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Biogeochemical Distribution of Trace Elements in Desert Soils and Medicinal Plants

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Abstract

The biogeochemical distribution of trace elements in desert soil–plant systems is of considerable importance for understanding element migration, nutrient cycling, and ecological adaptation in arid ecosystems. The aim of this study was to investigate the vertical distribution of Cr, Sc, Co, and Cs in desert soils and to evaluate their biological absorption by the medicinal plant *Silybum marianum* (L.) Gaertn. Soil samples collected from two profile horizons (0–28 and 28–48 cm) and leaf samples of *S. marianum* were analyzed using the neutron activation analysis method. The biological absorption coefficient (BAC) was calculated to evaluate the transfer of trace elements from soil to plant tissues. The results showed that the concentrations of Cr, Sc, Co, and

Cs increased with soil depth, indicating limited vertical migration and the predominant influence of parent material on trace-element distribution. Chromium exhibited the highest concentration in plant leaves, whereas scandium showed the lowest accumulation. The calculated BAC values followed the sequence $Cr = 0.039 > Co = 0.015 > Cs = 0.013 > Sc = 0.010$, with all values remaining below 0.1, indicating weak biological uptake under desert conditions. The findings demonstrate that trace-element distribution in the studied soil–plant system is controlled by the combined effects of soil geochemical characteristics and plant physiological selectivity. The low biological absorption coefficients indicate limited phytoavailability of the investigated elements and suggest that *Silybum marianum* can serve as a suitable bioindicator for assessing trace-element mobility and soil–plant biogeochemical interactions in desert ecosystems. These results provide a scientific basis for ecological monitoring and the sustainable management of medicinal plant resources in arid regions.

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1 Introduction

The biogeochemical distribution of trace elements in desert soils and medicinal plants is governed by the interactions among soil mineral composition, plant physiological adaptation, microbial activity, and environmental conditions. In arid ecosystems, low soil moisture, limited organic matter, high salinity, and alkaline conditions substantially influence the mobility, bioavailability, and transfer of mineral

elements from soil to plants. Therefore, evaluating soil–plant biogeochemical relationships is essential for understanding nutrient dynamics, assessing ecosystem stability, and developing sustainable management strategies for desert environments [3, 9, 12].

Recent studies demonstrate that medicinal plants growing under desert conditions exhibit species-specific mechanisms of mineral element accumulation. Hakimova and Abdualiyeva [1] reported that *Alhagi sparsifolia* selectively accumulated macroelements in different plant organs, following the sequence $K > Na > Ca$. Potassium predominated in generative tissues, reflecting its importance in metabolic activity and reproductive development, whereas sodium accumulated mainly in leaves as an adaptive mechanism for maintaining osmotic balance under water-deficient conditions. Although this study focused on macroelements rather than trace elements, it provides important evidence that desert medicinal plants possess selective mineral uptake mechanisms and can serve as reliable bioindicators for investigating element migration within soil–plant systems. This finding establishes a conceptual basis for future investigations of trace-element bioaccumulation in arid ecosystems.

Vegetation composition also plays a decisive role in regulating soil biogeochemical processes. Huang et al. [2] demonstrated that forest–medicinal plant intercropping significantly improved soil organic carbon, total nitrogen, ammonium nitrogen, and potassium contents while simultaneously increasing microbial diversity and restructuring soil microbial communities. The authors concluded that soil carbon stabilization is controlled through the combined effects of nutrient redistribution and microbial ecological regulation. Although their research was conducted in coastal saline-alkaline soils, the identified mechanisms indicate that vegetation can modify soil physicochemical properties and microbial activity, thereby indirectly influencing the mobility and availability of mineral elements. These findings are highly relevant for interpreting trace-element distribution in desert ecosystems where vegetation cover is sparse and nutrient cycling is limited.

The distribution of mineral elements within soil–plant systems cannot be explained solely by soil chemical composition. Current evidence indicates that nutrient availability is regulated through integrated biological and geochemical processes involving

plant roots, microorganisms, and soil minerals [3, 9]. Soil microorganisms accelerate organic matter decomposition, biological nitrogen fixation, phosphorus solubilization, and carbon stabilization while simultaneously modifying the geochemical behavior and phytoavailability of mineral elements [5, 6]. Likewise, balanced fertilization and integrated nutrient management improve microbial diversity, enzymatic activity, soil organic carbon, and nutrient transformation, thereby enhancing soil fertility and reducing environmental losses [4]. Collectively, these studies suggest that biological processes play an equally important role as physicochemical factors in determining the distribution of mineral elements within terrestrial ecosystems.

Environmental stress further modifies biogeochemical processes controlling element migration. Climate change, prolonged drought, and irregular precipitation alter soil moisture, microbial activity, and nutrient cycling, thereby affecting the mobility and bioavailability of mineral elements [7]. Similar mechanisms have been reported for degraded and acidic soils, where integrated biological, chemical, and agronomic restoration strategies improve nutrient cycling, carbon sequestration, microbial activity, and ecosystem resilience [10]. Furthermore, studies on restored floodplain soils and ancient clay deposits demonstrate that long-term geological substrates continue to participate in nitrogen and carbon cycling through active microbial communities, confirming that mineral substrates remain important regulators of contemporary biogeochemical processes [11, 13].

Despite substantial progress in understanding soil health, nutrient cycling, and microbial ecology, significant knowledge gaps remain regarding the biogeochemical distribution of trace elements in desert soil–medicinal plant systems. Most published studies have focused on soil fertility, microbial diversity, or ecosystem functioning independently, whereas quantitative investigations of trace-element transfer, bioaccumulation patterns, and soil–plant relationships under arid environments remain limited. In particular, insufficient information is available on the interaction between desert soil geochemistry, medicinal plant physiology, and microbial regulation of trace-element mobility. Future research should therefore integrate soil geochemistry, plant bioaccumulation analyses, microbial ecology, and environmental monitoring to clarify the mechanisms controlling trace-element distribution in desert ecosystems and to support the sustainable utilization of medicinal plant resources.

2 Materials and Methods

The study focused on desert soils and the medicinal plant *Silybum marianum* (L.) Gaertn. (milk thistle). The research object comprised the soil–plant system, while the research subject was the biogeochemical migration, accumulation, and distribution of chemical elements within this system.

Soil and plant samples were collected following standard sampling procedures. The elemental composition of the soil and plant samples was determined using the neutron activation analysis (NAA) method at the Activation Analysis Laboratory of the Institute of Nuclear Physics, Academy of Sciences of the Republic of Uzbekistan. The samples were irradiated in a nuclear reactor with a neutron flux of 5×10^{13} neutrons $\text{cm}^{-2} \text{s}^{-1}$. The concentrations of chemical elements were quantified based on the characteristic gamma radiation and the half-lives of the activated radionuclides.

3 Results and Discussion

Silybum marianum (L.) Gaertn. (Asteraceae), commonly known as milk thistle, is a biennial herbaceous medicinal plant characterized by an erect, branched stem reaching 30–60 cm in height. The branches terminate in solitary capitula (flower heads). The leaves are large, light green with distinctive white marbling, and covered with fine hairs on both surfaces. Basal leaves are petiolate, whereas the upper leaves are sessile with sharply spiny margins.

The capitula are spherical, measuring approximately 3–4 cm in diameter, and bear pale pink to purple florets. The fruits are obovoid achenes, about 6 mm long and 3 mm wide, slightly compressed, and grayish-brown in color.

Under the climatic conditions of Uzbekistan, *S. marianum* flowers from April to May, while seed maturation occurs between May and June. The species commonly occurs as a ruderal or weedy plant in irrigated agricultural areas and is naturally distributed in the Kashkadarya, Samarkand, and Surkhandarya regions.

Silybum marianum is recognized as an important medicinal species because its seeds are rich in biologically active compounds, particularly the flavonolignan complex silymarin. Owing to its hepatoprotective, antioxidant, and choleretic properties, the seeds are widely used in pharmaceutical preparations for the prevention

and treatment of liver and biliary disorders. In addition, the species is considered a promising bioindicator for investigating soil–plant interactions and the accumulation of mineral elements in arid environments, making it suitable for biogeochemical studies of desert ecosystems.

The vertical distribution of trace elements in the desert soil profile demonstrated a distinct differentiation between the surface and subsurface horizons (Table 1). The concentrations of Cr, Sc, Co, and Cs generally increased with soil depth, indicating a relatively lower accumulation of these elements in the cultivated surface layer (0–28 cm) compared with the subsurface horizon (28–48 cm).

Table 1. Vertical distribution and relative changes of trace elements in the desert soil profile

Soil depth (cm)	Cr ($\mu\text{g g}^{-1}$)	Sc ($\mu\text{g g}^{-1}$)	Co ($\mu\text{g g}^{-1}$)	Cs ($\mu\text{g g}^{-1}$)
0–28	31.0	7.7	9.6	6.2
28–48	45.0	21.0	10.6	7.8

Chromium (Cr) showed the most pronounced variation, increasing from $31 \mu\text{g g}^{-1}$ in the upper layer to $45 \mu\text{g g}^{-1}$ in the lower horizon, representing an increase of approximately 45.2%. A similar trend was observed for scandium (Sc), whose concentration increased from $7.7 \mu\text{g g}^{-1}$ to $21.0 \mu\text{g g}^{-1}$, nearly 2.7-fold higher in the subsurface layer. These results suggest that both Cr and Sc are predominantly associated with the parent material rather than with surface biological processes.

Cobalt (Co) exhibited only a slight increase from $9.6 \mu\text{g g}^{-1}$ to $10.6 \mu\text{g g}^{-1}$, indicating a relatively uniform distribution throughout the investigated soil profile. In contrast, cesium (Cs) increased from $6.2 \mu\text{g g}^{-1}$ in the cultivated layer to $7.8 \mu\text{g g}^{-1}$ in the lower horizon, reflecting moderate downward enrichment.

The relatively lower concentrations of trace elements in the surface horizon may be associated with biological uptake by vegetation, limited organic matter content, and anthropogenic influences resulting from agricultural cultivation. Conversely, the enrichment of Cr, Sc, and Cs in the subsurface layer indicates stronger lithogenic control and limited vertical mobility under arid environmental conditions. These findings demonstrate that the vertical distribution of trace elements in desert soils is influenced by both pedogenic processes and the geochemical composition of the

parent material.

Table 2. Biological absorption coefficient (BAC) of trace elements in *Silybum marianum* leaves

Element	Soil (0–28 cm), $\mu\text{g g}^{-1}$	Leaf, $\mu\text{g g}^{-1}$	BAC
Cr	31.0	1.20	0.039
Sc	7.7	0.079	0.010
Co	9.6	0.140	0.015
Cs	6.2	0.082	0.013

Overall, the obtained results indicate that the studied desert soil profile is characterized by a relatively stable vertical distribution pattern, with limited redistribution of trace elements within the upper 48 cm of the profile. Such information provides an important geochemical basis for evaluating element migration and subsequent accumulation in medicinal plants growing under desert conditions.

The calculated biological absorption coefficients (BAC) indicate that the accumulation of the studied trace elements in the leaves of *Silybum marianum* was generally low ($\text{BAC} < 0.1$), suggesting limited uptake from the desert soil. Among the investigated elements, chromium exhibited the highest biological absorption coefficient $\text{BAC} = 0.039$, followed by cobalt 0.015, cesium 0.013, and scandium 0.010.

Although chromium showed the highest BAC value, its coefficient remained well below unity, indicating that *S. marianum* does not actively accumulate chromium under the studied desert conditions. Similarly, the low BAC values of scandium, cobalt, and cesium suggest restricted transfer of these elements from soil to leaf tissues. This limited uptake is likely associated with the low phytoavailability of trace elements in arid sandy soils, where alkaline reaction, low organic matter content, and reduced moisture decrease element mobility.

Comparison of the soil profile and plant data further indicates that relatively higher concentrations of Cr, Sc, Co, and Cs in the subsurface soil horizon did not result in increased accumulation in leaf tissues. This observation suggests that plant uptake is controlled not only by the total elemental concentration in soil but also by element bioavailability and plant physiological selectivity. Consequently, *Silybum marianum* appears to regulate trace-element uptake effectively and maintains low accumulation levels under desert environmental conditions.

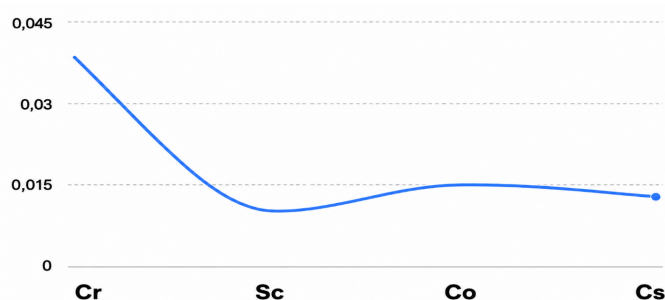


Figure 1. Biological absorption coefficient (BAC) of trace elements in *Silybum marianum* leaves

Overall, the obtained BAC values demonstrate that *Silybum marianum* behaves as an element excluder rather than an accumulator for the investigated trace elements. These findings indicate that the species has limited capacity to concentrate Cr, Sc, Co, and Cs in its aboveground tissues and may therefore serve as a useful bioindicator for evaluating trace-element bioavailability and soil–plant geochemical relationships in desert ecosystems.

Chromium Cr exhibited the highest biological absorption coefficient $\text{BAC} = 0.039$, whereas scandium Sc showed the lowest $\text{BAC} = 0.010$. The order of biological absorption was $\text{Cr} > \text{Co} > \text{Cs} > \text{Sc}$. Since all BAC values were < 0.1 , *Silybum marianum* demonstrated a low capacity to accumulate the investigated trace elements, indicating limited transfer from desert soil to leaf tissues under arid environmental conditions.

4 Conclusions

The present study demonstrated that the vertical distribution of Cr, Sc, Co, and Cs in the investigated desert soil profile was primarily controlled by lithogenic factors, with higher concentrations occurring in the subsurface horizon. Despite their presence in soil, the transfer of these elements into *Silybum marianum* leaves remained limited, as evidenced by biological absorption coefficients below 0.1. The accumulation sequence $\text{Cr} > \text{Co} > \text{Cs} > \text{Sc}$ indicates species-specific physiological regulation of trace-element uptake under arid environmental conditions. These findings suggest that the bioavailability of trace elements depends not only on their total concentration in soil but also on soil physicochemical properties and plant selective absorption mechanisms. Therefore, *Silybum marianum* can be considered a promising bioindicator for assessing trace-element mobility and soil–plant biogeochemical interactions in desert ecosystems.

Future investigations should include additional trace elements, different plant organs, and seasonal variations to improve understanding of element migration and bioaccumulation in arid environments.

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