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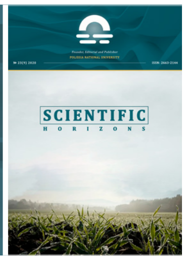

Agrochemical characteristics of mountain soils of the Fergana Valley

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Abstract. The relevance of examining the soils of the Fergana Valley is due to their diversity and importance for the agriculture of the region. Different soil types differ in their granulometric composition, fertility, and ability to retain moisture, which affects their agrochemical properties. The purpose of the study was a comprehensive analysis of the agrochemical characteristics of the soils of the Fergana Valley, including granulometric composition, humus content, acidity, carbonate content, water properties, and biological activity. The methods included field research, sampling from different altitude zones, and laboratory chemical composition analyses. Nitrogen was determined by the Kjeldahl method, phosphorus – the Machigin and Kirukov method, and potassium – flame photometry. The results of the study showed substantial differences in the composition and properties of different types of soils. Brown forest

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soils demonstrated the most favourable agrochemical parameters. The granulometric composition of brown forest soils is medium loamy, with a sand content of 35-45%, silt of 30-40%, and clay of 15-25%. High levels of humus (4.5-6%), total nitrogen (0.2-0.3%), available phosphorus (20-40 mg/kg), and potassium (high levels) were recorded in the soils. The biological activity, estimated by microbial abundance, was 2-4 million/g, which confirmed the high metabolic activity of the soil microflora. Mountain-brown carbonate soils were characterised by a heavier granulometric composition, with an increased clay content (25-35%) and moderate fertility rates: 2.5-4% humus, 0.1-0.2% nitrogen, 10-25 mg/kg of phosphorus, and a medium potassium level. Sandy soils have low moisture capacity, weak aggregate structure, and extremely low fertility rates: 0.5-1.5% humus, <0.1% nitrogen, 5-15 mg/kg phosphorus, and low potassium levels. Biological activity does not exceed 1 million/g. The acidity of soils varied: brown forest soils have a slightly acidic or neutral reaction with a pH of 5.8-6.5, which is favourable for the absorption of nutrients. Mountain-brown carbonate soils are alkaline with a pH of 7.5-8.2, which reduces the availability of certain elements. Sandy soils have a slightly alkaline pH of 6.8-7.4. The data obtained can optimise land use, increase soil productivity, and minimise soil degradation

Keywords: humus; granulometric composition; carbonate content; erosion processes; acidity; minerals; organics

INTRODUCTION

Soils are a key component of ecosystems that play a crucial role in ensuring food security and the sustainability of agroecosystems. Agrochemical characteristics of soils, including granulometric composition, organic matter content, acidity and carbonate content, directly affect their fertility and ability to support plant growth. The Fergana Valley, located at the intersection of Uzbekistan, Kyrgyzstan, and Tajikistan, is one of the most important agricultural territories in Central Asia, with unique climatic and geographical features that shape the agrochemical properties of the region's soils. Despite a great amount of research on the soil cover of Central Asia, the agrochemical characteristics of mountain soils, in particular, the Fergana Valley, are still insufficiently reviewed. These soils, especially mountainous and carbonate soils, are characterised by a complex structure and high spatial heterogeneity, which makes it difficult to classify and agronomically evaluate them. Thus, in the paper of D. Kholdarov *et al.* (2024), a detailed analysis of the chemical composition of saline soils in Central Fergana is conducted, where the features of chloride-sulfate salinisation were displayed, and the way irrigation changes their granulometric composition was described. In the context of the development of sustainable land use methods, the importance of an integrated approach to the examination of chemical and biological properties of soils is being evaluated by B. Lei *et al.* (2022), emphasising the role of organic and green fertilisers as factors that improve soil fertility and microbiological activity.

The problem of insufficient supply of organic matter and macronutrients to soils is becoming particularly relevant, which limits their productive potential. L. Mhoro *et al.* (2024), examining soils on the slopes of Kilimanjaro, found that fertility in lowland areas is substantially lower, which is facilitated by a shortage of manure and limited use of inorganic fertilisers. These conclusions are confirmed in the study by R. Sidle *et al.* (2023), stressing that in high-altitude areas, soil depletion is associated with limited natural resources and requires an adaptive approach to agroecological management. The problem of soil degradation is also considered in a broader regional context. R. Lal (2024) notes that processes such as erosion, salinisation, humus depletion, and structural disruptions directly threaten food security in South and Central Asia. These threats are reflected in the data of S. Measho *et al.* (2022), which recorded an increase in soil electrical conductivity, an indicator indicating increased salinity, especially in pastures and marginal lands. In turn, I. Stavi *et al.* (2021) underline the importance of accurate monitoring and mapping of saline lands using modern remote sensing methods. Against the background of climate change and unstable land use, the agrochemical properties of soils are under increasing pressure. S. Song *et al.* (2025) have developed an indicator system to identify priority conservation areas in Central Asia, especially in mountainous and oasis areas, which highlights the importance of integrating agroecological and socio-economic approaches.

Finally, organic technologies play a special role in increasing soil resistance to degradation. B. Lei *et al.* (2022) have shown that the use of green fertilisers can increase the microbiological activity of the soil and improve its structure. Similar results were obtained by A.M. Visscher *et al.* (2024), conducted in the Andes, where the use of organic sheep manure helped preserve the yields of traditional crops with a warming climate and a shortening of the growing season in high-altitude areas. Despite the accumulated knowledge, key issues regarding the agrochemical potential of mountain soils in arid climates and intensive land use remain unresolved. There is no systematic analysis of the interaction of physico-chemical and biological properties of soils at various altitude levels, or consideration of anthropogenic and climatic factors affecting degradation processes. The mechanisms of changes in the content of organic matter, the transformation of macronutrients, and the dynamics of acidity depending on agrotechnical measures are not sufficiently covered. The problem of increasing fertility is particularly relevant in conditions of limited water supply and salinity typical of the Fergana Valley.

The purpose of this study was the agrochemical characterisation of the mountain soils of the Fergana Valley with an emphasis on their physico-chemical and biological properties.

MATERIALS AND METHODS

The study was conducted on the mountainous soils of the Fergana Valley within the Uzbek part of the region, covering the territories near the settlements of Rishtan, Vuadil, and Yaypan, at altitudes from 600 to 1,400 meters above sea level. The study examined brown forest soils, mountain-brown carbonate soils, and sandy soils typical of this orographic zone. The selection of sites was conducted considering their geographical location, altitude zone, climatic conditions, and features of soil-forming processes. At the first stage of the study, field work took place, which included the laying of soil sections with a morphological description of the horizons. 12 soil sections were laid with an even distribution over the area under study. The distance between the points ranged from 2 to 5 km, depending on the accessibility of the site and the uniformity of the relief. At each site, samples were taken from four standard depths (0-10, 10-30, 30-50, and 50-100 cm). The selection was repeated three times to ensure reliability. The climatic conditions at the time of sampling (April-May) were characterised by an average daily air temperature of +17°C and a total precipitation of about 40 mm, according to the Kokand weather station. Soil moisture was at the level of 15-25%, depending on the site, which is important when interpreting indicators of water balance and biological activity. GPS mapping was used to fix the coordinates of the sampling points, ensuring the accuracy of subsequent spatial analysis.

After the field stage, all soil samples were sent to the laboratory for physico-chemical analyses. The granulometric composition was determined by a combined pipetting and dry sieving method in accordance with ISO 11277:2020 (2020), which ensured reliable determination of the content of sandy, silty, and clay fractions. The organic matter content was determined by two methods: oxidation with a chromium mixture according to Turenne (ISO 14235:1998, 1998) and elemental analysis according to ISO 10694:1995 (1995). Soil acidity was measured potentiometrically in aqueous and saline suspensions (ISO 10390:2021, 2021). The soil carbonate content was assessed by the gasometric method using HCl solution, considering the requirements of ISO 10693:1995 (1995), which allows quantifying the content of calcium and magnesium carbonates in each horizon. The method of determining the cation exchange capacity (CEC) using ammonium acetate (ISO 23470:2007, 2007) was applied to assess the sorption capacity of soils. This indicator is critically important in assessing the ability of the soil to retain nutrients by ions. The macro- and microelement composition (N, P, K, Ca, Mg, Fe, Cu, Zn) was analysed using atomic absorption spectrometry (ISO 11047:1998, 1998) and flame photometry (ISO 9964-3:1993, 1993). Additionally, the content of mobile forms of phosphorus and potassium was determined by the Machigin and Kirukov method, which allowed assessing the availability of these elements for plants. The technique was chosen based on its high sensitivity to mobile forms and effectiveness in carbonate soils. The assessment was in accordance with the principles of ISO 11263:1994 (1994) for phosphorus.

The water-physical properties of soils were assessed by determining moisture by gravimetry (ISO 11465:1993, 1993), water-strength aggregation by wet sieving, and water permeability by cylindrical infiltration. The data obtained allow evaluating the ability of soils to retain moisture, resist destruction under the influence of external factors and provide optimal conditions for plant growth. Special attention was paid to the analysis of the soil water regime, including the groundwater level, capillary rise of moisture and filtration coefficient. A method of determining the content of easily eroded particles and the calculation of the erosion potential, considering the slope of the terrain and climatic factors, was used to assess the risk of soil erosion. Studies on the biological activity of soils were conducted, including the analysis of the microbiological composition by the method of sowing on nutrient media and the of the respiratory activity of the soil for the release of CO_2 (ISO 17155:2002, 2002). Thus, the use of an integrated approach, including field research, laboratory analyses, mathematical modelling, and statistical data processing, allowed obtaining a comprehensive agrochemical characteristic of the mountain soils of the Fergana Valley.

RESULTS

The Fergana Valley, being an important agricultural region, has a variety of soils due to difficult geographical and climatic conditions. Local soils are formed under the influence of many factors, including topography, climate, vegetation composition, and anthropogenic influences. As part of the study, a detailed examination of the morphological characteristics of soils was conducted, which allowed identifying the key features of soil types, their orientation, and structure. Brown forest soils occupy the central part of the Fergana Valley, which is characterised by a moderately arid climate and high rainfall. They formed in areas where vegetation prevails, actively contributing to the accumulation of organic substances. As a result of this process, brown forest soils have a pronounced horizontal character, which is due to the long-term processes of rotting of plant residues. The soils have a well-formed humus horizon with a thickness of 20-40 cm, which is an indicator of a high content of organic matter since humus is actively formed in conditions of moderate moisture. The colour of these soils is dark brown, which is associated with a high level of organic matter in the upper horizon. The structure of brown forest soils is dense, with a good aggregate structure, which contributes to their water-retaining properties. Such soils have a high content of water-soluble salts, which is important for the nutrition of crops. These soils have a high moisture capacity of up to 20-25%, which is especially important for regions where seasonal precipitation is not always sufficient for the needs of plants (Juliev *et al.*, 2022). The developed root system of plants, good mechanical properties of the soil, ensure their resistance to erosion processes. This allows the use of brown forest soils for intensive agriculture, including the cultivation of crops such as cotton, wheat, and fruits.

The mountain-brown carbonate soils common in the higher mountainous parts of the Fergana Valley are characterised by unique morphological features due to the mountainous landscapes and climate features. In these soils, a carbonate horizon is present at a depth of 40-60 cm, indicating a high content of calcite and other carbonate minerals, leading to an alkaline soil reaction (pH 7.5-8.2) (Abakumov *et al.*, 2023). This composition makes it difficult for plants to absorb certain macro- and microelements, such as phosphorus and iron, which requires the use of special agrotechnical techniques, such as acid fertilisers, to improve the availability of nutrients. Soils have a looser structure compared to brown forest soils, which contributes to better water penetration into deeper soil layers, but also reduces their water retention capacity (humidity is 15-20%) (Masharobich & Saidakbarovich, 2024). The medium-loamy composition makes mountain-brown carbonate soils good for growing some types of crops; however, due to the low humus content (2.5-4.5%), regular application of organic fertilisers is required to improve their fertility. In these soils, it is also necessary to consider the tendency to erosion, especially in areas with sudden temperature fluctuations and heavy rains.

Sandy soils were found in the eastern and southern parts of the Fergana Valley, where the climate is drier and precipitation levels are drastically lower. These soils have a weak horizontal orientation, which indicates their immaturity and limited opportunities for the accumulation of organic substances. The humus layer in sandy soils is thin, not exceeding 10-20 cm, which is explained by the rapid decomposition of organic substances in conditions of high temperature and low humidity. The colour of these soils is light, yellowish-beige, which also indicates a low content of humus and organic matter. Sandy soils have high water permeability, which means that water quickly escapes through them without lingering in the upper layers (Filss *et al.*, 1998). The moisture content of sandy soils varies from 5 to 10%, making them less suitable for non-irrigated farming. These soils have a low nutrient content, which reduces their fertility, and require regular application of organic fertilisers and pH adjustments to improve the structure and increase water retention.

The granulometric composition of the examined soils of the Fergana Valley revealed pronounced differences in the mechanical structure of various types of soils, which determines their agronomic and physico-chemical properties. The analysis showed that brown forest soils are mainly characterised by a medium-loamy composition, in which the content of the sand fraction varies from 35 to 45%, silt – from 30 to 40%, and clay – from 15 to 25% (Table 1). Such a ratio of granulometric fractions contributes to the formation of a loose and resistant to water erosion structure, which has a high moisture retention capacity and is favourable for the development of the root system of plants. Such soils have good aeration, heat capacity, and water permeability, which together make them promising for high-productivity agriculture.

Table 1. *Granulometric composition of soils in the Fergana Valley*

Soil type	Sand, % fraction	Silt, % fraction	Clay, % fraction
Brown forest trees	35-45	30-40	15-25
Mountain-brown carbonate rocks	25-35	35-40	35-35
Sandy	Up to 80	10-15	5-10

Source: *created by the authors*

In contrast, mountain-brown carbonate soils have a heavier mechanical composition due to an increased proportion of clay particles ranging from 25 to 35%. At the same time, the content of silt is in the range of 35-40%, and the sand fraction is about 25-35%. This structure gives soils a high density, reduces permeability and promotes caking, especially during waterlogging. However, a high proportion of clay has a positive effect on the water retention capacity and increases the cation exchange capacity of soils, contributing to the fixation and prolonged action of batteries. Notably, mountain-brown soils require a balanced approach to cultivation, especially in arid climates and when using heavy machinery, since excessive compaction can lead to deterioration of their structure. Sandy soils, on the contrary, are characterised by a light granulometric composition, in which the content of the sand fraction reaches 80%, while the content of silt varies from 10 to 20%, and clay – from 10 to 15%. This structure determines high porosity and water permeability, but extremely low moisture retention, which leads to rapid leaching of nutrients from the root layer and a decrease in overall productivity. In addition, the weak aggregation of sandy soils makes them vulnerable to wind and water erosion. In this regard, effective agricultural use of sandy soils is possible only if a complex of soil-improving measures is conducted, including the introduction of organic materials, the formation of moisture storage structures and the use of mulching technologies.

The revealed differences in the granulometric composition of the soils of the Fergana Valley indicate the need for a differentiated approach to their agrotechnical use. Medium-loamy brown forest soils have the greatest potential for crop production due to their balanced structure. Mountain-brown carbonate soils require increased attention to preventing compaction and caking, while sandy soils require active land reclamation and fertility maintenance. Consideration of the mechanical composition of soils in the development of agricultural technologies and fertiliser systems is crucial for increasing the sustainability and productivity of agroecosystems in the region. An analysis of the humus content in various types of soils in the Fergana Valley revealed substantial differences in the level of organic matter, reflecting the features of their formation, climatic conditions, and the nature of vegetation cover. The highest humus content was recorded in brown forest soils, where its concentration ranges from 4.5 to 6%. These soils are formed in a moderately humid climate, are characterised by a high level of biological activity and a rich vegetation cover, which contributes to the constant supply of organic residues to the upper horizons of the soil. The active activity of soil microflora and fauna in combination with sufficient humidity ensures an effective process of humus formation. The high humus content has a positive effect on the soil structure, its water-physical properties, cation exchange capacity and agrochemical activity, thereby increasing the overall fertility and stability of agroecosystems (Brovko *et al.*, 2025).

In mountain-brown carbonate soils, the humus content was moderate and ranged from 2.5-4%. These soils are formed in more arid conditions, with lower vegetation density and elevated temperatures, which contributes to accelerated mineralisation of organic residues. The carbonate nature of the soil-forming rocks also affects the processes of organic decomposition: carbonates contribute to the alkaline reaction of the soil solution, which is less favourable for the stability of humic compounds (Kruglov *et al.*, 2023). However, despite this, the organic matter content remains at a relatively good level, which indicates the presence of stable forms of humus and the compensatory role of clay components that contribute to the fixation of organic molecules in the soil matrix. Systematic application of organic fertilisers and green manure crops is recommended to increase the humus content in such soils.

The minimum humus content was found in sandy soils, where its level was only 0.5-1.5%. This is primarily due to the extremely unfavourable conditions for the accumulation of organic matter. Sandy soils are characterised by high water permeability and low moisture retention, which sharply limits biological activity and reduces the intensity of humus formation processes. In addition, the coarse-grained structure and the absence of clay fractions contribute to the rapid leaching of organic compounds and a decrease in cation exchange capacity. In conditions of high temperature and lack of moisture, the mineralisation of organic residues proceeds rapidly, while the weak development of vegetation cover limits the supply of new organic matter (Cholponbek *et al.*, 2025). These soils require a range of measures to improve their organic condition, including regular application of organic fertilisers, compost, siderates, and the use of mulch. Increasing the humus state of sandy soils is an important condition for improving their structure, increasing their water retention capacity, and ensuring sustainable crop growth. The level of humus content of the studied soils directly correlates with their granulometric composition, climatic, and biological conditions of formation.

The analysis of the acid-base state of the studied soils of the Fergana Valley demonstrated a clear dependence of the reaction of the soil solution on the granulometric composition and content of carbonate compounds. pH values vary in a wide range from slightly acidic to alkaline reactions, which has a substantial impact on the agrochemical properties of soils, primarily on the availability of nutrients and the activity of the microbiota. According to the data obtained, brown forest soils have a slightly acidic or close to neutral reaction, with a pH range from 5.8 to 6.5. This acidity is considered optimal for most cultivated plants, as it provides the best absorption of macro- and microelements, in particular, phosphorus, iron, manganese, and zinc. In addition, a slightly acidic environment promotes high biological activity of the soil, accelerates the processes of mineralisation of organic substances, and the formation of a stable structure. The presence of humus and clay particles contributes to buffering properties, preventing sudden pH fluctuations when applying fertilisers or in conditions of humidity changes.

Mountain-brown carbonate soils, on the contrary, are characterised by a pronounced alkaline reaction, with pH values in the range 7.5-8.2. The alkaline environment is caused by the high content of calcium and magnesium carbonates, which actively neutralise the acids formed during the decomposition of organic matter. Although such conditions can contribute to the stabilisation of organic forms of nitrogen, the alkaline reaction significantly reduces the availability of a number of nutrients, especially phosphorus, iron, copper, and manganese, which under these conditions turn into poorly soluble forms. This leads to hidden forms of deficiency of elements, even with their sufficient total content in the soil. To increase the agrochemical efficiency of mountain-brown soils, it is recommended to use acidifying fertilisers (for example, ammonium-containing ones), the use of organic additives, compost, and siderates that can partially compensate for carbonate buffering.

Sandy soils showed a slightly alkaline reaction with pH values from 6.8 to 7.4. Despite the absence of substantial amounts of carbonates, the neutral or slightly alkaline environment in these soils is due to the minimal buffer capacity and weak acid-neutralising ability. Such soils are subject to rapid pH changes in response to external influences, including watering, fertilisation, and climatic fluctuations. In addition, with a low content of organic matter and moisture, even a moderately alkaline environment can adversely affect the digestibility of nutrients. In this regard, to increase the agronomic efficiency of sandy soils, it is necessary to regularly apply organic fertilisers and maintain an optimal level of acidity using acid phosphates or humic additives. The content of macronutrients in soils is an important indicator of their agrochemical state and affects soil fertility, in addition to plant growth and development. The study found that the content of the main macronutrients – nitrogen, phosphorus and potassium – varies depending on the type of soil and its granulometric composition, which reflects the different abilities of the soil to provide plants with the necessary nutrients (Table 2).

***Table 2**. Humus content N, P, K*

Soil type	Humus, % fraction	Nitrogen, % fraction	Phosphorus, mg/kg	Potassium level
Brown forest trees	4.5-6	0.2-0.3	20-40	High
Mountain-brown carbonate rocks	2.5-4	0.1-0.2	10-25	Medium
Sandy	0.5-1.5	0.1	5-15	Low

***Source:** created by the authors*

Nitrogen is one of the key elements determining soil productivity, as it forms the basis for the synthesis of amino acids and proteins in plants. In brown forest soils, the nitrogen content varies from 0.2 to 0.3%, which is a relatively high level and sufficient to meet the nitrogen needs of most crops at the initial stages of growth. This is due to the good biological activity of the soil and the high content of organic matter, which gradually mineralises, providing plants with ammonium and nitrate forms of nitrogen. In mountain-brown carbonate soils, the nitrogen content decreases to 0.1-0.2%. This decrease is associated with a low level of organic matter and increased mineralisation in a warm climate. These soils may require additional doses of nitrogen fertilisers to maintain optimal nutrient levels for plants, especially in the early stages of their growth. In sandy soils, the nitrogen content does not exceed 0.1%, which is the minimum value among all types of soils. This is due not only to the low content of organic matter, but also to the high rate of mineralisation, which hinders the accumulation of nitrogen in an accessible form. For sandy soils, regular application of nitrogen fertilisers is especially important to maintain soil productivity.

Phosphorus is an essential element for the formation of the root system and photosynthesis processes (Bobunov *et al.*, 2023). In brown forest soils, available phosphorus ranges from 20 to 40 mg/kg, which is a high indicator that provides plants with good access to this element necessary for their growth and development. This is due to both the high content of organic matter and the moderate acidity of these soils, which contributes to good phosphorus mobility. In mountain-brown carbonate soils, the available phosphorus content varies from 10 to 25 mg/kg. Due to the high alkaline reaction of these soils, phosphorus in them is often deposited in insoluble forms, which limits its digestibility by plants. In such conditions, phosphorus becomes less accessible to plants, which requires the use of corrective measures, such as the introduction of acidifying fertilisers or organic additives. In sandy soils, the available phosphorus content ranges from 5 to 15 mg/kg. This is a fairly low level, which is due to both the low content of organic matter and its high permeability, which contributes to the leaching of phosphorus. It is necessary to regularly apply phosphorus fertilisers to increase the availability of phosphorus in sandy soils, which will help provide plants with the necessary elements for growth.

The potassium content in the soils of the Fergana Valley is quite high in all types of soils, but its availability differs depending on their structure. In brown forest soils, due to the high humus content and medium texture, potassium is available in a fairly good amount, which contributes to its effective absorption by plants. In mountain-brown carbonate soils and sandy soils, the availability of potassium is also rather high, but in sandy soils, this element tends to be quickly washed out due to its weak structure and low cation exchange capacity. During the examination of the soils of the Fergana Valley, an analysis of the number of microorganisms in various types of soils was conducted, which identified substantial differences in the level of biological activity. High microbiological activity is observed in brown forest soils, which is expressed in the number of microorganisms from 2 to 4 million per gram of soil. This indicator is the highest among all the soil types under study and indicates a high degree of humus content and active decomposition of organic substances in these soils. High biological activity is due to favourable conditions for microorganisms, such as optimal humidity, temperature, and the presence of a diverse vegetation cover, which serves as a source of organic residues. It also promotes increased mineralisation of nitrogen, phosphorus, and other elements needed by plants and supports the structural stability of the soil.

In mountain-brown carbonate soils, microbiological activity is slightly lower and ranges from 1-2 million microorganisms per gram of soil. Such indicators may be associated with a lower content of organic matter, which limits the number of available substrates for microorganisms. A more alkaline reaction of these soils can also negatively affect the activity of certain types of microorganisms, which leads to a smaller number of microbial fauna compared to brown forest soils. The lowest biological activity was found in sandy soils, where the number of microorganisms was less than 1 million per gram of soil. This indicator is due to the low content of organic matter, in addition to the high permeability of the soil, which contributes to the rapid leaching of organic residues and nutrients. The weak biological activity in these soils limits their ability to self-heal and requires regular application of organic fertilisers to maintain fertility.

One of the important aspects of the study was the assessment of the soil resistance of the Fergana Valley to erosion processes, including water and wind erosion. Soil erosion is the process of destruction and removal of the upper fertile soil layer, which can seriously affect its productivity and the sustainability of agricultural production (Yzakanov *et al.*, 2024). Brown forest soils are characterised by high resistance to erosion processes, both water and wind. This is due to their dense structure and good water-resistant aggregation. The high content of organic matter, especially humus, improves the soil structure, which increases its resistance to being washed out and loss of nutrients. The water-strength aggregates of these soils greatly exceed 85%, which minimises their susceptibility to water erosion. Due to this, brown forest soils can effectively retain moisture, which reduces the likelihood of their leaching and destruction under the influence of precipitation and water flows. Mountain-brown carbonate soils have less resistance to erosion compared to brown forest soils. Despite the presence of clay particles, which can contribute to some structural stability, these soils are prone to caking due to their denser structure and high content of calcium and magnesium carbonates. This reduces their water-resistant aggregates and makes them more vulnerable to surface washout, especially during heavy rains or strong water flows.

Sandy soils are the most vulnerable to erosion processes. They are characterised by a low content of organic matter and a weak aggregated structure, which makes them prone to weathering and washout. The low moisture retention capacity of sandy soils also contributes to their high susceptibility to water erosion. Under conditions of wind erosion, these soils lose their top layer, which is aggravated by the low content of humus and organic matter, which limits the ability to restore the soil structure. It is necessary to introduce agrotechnical measures, such as planting protective plants, using organic fertilisers, and improving soil structure using various soil-improving methods to lower the erosion processes on such soils. Differences in soil resistance to erosion emphasise the importance of an integrated approach to their use and protection. Brown forest soils have the best characteristics for agriculture in the conditions of the Fergana Valley, while mountain-brown and sandy soils require additional efforts to prevent erosion processes and improve their structure.

A quantitative assessment of the potential effect of the use of various agrotechnical measures was conducted, considering the local climatic and soil conditions of the region, to properly research the issue. The analysis indicated that applying organic fertilisers (compost or manure) on sandy soils at a dose of 25-30 t/ha over three years can increase the humus content from 0.5-1.5% to 2-2.2%. Thereby, the total nitrogen level increases from <0.1% to 0.12-0.14%, which, according to calculations, can increase the yield of grain and fodder crops by 35-40%. An additional effect is provided by the cultivation of perennial legumes (alfalfa, sweet clover), which increase microbiological activity by 2-2.5 times and improve the water-retaining properties of the soil. For mountain-brown carbonate soils (with a pH of 7.5-8.2), the combined use of organic fertilisers (15 t/ha) and ammonium sulfate (60 kg/ha) with superphosphate (40 kg/ha) is an effective measure. This reduces the pH to 7-7.2 and increases phosphorus availability by 40-50%, which increases grain yields by 20-25% under conditions of limited irrigation. On brown forest soils, despite the high natural fertility, measures to prevent erosion on the slopes remain effective. The use of mulch, minimal tillage, and green manure crops reduces the loss of humus and aggregate structure, retains moisture in the surface horizons, which contributes to sustainable productivity without additional fertiliser. The proposed measures, adapted to the conditions of the Fergana Valley, provide a projected increase in agrochemical indicators and yields by 20-40%, depending on the type of soil and the depth of intervention.

DISCUSSION

The conducted study on the agrochemical characteristics of the mountain soils of the Fergana Valley indicated pronounced differences in their composition, structure, and biological activity depending on the type of soil and relief conditions. The results obtained are compared with data from other studies conducted in various mountainous and arid regions of the world, which allowed for a comprehensive comparative analysis and identification of universal patterns and regional features. The brown forest soils of the Fergana Valley are characterised by a medium-loamy granulometric composition, with a predominance of silt and clay, which forms a good water retention capacity, stable structure, and favourable conditions for microbiological activity. The sand content is 35-45%, silt – 30-40%, clay – 15-25%. Such a combination of granulometric fractions contributes to the effective retention of moisture in the soil column and the formation of a structure with a high degree of porosity. As shown in the study by A.J. Franzluebbers *et al.* (2025), soils with a similar mechanical composition have an increased cation exchange capacity, are characterised by an active microbiological regime, and are resistant to physical and chemical degradation. Such properties are especially important during intensive exploitation of agricultural land and under conditions of increasing climatic stress. The humus content in brown forest soils is 4.5-6%, which represents a high level of organic accumulation, favourable for agrochemical balance and maintenance of the structure. H. Man *et al.* (2023) note that the thickness of the humus layer in China's boreal forests depends on height and slope, reaching up to 26.7 cm, and permafrost degradation accelerates humus depletion. Similar results are stated by M. Zhiyanski *et al.* (2017), where afforestation in the Central Balkans led to a decrease in organic carbon content and soil pH, especially after the replacement of hardwoods with conifers. The study also showed a decrease in humus content in mountain-brown soils (2.5-4%), and in sandy soils, it was only 0.5-1.5%.

Sandy soils containing up to 80% of the sand fraction exhibit extremely low moisture retention and weak aggregate structure. Such characteristics drastically worsen the conditions for plant development, increase the risk of erosion processes and contribute to the leaching of nutrients from the root zone. C.A. Brühl *et al.* (2024) underscore the serious danger associated with the accumulation of pesticides, which leads to a decrease in biodiversity and the destruction of soil structural stability, even in remote mountain ecosystems. This problem is becoming most relevant in agricultural regions with high intensity of land use and insufficient environmental control over the level of chemical pollution. The acidity of soils varies from slightly acidic to slightly alkaline. pH values from 5.8 to 6.5 were observed in brown forest soils, which is favourable for the absorption of macro- and microelements. In carbonate soils, the pH reaches 7.5-8.2, which may limit the bioavailability of certain forms of phosphorus and trace elements. In sandy areas, the pH value is in the range of 6.8-7.4. Similar results are presented in the paper of A.M. Belay *et al.* (2023), where the spatial distribution of pH in the mountainous regions of Ethiopia depends on precipitation, type of land use, and altitude. Y. Shen *et al.* (2021) also indicate that cyclical pH changes were observed in southern China from 1982 to 2018 under the influence of acid rain and organic matter reduction, which confirms the sensitivity of pH to exogenous factors. In this publication, the obtained values of soil acidity (from slightly acidic in brown forests to slightly alkaline in sandy soils) confirm the complex nature of pH regulation. Y.Y. Zhang *et al.* (2019) demonstrated that pH is particularly affected by variables such as slope exposure, precipitation, and parent rock, with the degree of influence varying between horizons A, B, and C. The use of CART models has shown high accuracy in acid prediction, which opens up opportunities for differentiated soil management in hilly and mountainous regions.

The nitrogen content in brown forest soils was 0.2-0.3%, which provided optimal conditions for plant development, especially in the early stages of vegetation. Mountain-brown soils showed a decrease to 0.1-0.2%, and sandy soils – less than 0.1%, which makes them dependent on external application of nitrogen fertilisers. Notable differences in phosphorus content were also found: in brown – 20-40 mg/kg, in carbonate – 10-25 mg/kg, in sandy – 5-15 mg/kg. The data is comparable to the results of Q. Li *et al.* (2021), where phosphorus availability was a limiting factor for meadows in the Qilian Mountains. B. Su *et al.* (2024) also emphasise the importance of spatial analysis of the distribution of nitrogen and phosphorus, considering terrain, temperature, and texture. The obtained patterns of changes in phosphorus and cation content depending on the type of soil and altitude above sea level are in good agreement with the results of P. De Bauw *et al.* (2016), who showed that soil fertility on the slopes of Mount Elgon decreases with increasing altitude due to a decrease in phosphorus and exchange cations. In addition, the authors identified the dependency of the mineral supply of plants on a specific relief zone: in the lower part of the slopes, magnesium deficiency occurs due to antagonism with potassium, and in the upper part – due to general depletion. This observation highlights the need for a localised approach to agrochemical regulation. Biological activity, estimated by the number of microorganisms, ranged from 2-4 million/g in brown forest soils to less than 1 million/g in sandy soils, which is fully consistent with the conclusions of D. Kodirova *et al.* (2023) on the key role of the humus horizon in maintaining the microbial community. Z.H. Aliyev and M.A. Quliyeva (2023) demonstrate that the introduction of perennial grasses leads to a substantial increase in microbiological activity due to the enrichment of soil with organic matter. Similar trends have been established by L. Rangel *et al*. (2019) and D. Salesa & A. Cerdà (2020), linking the degradation of the soil cover with trampling, excessive recreational loading and disruption of the pasture exploitation regime.

Special attention should be paid to soil resistance to erosion processes. According to the data, sandy soils are subject to the highest erosion due to their weak aggregate structure, while brown forest soils, due to their high water-strength aggregates (more than 85%), demonstrate stability even on slopes. Similar dependencies were identified in the study by H. Hag Husein *et al*. (2024), where, using the CORINE model, a high erosion vulnerability of soils was specified, including areas with dense vegetation, especially in conditions of intense precipitation. Researchers C. Jiang *et al*. (2021) and L. Wen *et al*. (2023) confirm that urbanisation and changing land use patterns immensely worsen erosion processes. The climate warming, according to J. Peng *et al*. (2021), can both contribute to an increase in organic matter in the soils of mountainous regions due to the lengthening of the growing season, and enhance rock weathering with sudden fluctuations in humidity. Such dual effects require monitoring, especially in vulnerable areas, as demonstrated by W. Sun *et al*. (2023) on the Tibetan Plateau. To stabilise the soil cover, it is necessary to introduce agroforestry measures, along with the systematic monitoring of landscape fragmentation as one of the key risk factors.

In general, a comparative analysis has shown that the agrochemical properties of the soils of the Fergana Valley are in the range typical for mountain systems of temperate and dry climates. However, features such as localised alkalinity, humus-poor sandy soils, and sensitivity to erosion require adapted land management programmes. This includes the use of organic fertilisers, the introduction of perennial crops, anti-erosion measures, and strategic land use planning based on topography, climate, and soil texture.

CONCLUSIONS

The analysis of the soils of the Fergana Valley revealed a substantial variety of their physico-chemical properties. Brown forest soils have a medium loamy composition (sandy fraction 35-45%, silt 30-40%, clay 15-25%), which contributes to a high moisture retention capacity. Mountain-brown carbonate soils contain 25-35% clay particles and less sand fraction. Sandy soils are dominated by sand particles up to 80%, which makes them unsuitable for agriculture without irrigation. The humus content is the highest at 4.5-6% in brown forest soils due to active biological activity. In mountain-brown carbonate soils, it is below 2.5-4%, and in sandy soils, it is at a minimum of 0.5-1.5% due to accelerated mineralisation of organic matter. In terms of soil acidity, there are pronounced differences: brown forest soils have a slightly acidic or neutral reaction (pH 5.8-6.5), which provides optimal conditions for the absorption of nutrients by plants. Mountain-brown carbonate soils are characterised by an alkaline environment (pH 7.5-8.2), which may limit the availability of certain macro- and microelements. A slightly alkaline reaction (pH 6.8-7.4) was established in sandy soils, while the low content of organic matter further reduces their agrochemical efficiency. The macronutrient composition differs, and the nitrogen content varies from 0.2-0.3% (brown forest soils) to less than 0.1% (sandy soils). Available phosphorus is higher in brown forest soils (20-40 mg/kg), and potassium is better retained in loamy soils. Water-physical properties affect erosion resistance, and in the process, it was determined that brown forest soils are characterised by high moisture capacity and erosion resistance. Mountain-brown soils are moderately moisture-intensive, while sandy soils require additional irrigation.

The data obtained allow formulating recommendations on the rational use of the soils of the Fergana Valley and developing measures to improve their fertility and resistance to degradation. However, the present study covered only a part of the territory of the Fergana Valley, which may limit the extrapolation of the data to the entire region. The analysis methods applied, although widely used, had certain errors related to the natural variability of soil characteristics. The study also did not account for seasonal changes in moisture and organic matter, which can considerably affect the agrochemical properties of soils. For more detailed research, it is necessary to conduct additional studies, including long-term monitoring of soil parameters and analysis of the influence of anthropogenic load and climatic factors.

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Агрохімічна характеристика гірських ґрунтів Ферганської долини

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Анотація. Актуальність дослідження ґрунтів Ферганської долини зумовлена їх різноманітністю та важливістю для сільського господарства регіону. Різні ґрунтові типи відрізняються за гранулометричним складом, родючістю та здатністю утримувати вологу, що впливає на їхні агрохімічні властивості. Метою дослідження був комплексний аналіз агрохімічних характеристик ґрунтів Ферганської долини, включаючи гранулометричний склад, вміст гумусу, кислотність, карбонатність, водні властивості та біологічну активність. Методи включали польові дослідження, відбір проб з різних висотних поясів, лабораторні аналізи хімічного складу. Визначення азоту проводилося методом К'єльдаля, фосфору – методом Мачигіна і Кірукова, калію – полум'яною фотометрією. Результати дослідження показали значні відмінності у складі та властивостях різних типів ґрунтів. Бурі лісові ґрунти продемонстрували найбільш сприятливі агрохімічні параметри. Гранулометричний склад бурих лісових ґрунтів середньосуглинковий, із вмістом піску 35-45 %, мулу 30-40 % та глини 15-25 %. У ґрунтах зафіксовано високі рівні гумусу (4,5-6 %), загального азоту (0,2-0,3 %), доступного фосфору (20-40 мг/кг) і калію (високий рівень). Біологічна активність, оцінювана за мікробною чисельністю, становила 2-4 млн/г, що підтвердило високу метаболічну активність ґрунтової мікрофлори.

Гірничо-коричневі карбонатні ґрунти характеризувались важчим гранулометричним складом, з підвищеним вмістом глини (25-35 %) і помірними показниками родючості: 2,5-4 % гумусу, 0,1-0,2 % азоту, 10-25 мг/кг форсфору та середній рівень калію Піщані ґрунти мали низьку вологоємність, слабку агрегатну структуру та вкрай низькі показники родючості: 0,5-1,5 % гумусу, <0,1 % азоту, 5-15 мг/кг фосфору, низький рівень калію. Біологічна активність не перевищувала 1 млн/г. Кислотність ґрунтів варіювалась: бурі лісові ґрунти мають слабокислу або нейтральну реакцію з pH 5,8-6,5, що сприятливо для засвоєння поживних речовин. Гірничо-коричневі карбонатні ґрунти лужні з pH 7,5-8,2, що знижує доступність деяких елементів. Піщані ґрунти мають слаболужну реакцію pH 6,8-7,4. Отримані дані дадуть змогу оптимізувати землекористування, підвищити продуктивність ґрунтів і мінімізувати їхню деградацію

Ключові слова: гумус; гранулометричний склад; карбонатність; ерозійні процеси; кислотність; мінерали; органіка