



ORIGINAL ARTICLE

ELEMENTAL PROFILE OF RHIZOSPHERE AND NON-RHIZOSPHERE SOILS IN WHEAT CROPS OF SOUTHERN TAJIKISTAN

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ABSTRACT

Understanding the elemental composition of soils at the micro-level is crucial for assessing agricultural productivity and environmental health. The rhizosphere—the narrow zone of soil influenced by root exudates—represents a highly dynamic biogeochemical interface that significantly differs from the bulk (non-rhizosphere) soil.

This study evaluates the spatial distribution and concentration gradients of a wide range of microelements, heavy metals, and oxides (As, Co, Cr, Cu, Fe₂O₃, MnO, Ni, Pb, Sr, TiO₂, V, Zn) in wheat (*Triticum aestivum*) plots across four distinct locations in Southern Tajikistan: Dangara, Hovaling, Temurmaliq, and Banjuwon. Quantitative analysis was performed using high-precision X-ray fluorescence (XRF) spectrometry. The collected and ground soil samples were analysed using a wavelength-dispersive X-ray fluorescence spectrometer (WDXRF), model Spectroscan MAKC G6060, with the software Spectrum-Quantum 6.0. To assess the reliability of the XRF data, the following instrument- and software-specific parameters would be required:

- LOD (Limit of Detection): lowest concentration distinguishable from the analytical background.
- LOQ (Limit of Quantification): lowest concentration that can be quantified with acceptable precision and accuracy.
- Error calculation: method used to calculate the reported error.
- Negative values: meaning of negative calculated concentrations.
- Intensity correction: whether reported intensity values are background-corrected.
- Matrix-specific calibration: whether the instrument was calibrated for soil samples.

The results revealed that regional geochemical factors exert a dominant influence on soil elemental profiles compared to the rhizosphere effect. Distinct localized anomalies were identified, such as Pb enrichment in Dangara and Temurmaliq, and elevated baseline concentrations of Co, V, and Cu in Hovaling. Major matrix components (Fe₂O₃, MnO, TiO₂) as well as stable elements (As, Cr, Ni, Sr) maintained absolute parity between

the rhizosphere and non-rhizosphere zones across all regions. However, a pronounced rhizosphere effect was recorded for essential micronutrients Co and Cu. A significant depletion of Co and Cu was observed in the root zone, particularly in Hovaling and Temurmaliik, indicating active uptake and bioaccumulation by the wheat root systems during vegetation.

The findings establish fundamental patterns of elemental migration at the soil–root interface in arid and semi-arid agroecosystems of Central Asia, providing a scientific basis for sustainable crop management and food security monitoring in Southern Tajikistan.

Keywords: Rhizosphere effect; bulk soil; wheat (*Triticum aestivum*); Southern Tajikistan; X-ray fluorescence analysis; heavy metals, trace elements; biogeochemical migration.

1. INTRODUCTION

Relevance of the Study

Wheat is one of the most important food crops worldwide and is vital for human sustenance and economic development [1].

Under the conditions of intensive anthropogenic pressure, climate aridity, and the transformation of agricultural ecosystems, a comprehensive assessment of the elemental composition of soils is of critical importance. Monitoring the soil cover not only allows for evaluating the environmental health of territories but also helps predict the productivity of essential agricultural crops, particularly wheat, which forms the backbone of regional food security [2].

Soil properties such as nitrogen content, organic carbon, and rhizosphere microorganisms significantly influence wheat's growth, development, and health [3,4]. Nitrogen plays a vital role in photosynthesis and metabolism. Sufficient nitrogen supply enhances leaf growth and boosts the efficiency of photosynthesis in wheat [5]. Soil organic carbon provides continuous nutrients and helps improve soil structure, enhancing aggregation and buffering capacity [6]. This makes the soil more resilient to fluctuations in pH and salinity, thereby promoting healthy wheat growth. Rhizosphere microorganisms, which are primarily beneficial, aid in nutrient availability, though some pathogenic microorganisms can negatively affect wheat's health [7]. Managing these soil properties is essential for ensuring robust and healthy wheat cultivation.

Of particular scientific interest is the study of soil chemistry at the micro-level—specifically within the "soil–plant root" system. Dividing the soil pool into the rhizosphere (the near-root zone subject to active biochemical influence from root exudates and the associated microbiome) and the non-rhizosphere (the bulk, relatively stable soil mass) opens up new avenues for a profound understanding of the mechanisms governing chemical migration, transformation, and bioavailability. The current deficit of detailed data regarding elemental differentiation between these two spheres under specific soil and climatic conditions underscores the relevance of this research [8]. Simultaneously, rhizospheric microbial metabolism influences root exudate release by modifying the mineral composition of the rhizosphere, root cell membrane permeability, root metabolic activity, and the absorption/utilization of root secretions [9,10].

Geographical Localization

The objects of this study are the soil complexes of Southern Tajikistan, a region characterized by unique geochemical conditions, an arid/semi-arid climate, and a highly diverse topography. The experimental material was collected from four key locations within the region in July 2026 under the wheat lands: **Dangara**, **Temurmaliik**, **Baljuwon** and **Hovaling**. The method for collecting rhizosphere and non-rhizosphere soil samples was as follows: first, loose soil was shaken off the wheat roots, and then approximately 1 mm of soil covering the roots was collected using a sterile brush [11]. After removing any plant root debris, the collected soil samples were stored at -20°C . Investigating the soils of this zone carries high regional and global scientific value, as it helps identify background geochemical features of the arid zones of Central Asia and evaluates the degree of spatial variability of elements depending on local landscape factors [12].

Importance of Determining Trace Elements in Soil.

Trace elements and metalloids, despite their low quantitative abundance in the soil mass compared to macroelements, play a decisive role in the functioning of the biosphere:



Figure 1. Map of sample collection in Southern Tajikistan Dangara, Temurmalik, Baljuwon and Hovaling.

- **Physiological Significance:** Elements such as cobalt (Co), copper (Cu), manganese (Mn), zinc (Zn), nickel (Ni), and vanadium (V) are essential micronutrients. They are integral components of enzymes and regulate photosynthesis, respiration, and nitrogen metabolism in wheat plants. Their deficiency or excess directly limits the development of both the root system and aboveground biomass.

- **Environmental Risks:** A number of elements, including arsenic (As), lead (Pb), and chromium (Cr), exhibit pronounced toxic properties when threshold concentrations are exceeded. Determining their total content and mobility in the rhizosphere–non-rhizosphere system is critical for assessing the risks of their entry into trophic chains and subsequent accumulation in grain products.

- **Indicators of Soil Formation:** The distribution of inert oxides and stable elements (Fe_2O_3 , TiO_2 , Sr) serves as a reliable marker of soil genesis, allowing for the differentiation of natural geochemical anomalies from anthropogenic pollution [13].

The Aim of this Work is to evaluate the influence of the trace element pool on the formation of the biochemical environment in the rhizosphere zone of wheat compared to the bulk (non-rhizosphere) soil mass of Southern Tajikistan (using Dangara, Temurmalik, Baljuwon and Hovaling as case studies) via X-ray fluorescence analysis.

To achieve this aim, the following **objectives** were formulated:

1. To determine the quantitative content and spatial distribution of a wide range of trace elements, heavy metals, and oxides (As, Co, Cr, Cu, Fe_2O_3 , MnO, Ni, Pb, Sr, TiO_2 , V, Zn) in the soils of the studied locations using X-ray fluorescence analysis (XRF).
2. To conduct a comparative analysis of the elemental composition between the rhizosphere (near-root) zone of wheat and control samples of non-rhizosphere soil.
3. To identify the specifics of the rhizosphere effect in wheat crops (selective absorption or barrier retention of metals by the root system) under various geochemical conditions of Southern Tajikistan.
4. To assess the risks of mobility and accumulation of toxic elements (Pb, As, Cr) in the direct contact zone with the wheat root system to forecast the quality of future agricultural outputs.

Scientific Novelty

- For the **first time**, comprehensive data on the differentiation of trace element compositions in the "wheat rhizosphere — non-rhizosphere" system for the soil-climatic complexes of Southern Tajikistan (Dangara, Temurmalik, Baljuwon, Hovaling) have been obtained using high-precision XRF analysis.

- The nature of the biogeochemical response of the wheat root system to local geochemical anomalies (specifically regarding cobalt, copper, and vanadium) was established, manifesting as changes in concentration gradients at the "root–soil" interface.

2. MAIN RESULTS AND DISCUSSION

Based on the obtained X-ray fluorescence analysis data, (Statistical analysis and graphical visualization of data were performed in the RStudio environment (v. 2023.12.1) using the R programming language (v. 4.3.2; R Core Team, 2023) a grouped bar chart of element concentrations was constructed on a logarithmic scale (mg/kg, log scale), allowing for a direct comparison between the rhizosphere and non-rhizosphere soil pools across all four studied locations.

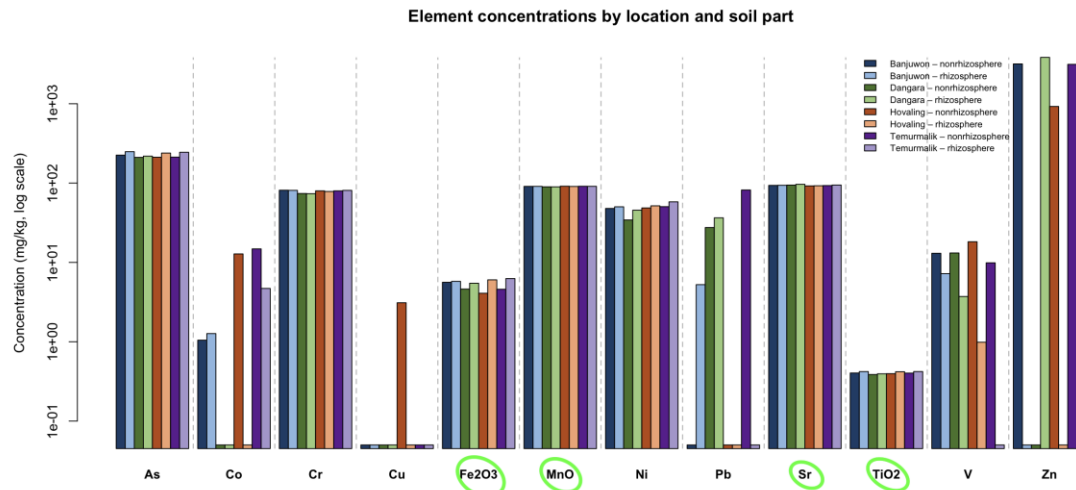


Figure 2: Histogram of all measured elements, with colors distinguishing sampling locations and samples from the rhizosphere and non-rhizosphere. The y-axis is shown on a logarithmic scale.

element	n	negative_value	n	negative_value_percent	negative_intensity	n	negative_intensity_percent	mean_value	median_value	mean_error	median_error	median_relative_error	median_value_error_ratio	reliable	n	uncertain	n	very_uncertain	n	reliable_percent	usable_for_analysis	recommendation
Si	8	0	0	0	0	0	0	93.85	93.71	0.77	0.76	0.81	123.76	8	0	0	0	0	100	JA	quantitativ gut verwendbar	
Pb	8	4	50	5	62.5	-2.31	-11.64	436.99	434.45	1346.68	434.45	1346.68	0.07	0	0	4	0	0	0	NEIN	nicht zuverlässig quantifizierbar	
As	8	0	0	0	0	0	0	226.4	221.81	180.24	179.5	78.76	1.27	0	8	0	0	0	0	NEIN	nicht zuverlässig quantifizierbar	
Zn	8	3	37.5	3	37.5	1795.31	2030.87	103.79	106.54	5.65	106.54	5.65	17.71	5	0	0	0	0	62.5	NEIN	nicht zuverlässig quantifizierbar	
Cu	8	7	87.5	0	0	0	0	-8.5	-8.8	3.8	3.79	43.61	2.32	0	1	0	0	0	0	NEIN	nicht zuverlässig quantifizierbar	
Ni	8	0	0	0	0	0	0	48.35	48.44	31.47	31.15	63.49	1.58	0	8	0	0	0	0	NEIN	nicht zuverlässig quantifizierbar	
Co	8	3	37.5	0	0	0	0	3.34	1.16	38.41	38	1113.95	0.09	0	0	5	0	0	0	NEIN	nicht zuverlässig quantifizierbar	
Fe2O3	8	0	0	0	0	0	0	5.3	5.54	0.23	0.25	4.4	22.72	8	0	0	0	0	100	JA	quantitativ gut verwendbar	
MnO	8	0	0	0	0	0	0	90.67	90.88	0.9	0.9	0.99	101.07	8	0	0	0	0	100	JA	quantitativ gut verwendbar	
Cr	8	0	0	0	0	0	0	78.58	79.81	34.41	34.03	42.14	2.37	0	8	0	0	0	0	NEIN	nicht zuverlässig quantifizierbar	
V	8	1	12.5	2	25	7.77	8.55	296.82	295.28	3526.79	295.28	3526.79	0.03	0	0	7	0	0	0	NEIN	nicht zuverlässig quantifizierbar	
TiO2	8	0	0	0	0	0	0	0.41	0.4	0.06	0.06	13.9	7.2	8	0	0	0	0	100	JA	quantitativ gut verwendbar	

Figure 3: Measurement quality assessment. Green indicates relatively reliable measurements, while red indicates high relative uncertainties.

Only four elements met the specified quality criteria. Zinc showed generally strong signals and low uncertainties, but large intersample variations. As showed relatively stable calculated concentrations but very large uncertainties, for example, 221.81 ± 179.50 . Lead and vanadium showed similarly large uncertainties relative to measured values. These results limit the reliability of their absolute concentrations. Despite these limitations, the data reveal potentially important patterns.

Analysis of the Non-Rhizosphere Pool (Bulk Soil Mass)

The non-rhizosphere zone reflects the baseline background content of elements, primarily determined by the composition of the parent rock in Southern Tajikistan. The geochemical profile of this zone demonstrates high spatial stability for major matrix components and macro-oxides, such as Fe_2O_3 (at a level

of approximately $5\text{--}6 \times 10^0$ mg/kg), MnO (10^2 mg/kg), and TiO_2 (4×10^{-1} mg/kg). High uniformity is also characteristic of As, Cr, and Ni distribution.

However, clear regional geochemical anomalies were recorded in the bulk soil. For instance, sharply elevated background concentrations of cobalt (Co), vanadium (V), and copper (Cu) were detected in the Hovaling location. Copper (Cu) in significant quantities (around 3×10^0 mg/kg) is identified exclusively in the non-rhizosphere of Hovaling, remaining below detection limits in the other regions. Conversely, a pronounced enrichment of the soil profile with lead (Pb) is observed in the Dangara and Temurmalik locations.

Analysis of the Wheat Rhizosphere Zone.

A comparative analysis of paired samples ("non-rhizosphere" represented by the darker left bar, and "rhizosphere" represented by the lighter right bar within each cluster) showed that the wheat root system exerts a selective influence on element migration.

For most stable components (As, Cr, Fe_2O_3 , MnO, Ni, Sr, TiO_2), no statistically significant differences were found between the near-root zone and the bulk soil mass. This indicates the absence of an active biochemical barrier or hyperaccumulation of these elements by the crop.

The most dynamic rhizosphere effect was recorded for essential micronutrients—cobalt (Co) and copper (Cu):

- In the Hovaling and Temurmalik locations, the concentration of Co in the wheat rhizosphere is noticeably *lower* than in the non-rhizosphere. This directly indicates active cobalt uptake by the developing wheat root system to satisfy the physiological needs of the plant.
- The complete absence of Cu in the rhizosphere zone of Hovaling, contrasted against its presence in the adjacent bulk soil, supports the hypothesis of intensive root absorption or a shift in copper mobility driven by wheat root exudates.

CONCLUSION

1. **Biogeochemical Parity of Major Components:** Iron compounds (Fe_2O_3), manganese (MnO), and titanium (TiO_2), as well as arsenic (As) and chromium (Cr), demonstrate strict stability between the wheat rhizosphere and the non-rhizosphere across all studied regions of Southern Tajikistan. The vital activity of the wheat root system does not exert a significant impact on the total distribution of these matrix and trace components.

2. **Dominance of the Regional Geochemical Factor:** The spatial (geographical) variability of the soil elemental composition is expressed much more strongly than the rhizosphere effect within a single location. Local anomalies—such as the lead (Pb) enrichment of soils in Dangara and Temurmalik, or the elevated content of vanadium (V) and cobalt (Co) in Hovaling—are dictated by the natural soil genesis of the region.

3. **Selective Root Activity of Wheat:** The highest sensitivity to the rhizosphere effect was identified for the micronutrients Co and Cu. A noticeable decrease in their concentrations within the near-root zone (especially in Hovaling and Temurmalik) proves their high biophilicity and active uptake by the wheat root system during the vegetative period.

Summary

The elemental composition of soils in Southern Tajikistan (including Dangara, Temurmalik, and Khovaling) is primarily influenced by the region's natural geochemical factors, rather than by plant activity.

Despite the stability of matrix components (manganese, iron, titanium) and some microelements in all studied zones, the wheat root system exhibits selective biophilicity, specifically absorbing cobalt and copper during the growing season.

Spatial natural soil variability is crucial. Local anomalies in chemical accumulation outweigh the rhizosphere effect [14, 15].

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AUTHOR CONTRIBUTIONS

CONCEPTUALIZATION - F. YU. NASYROVA

METHODOLOGY - M. NIGMONOV

INVESTIGATION - S. BAROTOV, DILSHODI Khabibullo, M. N. KAFARI

STATISTICAL ANALYSIS - MIRIAM MOSER

WRITING AND PREPARATION OF THE INITIAL VERSION - F. YU. NASYROVA

ALL AUTHORS HAVE READ AND AGREED TO THE PUBLISHED VERSION OF THE MANUSCRIPT.

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DATA AVAILABILITY

THE DATASETS GENERATED AND ANALYZED DURING THIS STUDY ARE AVAILABLE FROM THE CORRESPONDING AUTHOR UPON REQUEST.

CONFLICT OF INTERESTS

The author(s) declare that there is no conflict of interests.

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