop the soil layers where the organic matter needs to accumulate and process them (Samadov, 2024).

The main dominant groups of mesofauna, bacilli, and micromycetes in the forest biotopes of the studied soils are available in Table 2. The soil biota groups appeared most adapted to the eco-climatic conditions of soil development in humid subtropics. Based on their joint activity, the transformation of energy of organic remains materialized along the trophic (food) structure (blocks) of the ecological pyramid up to the humus block, where concentrations of the major energy compound of the ecosystem existed. The studied soils have their inherent quantitative indicators for humus and nitrogen.

Determination of humus and nitrogen indicators by their gross content in mountain-forest brown soils, their quantitative values in individual layers (0–10, 10–20, and 20–30 cm)
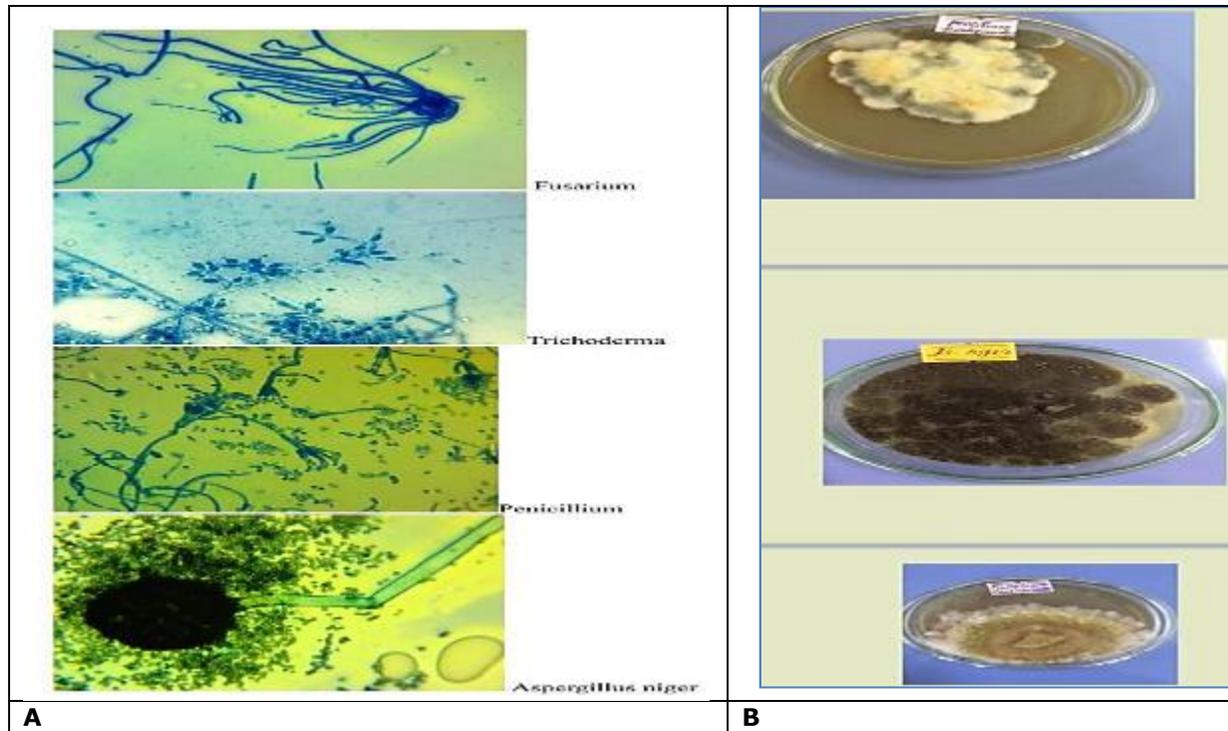
Figure 3. A. Microscopic structure of fungi during growth, B. Macroscopic structure of fungi during growth.

Table 2. Dominating groups of mesofauna, bacilli, and micromycetes in forest biotopes of the researched soils.

Soil biota	Mountain-forest brown soil forest biotope	Mountain-forest dark brown soil forest biotope
Invertebrates: mesofauna	*Lumbricidae, Mollusca Isopoda, Diplopoda, Chilopoda, Insecta*	*Lumbricidae, Isopoda, Diplopoda, Chilopoda, Insecta*
Microorganisms: bacilli	*Bac. mycoides, Bac. cereus, Bac. idosus.*	*Bac. cereus, Bac. idosus, Bac. megaterium*
Micromycetes	*Penicillium, Trichoderma, Mucorales, Mucor ramanianus*	*Penicillium, Aspergillus, Trichoderma*

vary within the range of 8.3%, 6.5%, and 6.0% and 0.5%, 0.33%, and 0.30%, respectively. Accordingly, these indicators vary between 7.5%, 5.8%, and 5.4% and 0.32%, 0.29%, and 0.27% in mountain-forest dark brown soils. The humus and nitrogen reserves in the studied soils were 76.17 and 1.17 t/ha and 75.30 and 3.93 t/ha, respectively. In mountain forest brown soils, fulvic acids predominate in the humus composition, and the $C_{g.a}/C_{f.a}$ ratio was 0.5–0.6. The

condensation of the aromatic nucleus of humic acids was weak.

In humus composition, organomineral complexes had main representations of Al-Fe compounds and, particularly, Ca humates. The humus composition is fulvate-humate or humate in mountain-forest dark brown soils, and the ratio of $C_{g.k}/C_{f.k}$ was 0–0.8–1.2. A significant portion of humic substances sustained combination with Ca, as presented by humate-calcium organomineral complexes.
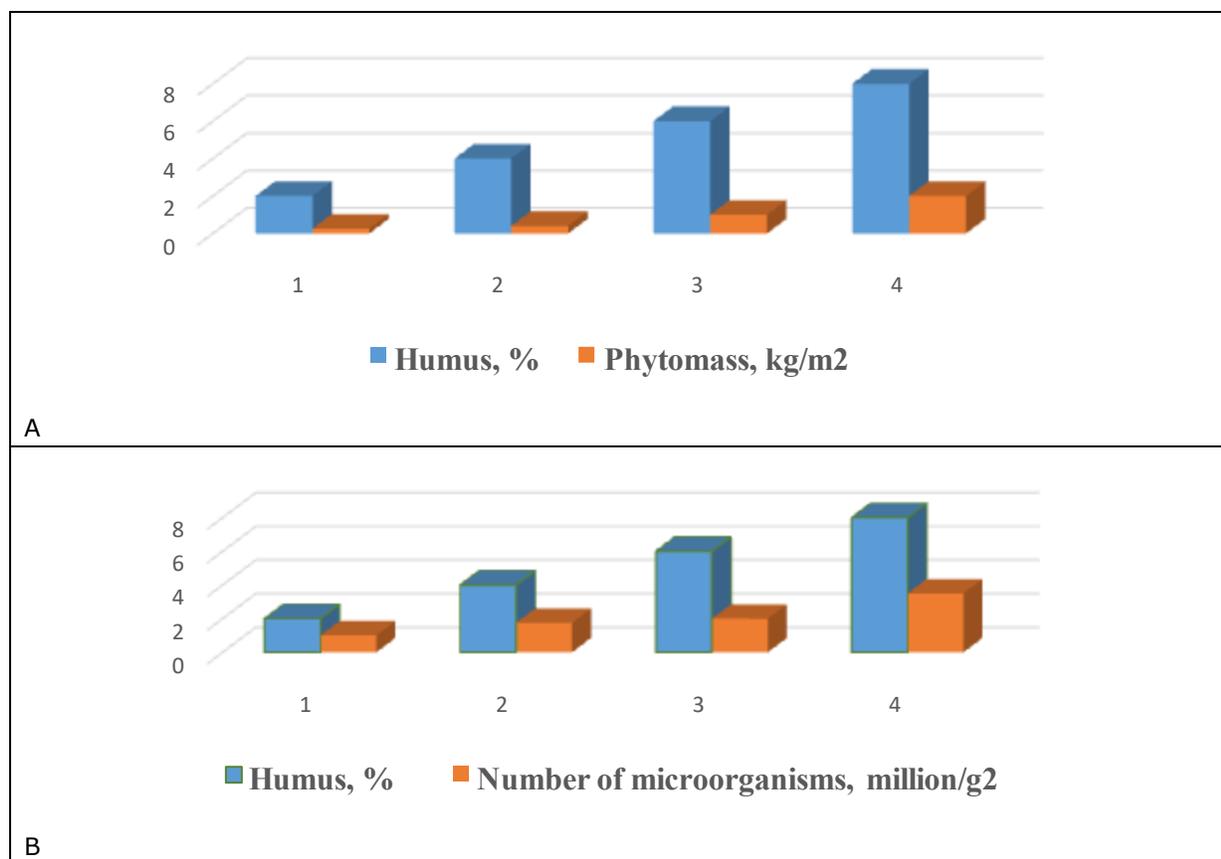
Figure 4. A. Relationship between total humus content and phytomass in mountain-forest brown and mountain-forest dark brown soils, B. The relationship between the humus content and the number of microorganisms in mountain-forest brown and mountain-forest dark brown soils.

The condensation of the aromatic nucleus of humic acids was also high. The studied soils also differed in some physical and chemical indicators (Aliyeva, 2022).

Mountain-forest dark brown soils were well differentiated for granulometric composition, as heavy loamy. In the upper horizons, the silt particle content was 26.5%–32.7%, with physical clay having a percentage of 5.7%–62.1%. The process of converting phytomass residues into humic substances with the participation of biological factors was quite complex and comprised two complementary stages. The first stage had an association with the participation of dominant groups of invertebrates (Table 2) and comprised mechanical processing, crushing, maceration, and primary humification of phytomass residues (green plant residues). The second stage distinctly had the participation of the main groups of microorganisms in the formation of humic substances. However, based on the specific participants in this process, the form of humus may be different (Table 2).

The vegetation, invertebrates, and microorganisms attained unity from a single soil-forming activity. Graphical analysis of the relationship between biotic indicators (humus, phytomass, and microbes) and soil showed a close evolutionary connection among them as the main components of the biogeocenoses. Microbiological and zoological (soil invertebrates) research continued on natural biotopes (forest ecosystems) of mountain-forest brown and mountain-forest dark brown soils, identifying their dominant groups. Clay minerals and the silt fraction emerged as active adsorbents of humic substances because of forming clay-humic complexes (Figure 4).

CONCLUSIONS

A close relationship succeeded its establishment among the soil's total humus content, microorganisms, and phytomass. Sorption interactions formed between the absorption capacity (cations and clay minerals) and soil humus, resulting in the shaping of clay-humus complexes. The digital elevation model map (DEM) and soil map of the Lankaran district achieved their preparations during the research.

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