



Microelement Biogeochemistry in Meadow-Oasis Soils and Legumes of the Fergana Valley

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Abstract

This study is devoted to the geochemical assessment of the composition and spatial distribution of chemical elements in meadow–oasis soils developed within the alluvial fans of the Isfara and Sokh rivers in the western part of the Fergana Valley, as well as in associated leguminous crops, including *Vigna radiata*, *Phaseolus aureus*, and *Arachis hypogaea*. The vertical distribution patterns of microelements in soil profiles were investigated, and key geochemical regularities of element accumulation were identified. Clarke concentrations and dispersion coefficients were calculated relative to lithospheric and soil background values to evaluate elemental enrichment and depletion.

In addition, the distribution of chemical elements within different plant organs was analyzed, and biological absorption coefficients *C_b* were determined. Based on *C_b* values, absorption activity sequences were established, enabling classification of elements according to their bioaccumulation potential in plant biomass. The results indicate that Mo, Zn, and Ni exhibit the highest biological activity and accumulation capacity, whereas Fe, Cr, and Co demonstrate comparatively low biological uptake.

Keywords: meadow-oasis soils, microelements, geochemistry, Clarke concentration, biological absorption coefficient (*C_b*), alluvial fans.

1 Introduction

Recent advances in soil biogeochemistry have demonstrated that the distribution, mobility, and bioavailability of macro- and microelements in soils are controlled by a combination of intrinsic soil properties, climatic conditions, and anthropogenic influences. At the global scale, nutrient availability in topsoils is primarily governed by soil pH, organic matter content, and mineral composition, while environmental change significantly intensifies spatial heterogeneity in element cycling processes [1].

In agroecosystems, soil physicochemical characteristics strongly regulate the bioavailability and plant uptake of trace elements, thereby influencing crop productivity and nutritional quality. Variations in soil texture, salinity, and organic matter content determine the mobility of microelements and their transfer into plant tissues, linking soil geochemistry with agricultural and human health systems [2]. In addition, enzymatic activity in soils plays a crucial role in regulating nutrient cycling processes, including the transformation and stabilization of macro- and

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microelements such as P, K, Mg, Zn, and Cu, thereby contributing to soil fertility and carbon dynamics [3].

Meadow–oasis soils of irrigated regions in Central Asia represent complex geochemical systems formed under the combined influence of alluvial sedimentation and long-term irrigation practices. These soils are characterized by pronounced spatial and vertical heterogeneity of microelements, reflecting both natural soil-forming processes and anthropogenic impacts [4]. In irrigated agroecosystems of the Fergana Valley, biogeochemical behavior of microelements is further shaped by continuous agricultural use, irrigation regimes, and geochemical background conditions, resulting in dynamic element redistribution within soil profiles [7].

Plant–soil interactions are a key component of element cycling in such systems. Different plant species exhibit distinct patterns of microelement uptake depending on soil composition and physiological characteristics, indicating that biological absorption processes are species-specific and environmentally controlled [5]. Trace elements also play an important role in regulating vegetation structure and ecological stability in regional ecosystems, reflecting the close coupling between soil chemistry and plant biogeochemical behavior [12].

Irrigated agricultural soils are particularly sensitive to anthropogenic and environmental changes. Temporal variability of microelement concentrations in soils and crops is strongly influenced by irrigation practices and land management systems, which can alter element mobility and availability [6]. In Central Fergana, salinization processes significantly modify the biogeochemical state of soils, leading to elemental imbalance, reduced fertility, and ecosystem degradation [10]. Similar processes of salinity and sodicity are recognized as major constraints in dryland and irrigated soils worldwide, affecting soil structure and nutrient availability [15].

Changes in irrigation water sources and quality further influence the geochemical behavior of potentially toxic elements in soils. Long-term use of alternative irrigation water can significantly alter the mobility, accumulation, or depletion of trace elements depending on soil buffering capacity and geochemical conditions [14]. In calcareous soil environments, flooding conditions can also modify the mobility of trace and alkaline metals, thereby affecting their distribution in soil systems [13].

Soil fertility variability across cultivated landscapes highlights the necessity of site-specific agrochemical assessment for sustainable land management. Spatial heterogeneity in soil chemical properties requires targeted nutrient management strategies to optimize agricultural productivity and maintain ecological balance [16]. In addition, soil microbial communities are fundamental regulators of nutrient cycling processes, enhancing organic matter decomposition and stabilizing soil biogeochemical functions [8].

Climatic factors also significantly influence soil–plant element dynamics. Temperature and precipitation regimes affect element mobility, solubility, and plant uptake efficiency, thereby contributing to seasonal and spatial variability in microelement composition [9].

Overall, meadow–oasis and irrigated soils of the Fergana Valley represent highly dynamic biogeochemical systems shaped by the interaction of natural soil formation processes and long-term anthropogenic influences. However, despite extensive research, integrated studies combining vertical microelement distribution, Clarke concentration analysis, and biological absorption coefficients (C_b) in leguminous crops remain limited. This is particularly relevant for agroecosystems involving *Vigna radiata*, *Phaseolus aureus*, and *Arachis hypogaea*, where soil–plant transfer mechanisms are still insufficiently quantified.

Therefore, a comprehensive geochemical and biogeochemical assessment is required to elucidate elemental distribution patterns, identify accumulation regularities, and evaluate soil–plant transfer processes under irrigated meadow–oasis conditions of the Fergana Valley.

2 Research Object and Methods

The objects of this study were meadow–oasis and irrigated meadow soils formed within the Sokh and Isfara alluvial fans of the Fergana region, as well as associated leguminous crops naturally grown in these agroecosystems, including *Phaseolus aureus*, *Vigna sinensis*, and *Arachis hypogaea*. The subject of the research included the content, migration patterns, and accumulation processes of microelements within the soil–plant system.

Soil morphological characteristics were investigated using the morphogenetic approach developed by V. V. Dokuchaev, allowing for detailed characterization of genetic horizons and soil profile structure. Agrochemical properties of the soils were determined

using standard analytical procedures widely accepted in soil science.

The elemental composition of soil and plant samples was analyzed using neutron activation analysis (NAA). Samples were irradiated in a nuclear reactor under a thermal neutron flux of 5×10^{13} neutrons/(cm² · s) at the Laboratory of Ecology and Biotechnology of the Institute of Nuclear Physics, Academy of Sciences of the Republic of Uzbekistan. Element concentrations were determined based on gamma-ray spectrometry of induced radionuclides, considering their characteristic half-lives.

To evaluate the intensity of biological uptake of elements, the biological accumulation coefficient (K_b) was calculated using the following equation:

$$K_b = \frac{R}{P} \quad (1)$$

where *R* represents the concentration of a given chemical element in plant ash (mg/kg), and *P* represents its concentration in the corresponding soil (mg/kg).

Clarke concentration and dispersion coefficients were calculated using standard geochemical approaches according to the methodologies of Alekseenko and Perelman, enabling quantitative assessment of elemental enrichment and depletion in soil–plant systems.

All experimental data were processed using Microsoft Excel and OriginPro software packages. Each measurement was performed in triplicate, and results are presented as mean values with standard deviation (±SD) to ensure statistical reliability.

Part of the data related to the Isfara alluvial fan has been previously published; however, in the present study, the dataset has been significantly expanded to include comparative geochemical information from the Sokh alluvial fan. Additionally, biological absorption characteristics of microelements and detailed vertical soil profile analyses were incorporated to provide a more comprehensive assessment of element migration and accumulation processes in the studied agroecosystems.

3 Results

The western part of the Fergana Valley is characterized by an arid continental climate and a complex geomorphological structure composed of alluvial fan systems of the Sokh and Isfara rivers, inter-fan

depressions, and the alluvial plains of the Syr Darya River. The lithological composition of the area is dominated by proluvial, proluvial-alluvial, and alluvial deposits, which form the parent material of the regional soil cover.

Hydrogeological conditions are characterized by a shallow groundwater table, typically occurring at depths of 1–3 m. Groundwater salinity varies considerably, ranging from 1 to more than 10 g/L, with hydrochemical composition predominantly of bicarbonate–sulfate and sulfate types. These conditions play a significant role in soil salinization processes and influence the geochemical behavior of elements within the soil profile.

For centuries, the western Fergana Valley has been intensively utilized for agricultural production. Long-term irrigation practices, mechanized soil cultivation, regular application of mineral fertilizers, and microclimatic alterations have substantially modified the natural soil-forming processes, particularly in the middle and lower parts of alluvial fans under conditions of permanent moisture supply.

As a result of these anthropogenic impacts, originally formed meadow soils have undergone significant transformation and have acquired morphological, physicochemical, and geochemical characteristics typical of meadow–oasis soil types. These transformations have markedly influenced soil morphogenesis, vertical profile differentiation, and the overall geochemical structure of the soil system.

The mechanisms of chemical element uptake by plants from soil substrates are governed by principles of physiological selectivity. However, the efficiency of element absorption is largely determined not only by their total concentrations in soils but also by their chemical forms and mobility within the soil matrix. Both deficiency and excess of individual elements can significantly influence plant physiological status and metabolic functioning.

In the studied meadow–oasis soils, relatively elevated concentrations of sodium, iron, and manganese were observed compared to other elements; however, their levels remained below the average lithospheric background values. The vertical distribution of iron, manganese, molybdenum, and zinc within the soil profiles exhibited weak horizontal differentiation, indicating limited lateral geochemical redistribution.

Minimum concentrations of these elements were

Table 1. Elemental Composition and Concentration of Chemical Elements in Soils of the Western Fergana Alluvial Fans ($\mu\text{g/g}$)

Depth (cm)	Chemical Elements									
	Fe	K	Na	Ba	Mn	Sr	Zn	Cr	Ni	Co
<i>Isfara</i>										
0–27	27810	20700	12300	1095	612	364	112	61.27	22.6	10.2
27–47	30100	21400	12760	1324	534	293	102	61.14	19.1	10.1
<i>Sokh</i>										
0–24	28500	22300	13120	1188	497	325	99	59.45	19.7	9.9
24–42	29300	22100	13200	1138	560	285	109	48.47	23.7	11.9

recorded within the transitional horizon separating the soil layer from the parent material. In contrast, localized enrichment of chromium, nickel, and cobalt was detected in the upper part of this horizon, while a secondary accumulation maximum of these elements was also observed in the lower soil horizons (Table 1). This pattern reflects differentiated geochemical migration processes and element-specific behavior within the soil profile.

The vertical distribution of chemical elements in the studied alluvial fan soils of the Isfara and Sokh regions demonstrates a generally weak but element-specific differentiation across soil depth. The dominant macroelements (Fe, K, and Na) exhibit relatively high and stable concentrations, reflecting the lithogenic background and alluvial origin of the parent material.

Fe shows a slight increase with depth in both soil profiles, indicating limited downward migration and possible accumulation in lower horizons. K and Na display comparatively stable vertical behavior, suggesting weak eluviation–illuviation processes and strong geochemical buffering within the soil matrix.

Among trace elements, Mn and Zn demonstrate moderate variability with depth, reflecting their higher mobility and sensitivity to redox and moisture conditions in meadow–oasis environments. In contrast, Ba and Sr show irregular but noticeable redistribution patterns, which may be associated with carbonate and sulfate geochemical phases.

Transition metals Cr, Ni, and Co exhibit pronounced spatial heterogeneity. In the Isfara fan, a slight decrease in Ni with depth is observed, while in the Sokh fan, Ni and Co show a tendency toward increased accumulation in deeper horizons. Cr demonstrates relatively lower variability but indicates localized enrichment zones, particularly in the lower soil layers of the Sokh profile.

Overall, the results suggest that microelement distribution in the studied soils is primarily controlled by parent material composition and alluvial deposition processes, while secondary redistribution is influenced by soil moisture dynamics and anthropogenic irrigation impact. The observed patterns confirm weak vertical differentiation but clear element-specific geochemical behavior within meadow–oasis soil systems.

A clear vertical differentiation of chemical elements across soil profiles, including the agro-irrigation layer, transitional horizon, and parent material, is not distinctly expressed. The amplitude between maximum and minimum elemental concentrations is relatively low (Fig. 1, 2), indicating weak geochemical contrast within the studied soil systems. Overall, the elemental composition of soils from the Isfara and Sokh alluvial fans does not show significant differences.

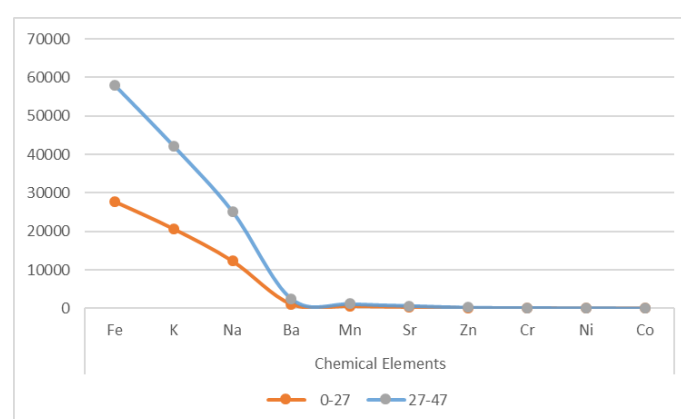


Figure 1. Vertical Distribution of Chemical Elements in Soils of the Sokh Alluvial Fans of the Western Fergana Region

In the Isfara alluvial fan soils, a slight accumulation of Na, Ba, Zn, and Mo is observed in the agro-irrigation layer of meadow–oasis soils. In contrast, Fe, K, Mn, and Co tend to show higher relative concentrations closer to the parent material. The transitional horizon

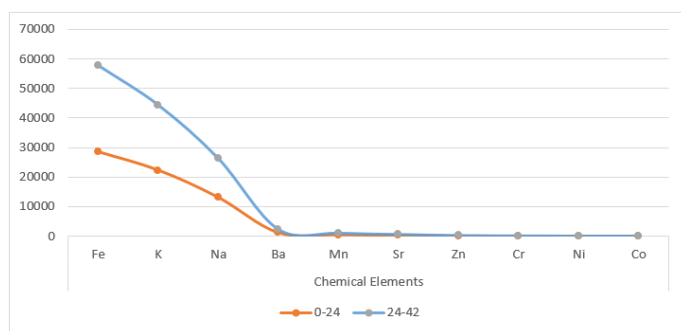


Figure 2. Vertical Distribution of Chemical Elements in Soils of the Western Fergana Alluvial Fans: Isfara

is generally characterized by lower concentrations of most studied elements; however, localized increases of Cr, Ni, and Co are detected within this layer, indicating element-specific redistribution within the soil profile.

In the Sokh alluvial fan soils, weak differentiation is observed for Fe, Zn, Mn, and Sr within the transitional horizon. Meanwhile, K, Na, Ba, and As demonstrate a tendency toward moderate accumulation in the upper soil horizons, reflecting limited vertical migration and weak eluviation processes in the studied agro-irrigated systems.

The spectral distribution of chemical elements in the soils of the Isfara and Sokh alluvial fans shows a generally similar geochemical pattern characterized by a strong dominance of major lithogenic elements (Fe, K, and Na) and relatively low concentrations of trace elements (Zn, Cr, Ni, and Co).

The highest spectral amplitudes are observed for Fe, K, and Na in both profiles, indicating their primary association with parent material composition and alluvial sediment inputs. These elements demonstrate a pronounced contrast with the remaining elements, reflecting their dominant geochemical role in the soil matrix.

A sharp decrease in element concentrations is observed after Ba, indicating a distinct geochemical threshold between major and minor element groups. This transition zone reflects a change in elemental behavior and mobility within the soil system.

Mn and Sr exhibit moderate and relatively stable distributions across the profiles, suggesting limited vertical migration and weak geochemical fractionation under meadow–oasis conditions.

In contrast, Zn, Cr, Ni, and Co show consistently low spectral amplitudes with minimal variation, indicating restricted mobility and low geochemical reactivity in

the studied soil environment.

In the lower soil horizons 24–42 cm and 27–47 cm, Fe and K show slightly higher values, suggesting weak accumulation in deeper layers likely controlled by lithogenic inputs. In contrast, Na and Ba demonstrate relatively higher concentrations in the upper agro-irrigation layer, which may be associated with surface-level redistribution processes influenced by irrigation practices.

Both the Isfara and Sokh alluvial fans exhibit weak vertical differentiation and high geochemical stability. However, minor variations in element distribution between upper and lower horizons indicate limited but detectable soil profile heterogeneity.

4 Conclusions

The obtained data on the elemental composition of soils in the Western Fergana alluvial fans (Isfara and Sokh sites) demonstrate clear vertical differentiation of chemical elements within the soil profile 0–47 cm. Overall, macroelements Fe, K, Na, Ba and microelements Mn, Sr, Zn, Cr, Ni, Co exhibit heterogeneous distribution patterns, reflecting the combined influence of lithogenic processes, pedogenic transformation, and possible anthropogenic inputs.

In the Isfara site, Fe, K, Na, and Ba show an increasing trend with depth, indicating their downward migration and subsequent accumulation in the lower soil horizon (e.g., Fe increases from 27,810 to 30,100 $\mu\text{g/g}$; Ba from 1,095 to 1,324 $\mu\text{g/g}$). In contrast, Mn, Sr, Zn, Cr, Ni, and Co tend to be relatively enriched in the upper horizon, which may be associated with biological cycling, organic matter accumulation, and surface environmental influences.

At the Sokh site, a similar but less uniform pattern is observed. Fe, K, and Na remain relatively stable with slight fluctuations, while Ba and Mn demonstrate noticeable variability between soil layers. Trace elements such as Cr, Ni, and Co show distinct vertical redistribution patterns (e.g., Cr decreases from 59.45 to 48.47 $\mu\text{g/g}$, whereas Ni increases from 19.7 to 23.7 $\mu\text{g/g}$), suggesting localized geochemical variability and potential anthropogenic impact.

In conclusion, the soils of the Western Fergana alluvial fans exhibit a non-uniform vertical distribution of chemical elements, governed by complex migration–accumulation processes. Macroelements are primarily controlled by lithogenic factors, whereas trace elements are more sensitive to ecological

conditions and anthropogenic influences. This confirms that the geochemical environment of the studied soils is dynamic and spatially heterogeneous.

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