

Biological Absorption Coefficients, Elemental Uptake, and Biogeochemical Activity of *Lycium Barbarum* L. in Relation to Plant Molecular Responses

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Abstract This study investigated the biological uptake and organ-specific distribution of macro- and microelements in the medicinal plant *Lycium barbarum* L. under different mineral fertilization regimes. Elemental concentrations and biological absorption coefficients (Ax) were used to assess accumulation intensity, selectivity, and biogeochemical activity in leaves, stems, and fruits. The results demonstrated that mineral fertilization significantly altered elemental uptake patterns, with the N₆₀P₆₀K₄₀ treatment showing the most pronounced and balanced effects. Potassium exhibited active uptake across all organs, while selenium and chlorine showed strong bioaccumulation in fruits, substantially increasing their functional and medicinal value. In contrast, iron, cobalt, scandium, and other potentially hazardous elements displayed very low Ax values, indicating effective physiological exclusion and ecological safety. Overall, the findings highlight the role of optimized fertilization in regulating selective element uptake and enhancing the biogeochemical and bioactive properties of *Lycium barbarum* L., providing a scientific basis for its safe cultivation and biofortification.

Keywords *Lycium barbarum* L., Biological absorption coefficient, Mineral fertilization, Bioaccumulation, Selenium, Biogeochemical activity

1. Introduction

Living organisms, particularly medicinal plants, possess the ability to selectively absorb and accumulate chemical elements from the soil within their tissues and organs. At the same time, the investigation of the chemical composition of plants plays a crucial role in the geochemical characterization of the soils in which they grow. Due to the selective uptake capacity of plants, the concentration of chemical elements in plant organs may differ significantly from their levels in the surrounding soil environment [1].

Plants represent a key component in the circulation of chemical elements within the soil–plant–atmosphere system. One of their fundamental characteristics is the ability to selectively absorb elements present in the soil solution and distribute them according to physiological and metabolic requirements. In the scientific literature, this process is commonly described as selective uptake or ion selectivity. This property is of considerable importance for plant adaptation to geochemical environments, resistance to environmental stress factors, and overall evolutionary development [2].

Selective element uptake enables plants not only to optimize nutrient acquisition but also to protect themselves from the adverse effects of toxic elements, enhance competitive ability, and regulate biogeochemical processes. Numerous scientific studies indicate that ions are actively and selectively absorbed through specialized transport systems located in the membranes of plant root cells. This mechanism allows plants to efficiently acquire essential macro- and microelements even under conditions of low elemental availability in the soil [3]. As a result, plants are capable of sustained growth and development in ecosystems characterized by limited nutrient resources.

In addition, selective uptake mechanisms protect plants from the harmful effects of heavy metals and other toxic elements. Certain plant species are capable of retaining elements such as Cd, Pb, and Hg within the root system, thereby limiting their translocation to aboveground organs [4,5]. At the same time, elements such as Ca, Si, and Zn can mitigate the intracellular activity of toxic ions. Selective element uptake also ensures the optimal functioning of enzymatic systems. Microelements are incorporated into enzyme structures only in the required amounts, which reduces antagonistic interactions between elements. As noted by previous studies, this process enhances the efficiency of photosynthesis, respiration, and protein synthesis [6].

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Moreover, ion selectivity plays a critical role in plant adaptation under salinity, drought, and other abiotic stress conditions. Demonstrated that the restriction of Na^+ ion uptake and the preferential absorption of K^+ ions are essential for plant survival in saline soils. In addition, elements such as Si and Ca enhance cell membrane stability, thereby strengthening plant tolerance to stress factors [7].

The selective accumulation of elements by plants has been reported to exert a direct influence on landscape geochemistry [8,9]. Certain plant species gain a competitive advantage in environments enriched with specific elements, leading to the formation of ecological groups such as metallophytes and selenophytes. This phenomenon represents one of the key pathways of evolutionary adaptation. A review of the literature indicates that the ability of plants to selectively assimilate chemical elements provides them with extensive ecological and physiological advantages. This characteristic is crucial for survival under conditions of nutrient deficiency and toxic environments, optimization of metabolic processes, enhancement of stress tolerance, and regulation of biogeochemical cycles. Consequently, selective element uptake is considered one of the fundamental mechanisms underlying the stable development of plants in both natural and anthropogenically influenced ecosystems.

Goji berry (*Lycium barbarum* L.) is a perennial medicinal shrub of the Solanaceae family widely cultivated in Central and East Asia. The plant is tolerant to arid and saline soils and is known for its capacity to selectively absorb and accumulate mineral elements from the soil. Its fruits contain biologically active compounds such as polysaccharides, carotenoids, flavonoids, vitamins, and essential trace elements, which contribute to antioxidant and immunomodulatory effects. Due to its selective elemental uptake and bioaccumulation ability, *L. barbarum* is considered a suitable model species for studies on biological absorption coefficients, plant–soil interactions, and biogeochemical activity.

2. Materials and Methods

The study was conducted on the introduced medicinal plant goji (*Lycium barbarum* L.) cultivated under open-field conditions in the southern part of the Fergana Valley, Uzbekistan. Two contrasting soil environments were selected: irrigated typical sierozems located on foothill sloping plains and irrigated meadow saline soils situated in the desert plain zone. The region has a sharply continental climate characterized by hot, dry summers and low annual precipitation (180–220 mm).

One-year-old uniform seedlings were planted in spring 2023. Sampling was performed during the peak vegetation and fruiting stage (July–August 2024). Plants grown on typical sierozems were considered the control group, while plants cultivated on meadow saline soils represented the treatment group exposed to natural soil salinity conditions. Each site included three replicated plots, with 20 plants per plot.

Irrigation was applied using a drip system at 7–10 day intervals throughout the growing season using local irrigation

water of low mineralization. No mineral fertilizers were applied during the experimental period in order to evaluate natural soil–plant elemental interactions.

Soil samples were collected from the root zone (0–30 cm depth) adjacent to sampled plants. Plant samples included leaves and mature fruits collected from randomly selected individuals within each replicate. Plant material was washed with distilled water, oven-dried at 60 °C to constant weight, and ground to a fine powder. Soil samples were air-dried, homogenized, and sieved through a 1-mm mesh.

The physicochemical properties of the soils were determined using standard methods. Typical sierozems had light loamy texture, pH 7.6–7.8, low salinity (0.2–0.3% soluble salts), and humus content of 1.0–1.2%. Meadow saline soils were characterized by heavier texture, alkaline pH (8.1–8.4), and elevated soluble salt content (0.8–1.2%), dominated by chlorides and sulfates.

Elemental composition of soil and plant samples was determined by neutron activation analysis (NAA) at the Activation Analysis Laboratory of the Institute of Nuclear Physics, Academy of Sciences of the Republic of Uzbekistan. Approximately 0.3–0.5 g of dried samples were sealed in polyethylene capsules and irradiated in a research reactor under a neutron flux of 5×10^{13} neutrons/cm²s. After appropriate decay periods, gamma-ray spectra were measured, and elemental concentrations were calculated based on characteristic half-lives and gamma energies of radionuclides. Certified reference materials were used for quality control.

The following elements were quantified (mg/kg dry weight): Fe, Mn, Zn, Cu, Co, Ni, Cr, Sr, Ba, Rb, Cs, Ca, K, and Na. Biological absorption coefficients (BAC) were calculated as the ratio of element concentration in plant tissues to that in the corresponding soil. All measurements were performed in triplicate and expressed as mean \pm standard deviation. Statistical comparisons between control and saline soil conditions were evaluated using Student's t-test with significance accepted at $p < 0.05$.

3. Results

The precise quantitative determination of macro- and microelements in medicinal plants, as well as the identification of hazardous or toxic concentrations of heavy metals, represents a critical step in assessing safety for both plants and consumers. In addition, obtaining detailed information on hyper accumulator plants and the distribution of elements within their organs is of significant importance for biogeochemical and ecological research. Hyper accumulator plants are capable of absorbing exceptionally high concentrations of heavy metals from soils, accumulating metals at levels approximately 50–100 times higher than those observed in non-accumulating plant species [10,11]. Currently, approximately 500 plant species worldwide have been recognized as hyper accumulators, representing only about 0.2% of all angiosperm species [12].

The mobile fractions of macro- and microelements in soils

play a crucial role in their uptake by medicinal plants, with their primary function being the retention and regulation of elemental circulation within the biosphere. To evaluate the ability of living organisms to absorb and accumulate chemical elements, an index of element uptake intensity (A_x) was proposed, which was later termed the biological absorption coefficient by A.I. Perelman (1971) [13,14]. This coefficient serves as an important scientific and practical tool for analyzing the biogeochemical behavior of elements in medicinal plants, as well as for assessing plant material quality. When $A_x > 1$, elements are considered to be accumulated by plants, whereas when $A_x < 1$, they are regarded as retained or excluded [13,14].

Element biophilicity (B) is calculated as the ratio of the elemental Clarke value in living organisms to that in the lithosphere or soil, and its relative magnitude should be taken into account in biogeochemical assessments [13].

Thus, the investigation of the quantitative and qualitative elemental composition of medicinal plants under diverse soil and climatic conditions enables the assessment of their biogeochemical characteristics through the biological absorption coefficient. This methodology is important not only for determining the physiological and bioactive properties of plants but also for understanding the migration of macro- and microelements under conditions of soil degradation.

The figure 1 illustrates the distribution of macro- and microelements (Fe, Ca, Na, K, Mo, Mn, Ba, Sr, and Zn) in different organs of *Lycium barbarum* L., including old leaves, young leaves, one-year-old stems, and two-year-old stems, under control (non-fertilized) conditions. Elemental concentrations demonstrate pronounced organ-specific accumulation patterns, with higher levels generally observed in leaf tissues compared to stems.

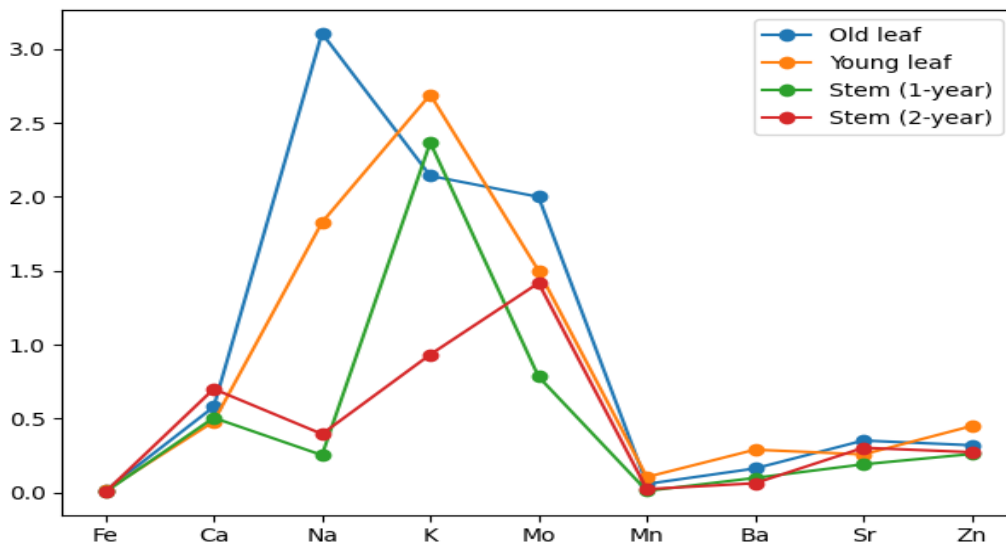


Figure 1. Elemental distribution in different organs of *Lycium barbarum* L. under control conditions (no fertilizer)

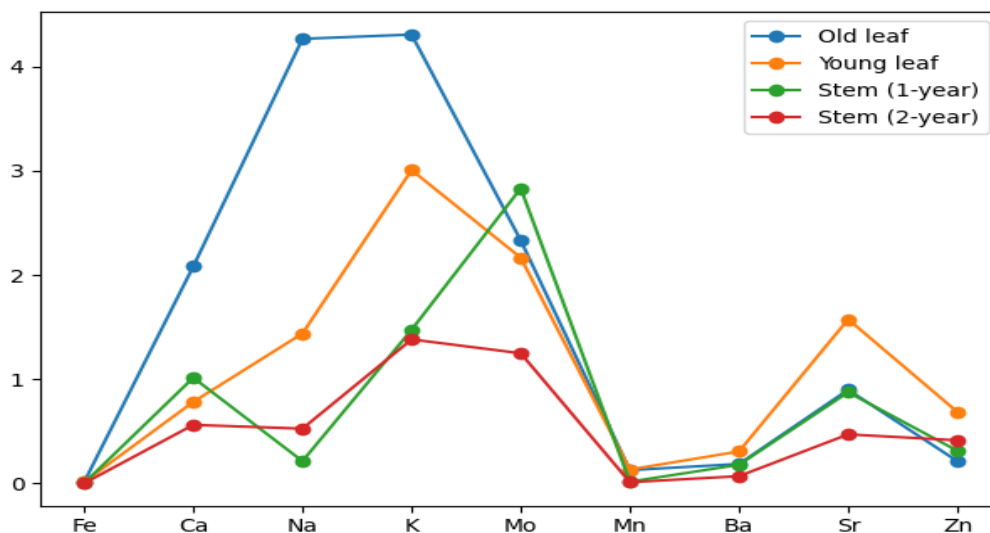


Figure 2. Elemental distribution in different organs of *Lycium barbarum* L. under N₃₀P₆₀K₄₀ fertilizer treatment

The figure shows the distribution of macro- and microelements (Fe, Ca, Na, K, Mo, Mn, Ba, Sr, and Zn) in old leaves, young leaves, one-year-old stems, and two-year-old stems of *Lycium barbarum* L. under the $N_{30}P_{60}K_{40}$ fertilizer treatment. The application of mineral fertilizers significantly increased the accumulation of Na, K, Mo, and Sr, particularly in leaf tissues, while stem organs exhibited comparatively lower concentrations. Organ-specific differences indicate selective uptake and redistribution of elements in response to fertilization.

The results of the study indicate that the biological absorption coefficient (Ax) in the organs of the medicinal goji plant (*Lycium barbarum* L.) changes significantly under conditions of mineral fertilization. Under unfertilized conditions (Variant 1), most elements—particularly Fe, Mn, K, and the macroelements Ca and Na—exhibited relatively low Ax values in both leaves and stems, indicating limited elemental activity and uptake within plant organs.

In contrast, nitrogen-enriched fertilizer treatments (N_{30} , N_{60} , and N_{90}) led to a pronounced increase in Ax values, promoting more intensive uptake of Fe, K, Ca, Na, and Mn in leaves and stems. At the same time, the Ax values of Mo, Se, and other microelements showed selective distribution among plant organs, with higher values observed in organs directly involved in growth and key physiological processes.

In conclusion, the biological absorption coefficient (Ax) in the medicinal goji plant (*Lycium barbarum* L.) undergoes significant changes under mineral fertilization conditions. Optimal fertilization, particularly the $N_{60}P_{60}K_{40}$ treatment, stimulates the selective uptake of chemical elements, thereby enhancing the bioactive and medicinal properties of plant organs. In contrast, unfertilized or low-nitrogen conditions are characterized by reduced Ax values, which limits the plant's medicinal potential and its capacity to accumulate essential bioelements.

These findings demonstrate the considerable scientific and practical significance of optimizing fertilization strategies in the cultivation of medicinal plants, as well as ensuring the safe and efficient uptake of elements to improve plant quality and therapeutic value.

In the aboveground vegetative organs of the goji plant (*Lycium barbarum* L.), the biological absorption coefficients (Ax) of the studied elements were less than one ($Ax < 1$). According to the accepted classification, this indicates weak or very weak biological retention. The elements classified within this group in the medicinal goji plant include Fe, Mn, Ba, Zn, Ni, Co, Hf, Sb, Rb, Sc, Cs, Ce, La, Sm, Eu, Lu, Yb, Au, and Th.

The values of the biological concentration coefficient (BCC) not only determine the biological activity of elements under the influence of mineral fertilizers but also serve as a basis for assessing the ecological quality of the cultivated goji plant. In addition, these values provide a foundation for establishing biological absorption series of elements that

reflect the physiological characteristics of living organisms.

The chemical composition of plants, particularly their elemental composition, is not constant and may vary depending on the physical properties and chemical composition of the soils in which plants grow, climatic conditions, and the applied system of agrotechnical practices. In this context, the biogeochemical activity index (BGA) of plant species represents an important parameter. This index has been proposed to be calculated based on the sum of biological absorption coefficients (Ax) [15].

The biogeochemical activity of the organs of the introduced medicinal goji plant (*Lycium barbarum* L.), assessed for 29 elements under the influence of mineral fertilizers, showed a clear decreasing trend as follows: Variant 4 ($N_{90}P_{60}K_{40}$), leaves (23.77) – stems (9.55) > Variant 3 ($N_{60}P_{60}K_{40}$), leaves (21.75) – stems (10.08) > Variant 2 ($N_{30}P_{60}K_{40}$), leaves (17.04) – stems (8.43) > Variant 1 (control, no fertilizer), leaves (13.38) – stems (6.67).

Under the conditions of irrigated typical sierozems, the biogeochemical activity of the fruits of the introduced medicinal goji plant in response to mineral fertilization decreased in the following order: Variant 3 ($N_{60}P_{60}K_{40}$) – 67.25 > Variant 2 ($N_{30}P_{60}K_{40}$) – 57.30 > Variant 4 ($N_{90}P_{60}K_{40}$) – 55.29 > Variant 1 (control, no fertilizer) – 39.72.

The table 1 demonstrates that the $N_{30}P_{60}K_{40}$ and, in particular, the $N_{60}P_{60}K_{40}$ treatments increased the concentrations of K, Ca, Na, and certain microelements (e.g., Se and Cu) in the fruits. The most pronounced increases were observed for K (from 18,800 to 31,900 $\mu\text{g/g}$) and Ca (from 550 to 670 $\mu\text{g/g}$). These findings are consistent with general trends reported in the literature, indicating that nitrogen and potassium supply in *Lycium barbarum* significantly affects fruit yield as well as the concentration of specific metabolites and elements. In some cases, increased nitrogen availability has also been shown to alter polysaccharide and betaine profiles [16].

Selenium (Se) exhibited a markedly higher relative increase (from 0.19 to 1.02 $\mu\text{g/g}$), accompanied by a sharp rise in the corresponding biogeochemical activity (BGA) values (from 3.8 to 20.4). This pattern indicates a pronounced shift in Se biogeochemical activity and bioconcentration within the fruits. Previous studies have reported that Se content in goji cultivars is strongly dependent on soil characteristics and fertilization strategies, and that targeted Se biofortification approaches can effectively enhance Se accumulation in fruits. Moreover, the importance of controlling Se concentrations in fruits has been emphasized in the context of medicinal and functional foods [16].

According to the table, the overall biogeochemical activity (BGA) increased from Variant 1 to Variant 3 and then slightly decreased in Variant 4 (39.7 \rightarrow 67.2 \rightarrow 55.3). This pattern indicates that increasing fertilization levels do not result in a linear increase in elemental accumulation in fruits but are instead governed by complex, non-linear interactions.

Table 1. Changes in the biological absorption coefficient and biogeochemical activity of fruits of the medicinal goji plant (*Lycium barbarum* L., Ningxia Cultivar) under mineral fertilization

Element	Concentration, µg/g				Biological absorption coefficient (Ax)			
	Variant 1 (Control, no fertilizer)	Variant 2 (N ₃₀ P ₆₀ K ₄₀)	Variant 3 (N ₆₀ P ₆₀ K ₄₀)	Variant 4 (N ₉₀ P ₆₀ K ₄₀)	Variant 1 (Control, no fertilizer)	Variant 2 (N ₃₀ P ₆₀ K ₄₀)	Variant 3 (N ₆₀ P ₆₀ K ₄₀)	Variant 4 (N ₉₀ P ₆₀ K ₄₀)
Fe	23,8	23,92	27,8	24,55	0,002	0,002	0,002	0,002
Ca	550	560	670	645	0,029	0,029	0,035	0,034
Na	1680	1699	1840	1780	0,224	0,227	0,245	0,237
K	18800	20750	31900	21800	1,567	1,729	2,658	1,817
Mo	0,32	0,35	0,48	0,47	0,267	0,292	0,400	0,392
Mn	10,4	8,8	10,7	7,4	0,027	0,023	0,027	0,019
Sr	6,3	6,9	6,6	7,5	0,030	0,033	0,031	0,036
Zn	19,2	20,1	8,96	21,9	0,256	0,268	0,120	0,292
Co	0,014	0,092	0,045	0,105	0,002	0,014	0,007	0,016
Se	0,19	0,64	1,02	0,79	3,800	12,800	20,400	15,800
Cu	4,5	5,53	6,33	3,75	0,225	0,277	0,317	0,188
Rb	2,4	2,77	1,88	1,46	0,050	0,058	0,039	0,030
Sc	0,0021	0,0038	0,0039	0,0047	0,0004	0,0007	0,0007	0,0008
Br	1,4	1,5	2,2	1,9	0,378	0,405	0,595	0,514
Ce	2,01	1,4	2,06	1,23	0,066	0,046	0,067	0,040
La	0,97	1,1	0,78	1,09	0,037	0,042	0,030	0,041
Au	0,00063	0,00057	0,00069	0,00066	0,064	0,058	0,070	0,067
Cl	3270	4100	4220	3576	32,70	41,00	42,20	35,76
Biogeochemical activity (BGA)					39,724	57,303	67,245	55,286

Table 2. Biological uptake intensity of chemical elements in medicinal goji (*Lycium barbarum* L.) (third treatment variant)

Plant and Organ Name		Element Groups (according to A. I. Perelman)					
		Biologically Accumulating (Ax > 1)			Biologically Retained (Ax < 1)		
		Very strong (10-100)	Strong (5-10)	Weak (1-5)	Moderate (0,1-1)	Weak (0,01-0,1)	Very weak (<0,01)
Medicinal Goji (<i>Lycium barbarum</i> L.)	Leaf		K, Se	Na, Mo, Br	Ca, Ba, Sr, Zn, Rb, Hg	Fe, Mn, Cr, Co, As, Sb, Sc, Au	Ni, Hf, Cs, Ce, La, Sm, Eu, Lu, Yb, Th
	Stem			K, Mo, Se	Ca, Na, Sr, Zn, Rb, Br, Hg, Au	Mn, Ba, Cr, As, Sb	Fe, Ni, Co, Hf, Cs, Sc, Ce, La, Sm, Eu, Lu, Yb, Th
	Fruit	Se, Cl		K	Na, Mo, Zn, Cu, Br	Ca, Mn, Sr, Rb, Ce, La, Au	Fe, Co, Sc

Similar complex responses have been reported in other studies, where different NPK combinations altered soil–plant nutrient dynamics, yield, and quality parameters (e.g., phenolics and carotenoids) in divergent ways. Therefore, optimal fertilization strategies should be tested under local conditions, taking into account soil properties, climatic factors, and cultivar-specific characteristics [17,18].

Furthermore, based on the biological absorption coefficient data obtained for the introduced medicinal goji plant, the intensity of biological absorption, evaluated according to the classification proposed by A.I. Perelman, can be arranged into the following series.

In the N₆₀P₆₀K₄₀ fertilizer treatment, the biological uptake (Ax) of chemical elements in different organs of medicinal goji (*Lycium barbarum* L.) differs markedly. In the leaves, potassium (K) and selenium (Se) stand out as biologically

accumulated elements, with Ax > 1, which is associated with the high physiological demand of goji for these elements. In particular, the manifestation of Se at the level of “weak accumulation” (Ax = 1–5) confirms the selective capacity of goji leaves to accumulate microelements. The classification of Na, Mo, and Br in the leaves as weakly accumulated elements indicates their active involvement in metabolism, while their uptake is strictly regulated by the plant. Many other elements, including Fe, Mn, Cr, Co, Sc, and Au, exhibit moderate to very weak uptake levels, indicating that the leaves do not actively accumulate these elements.

In stem tissues, the biological uptake of elements is more stable compared to leaf organs, with K, Mo, and Se again exhibiting a dominant tendency toward accumulation. In particular, the weak accumulation of potassium in the stem (Ax = 1–5) can be explained by its active involvement in ion

exchange, regulation of osmotic pressure, and substance transport within the plant. The presence of Ca, Na, Sr, Zn, Rb, and Br in the stem within the A_x range of 0.1–1 corresponds to their characteristic transport along the plant stem. In contrast, the very low A_x values (< 0.01) of elements such as Fe, Ni, and Co, which occur at low levels in the sierozem zone, indicate that the stem practically does not accumulate these elements.

In fruits, the intensity of element uptake differs fundamentally. Selenium (Se) and chlorine (Cl) stand out as biologically accumulated elements, with the particularly strong bioaccumulation of Se ($A_x > 10$) enhancing the value of Goji fruit as a natural source of selenium. Potassium (K) in fruits falls within the A_x range of 1–5, which is associated with its role in fruit formation, sugar transport, and cell division. Sodium (Na), molybdenum (Mo), zinc (Zn), copper (Cu), and bromine (Br) remain within the A_x range of 0.1–1 in fruits, indicating a moderate level of uptake. The very low A_x values of iron (Fe), cobalt (Co), and scandium (Sc) ($A_x < 0.01$) suggest the presence of physiological constraints that limit their accumulation in plant fruits. Overall, in the third treatment, the high bioaccumulation of Se and Cl in goji, the active uptake of K in all organs, and the differentiated inter-organ distribution of other elements clearly demonstrate the plant's selective bioelemental response adapted to mineral fertilizer application.

4. Conclusions

The present study demonstrates that mineral fertilization significantly influences the biological uptake, accumulation patterns, and biogeochemical activity of macro- and microelements in the medicinal goji plant (*Lycium barbarum* L.). The obtained results confirm that the biological absorption coefficient (A_x) is a sensitive and informative indicator for assessing element mobility, selectivity, and physiological relevance within different plant organs under varying fertilization regimes.

Among the tested treatments, the $N_{60}P_{60}K_{40}$ variant proved to be the most effective in stimulating selective bioaccumulation of essential elements. This treatment enhanced the uptake of potassium (K) across all organs, reflecting its fundamental role in osmotic regulation, metabolite transport, and cellular division. Notably, selenium (Se) and chlorine (Cl) exhibited pronounced accumulation in fruits, with Se showing very strong bioaccumulation ($A_x > 10$), thereby substantially increasing the nutritional and medicinal value of goji fruits as a natural selenium source. Such targeted enrichment highlights the potential of controlled fertilization strategies for biofortification of medicinal plants.

The organ-specific distribution of elements followed clear physiological patterns. Leaves showed selective accumulation of K and Se, while most other elements were either moderately retained or weakly absorbed, indicating strict regulatory mechanisms that prevent excessive

accumulation. Stem tissues displayed comparatively stable uptake behavior, functioning primarily as transport pathways rather than accumulation sites. Fruits demonstrated the highest biogeochemical activity, particularly under optimal fertilization, emphasizing their role as final sinks for biologically significant elements.

Conversely, elements such as Fe, Co, Sc, and several rare or potentially toxic metals consistently exhibited very low A_x values ($A_x < 0.01$), indicating effective physiological barriers against their accumulation in edible organs. This finding is of particular importance for ensuring the ecological safety and pharmacological quality of medicinal plant raw materials.

Overall, the study confirms that elemental uptake in goji plant (*Lycium barbarum* L.) is governed by complex, non-linear interactions between soil availability, fertilization level, and plant physiological selectivity. The results underscore the importance of optimized mineral nutrition in regulating biogeochemical activity, enhancing bioactive potential, and maintaining elemental safety in medicinal plants. These findings provide a scientifically grounded basis for developing sustainable fertilization strategies aimed at improving the quality, safety, and functional value of goji berries, which is of direct relevance to biogeochemistry, plant physiology, and molecular biology-oriented research fields.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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