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http://dx.doi.org/10.70728/jopen.be.0226.005

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Macro- and Microelement Variability in Soil-Plant Systems Across Vertical and Horizontal Zonation Gradients: A Comprehensive Literature Review

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Abstract

This article provides a comprehensive analysis, based on literature, of the distribution, bioaccumulation, and biogeochemical cycling patterns of macro- and microelements in the soil–plant system under conditions of vertical (altitudinal) and horizontal (landscape-geographical) zonality. The aim of the study is to identify and generalize the main factors influencing the dynamics of elements under different soil-climatic conditions. In the research, sources indexed in international scientific databases were selected and studied using qualitative and comparative analysis methods. The results showed that the distribution of macro- and microelements is closely related to the physical and chemical properties of the soil, climatic factors, biological characteristics of plants, and anthropogenic impacts. Vertical zonality determines the cycling of elements governed by climate, while horizontal zonality forms spatial heterogeneity through landscape and soil diversity. At the same time, the soil–plant–microbiome interaction acts as an important regulator in the assimilation and migration of elements. The research results demonstrate the necessity of evaluating macro- and microelement dynamics based on an integrative approach and have significant scientific and practical importance in the formation of sustainable agroecosystems.

Keywords: macroelements, microelements, vertical zonality, horizontal zonality, biogeochemical cycling, spatial variability, bioaccumulation, soil properties, agroecosystems.

Citation

Kenzhemirzha B., & Zokirjon I. (2026). Macro- and Microelement Variability in Soil-Plant Systems Across Vertical and Horizontal Zonation Gradients: A Comprehensive Literature Review. J Open, 02(02), 23–30.

Submitted: April, 2026
Accepted: June, 2026
Published: June, 2026

Vol. 02, **No.** 02, 2026.
10.70728/jopen.be.0226.005

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1 Introduction

Under conditions of vertical and horizontal zonality, soil types and vegetation cover are formed under the influence of climate, relief, parent material, hydrological regime, and other soil-forming factors. These processes cause significant differences in the composition, quantity, migration, and redistribution of macro- and microelements in the soil–plant system.

In particular, altitudinal zonation, slope exposure, degree of inclination, and landscape position directly affect the biogeochemical cycling of elements and their assimilation by plants. Therefore, the comprehensive analysis of macro- and microelement dynamics in the soil–plant chain in the context of vertical and horizontal zonality is considered a relevant scientific direction for modern soil science, biogeochemistry, and landscape ecology.

In recent years, the mobility, bioaccumulation, and mechanisms of transfer of macro- and microelements into plant organs in the soil–plant system have been actively studied under various ecological conditions. In particular, Bekmirzaev et al. demonstrated that the level of metal bioavailability in saline soils and their transfer to halophytic crops are directly regulated by soil salinity [1]. Yan et al., in turn, substantiated that plant elemental diversity increases ecosystem productivity and temporal stability, highlighting the ecological functional significance of elemental composition [2].

The transfer of elements from soil to plant products has also been studied under long-term field conditions. Zgavarogea et al. determined the dynamics of soil–fruit transfer of macro- and trace elements in raspberry fruits [3], while Borges et al. analyzed the bioaccumulation of macro- and microelements together with potentially toxic metalloids in the leaves and pods of Vigna unguiculata in contaminated areas [4]. In addition, Čeryová et al. assessed the genotype-dependent accumulation characteristics of essential and hazardous elements in Jerusalem artichoke tubers from the perspective of food safety [5].

Regional and ecological factors play an important role in the formation of elemental composition. Da Silva Gondim et al. evaluated the elemental composition of *Ilex paraguariensis* growing in the Brazil–Paraguay border region [6], while Batinić et al. showed that ecological factors influence mineral and phytochemical composition in the process from soil to bioactive compounds [7]. In particular, the study by Ballová et al. is significant in the context of vertical zonality, as it revealed the effect of altitude and shrub age on element accumulation in *Vaccinium myrtillus* in the alpine zone [8].

Microelements are an important factor not only in plant nutrition but also in the formation of the soil microbiome. Wang et al. emphasized that microelements in loquat orchards are an insufficiently assessed factor in determining soil microbial communities and fruit microelement composition [9]. Babeshina et al., in turn, studied the elemental composition of *Vaccinium myrtillus* shoots using the ICP-MS method and demonstrated the importance of modern instrumental analysis methods in identifying the spectrum of elements in plant organs [10].

The reviewed studies confirm the mobility, bioaccumulation, and variability of macro- and microelements in the soil–plant system depending on ecological factors. However, most of these studies were conducted within the framework of a single crop, a specific region, or a particular ecological factor. Therefore, a comprehensive literature analysis of the biogeochemical relationship between different soil types and vegetation cover under conditions of vertical and horizontal zonality remains a relevant scientific task.

Regional edaphic factors play an important role in shaping the elemental composition of plants and their bioindicator properties. Bastos et al. analyzed the elemental composition of *Xanthosoma sagittifolium* in the Amazon region and substantiated its importance not only in terms of nutritional value but also as a bioindicator sensitive to edaphic conditions [11]. At the same time, element cycling processes in forest ecosystems have also been studied in depth, and Enchilik et al. identified the main trends in the dynamics of chemical elements during the formation and decomposition of forest litter in the southern taiga region [12].

Agroecological management factors also have a significant effect on the elemental composition of plants. Rodríguez-Estrada et al. showed the effect of irrigation regimes on the elemental composition of apricot fruits [13], while Choudhary et al. emphasized that the long-distance transport of mineral elements from soil to seed under climate change conditions is important for food quality [14]. At the same time, Stojanova et al. found that the application of Fe, Zn, B, and Mg through soil and leaves improves the quality and antioxidant properties of apricot fruits [15].

Element stoichiometry in the soil–plant system and its controlling factors are also at the center of modern research. Irmscher et al. showed that plant traits, soil, and land-use intensity significantly affect element ratios in grassland ecosystems [16]. In addition, the possibilities of improving plant nutrition through microorganisms and biofertilizers are also being investigated. Galelli et al. found that Bacillus subtilis biofilm stimulates lettuce growth under heavy metal conditions [17], while Mumenthey-Zorrilla et al. showed that the nutritional value of plants can be increased through rhizobial biofortification [19].

From the perspective of sustainable agriculture, macroelement management is of particular importance. Ghanameh et al. substantiated that managing macroelement balance in palm plantations is important for sustainably increasing productivity [18], while Kizilkaya et al. showed the possibilities of improving plant nutrition and growth through biomass-derived fertilizers [20].

Recent studies confirm that the distribution, cycling, and biological assimilation of macro- and microelements in the soil–plant system are multifactorial processes. However, these works have mainly been conducted within the framework of agroecosystems, individual species, or specific management factors, and the need to analyze element dynamics under conditions of vertical and horizontal zonality based on a comprehensive and integrative approach remains.

Microelement chemistry and the mechanisms of their transfer from soil to plants are considered one of the important directions of modern soil science and plant nutrition research. Khattak et al. systematically highlighted the chemical forms of microelements in the soil environment and the processes of their assimilation by plants [21]. At the same time, the physiological role of individual microelements is also being studied in depth. Shiponi and Bernstein found that excess and deficiency of zinc (Zn) significantly affect plant metabolism, particularly the synthesis of bioactive compounds [22].

The soil–plant–microbiome interaction is of great importance in understanding element dynamics. Boutafda et al. showed that silicon modifies the rhizosphere structure and increases plant resistance to stress [23]. In addition, it has been substantiated that soil fertility and heavy metal contamination can be managed through the combination of local biochar, pumice, and arbuscular mycorrhizal fungi [24].

Within sustainable agrotechnologies, the use of biofertilizers and organic resources is considered an important factor in optimizing element cycling. Tsombou et al. showed the possibilities of improving the quality of arid soils and stimulating the initial development of plants using biofertilizers [25]. Fodor et al. assessed the long-term ecological and agrochemical effects of applying high doses of sewage sludge [26]. Musani et al. found that gyplime derived from industrial waste is effective in improving soil health and wheat productivity [27].

Biofortification with elements and their effects on plant quality are also considered relevant directions. Brodowska et al. showed that the application of selenium and sulfur significantly changes the mineral composition of wheat grain [28]. Soil properties, including differentiation by depth, also affect element distribution. Yılmaz et al. found that soil quality indicators vary significantly depending on depth in semi-arid and semi-humid regions [29]. In addition, Patial et al. analyzed the physiological and nutritional responses of plants under iron deficiency (chlorosis) conditions and substantiated that microelement deficiency has a serious effect on plant development [30].

In general, these studies show that the movement, transformation, and biological assimilation of macro- and microelements in the soil–plant system are multifactorial and interrelated processes. However, they have mainly been studied under agrotechnological or local ecological conditions, while the issue of integrative and systematic analysis of element dynamics under conditions of vertical and horizontal zonality has not yet been sufficiently covered.

Recent studies are also widely examining innovative forms of microelements and their role in plant nutrition. Alghofaili et al. found that manganese-doped nanomaterials can improve barley growth and physiological indicators under manganese deficiency conditions [31]. At the same time, the direction of optimizing plant nutrition through microbiological factors is also developing. Hashmat et al. confirmed the role of *Acinetobacter schindleri* in improving the assimilation of nutrient elements by plants and reducing oxidative stress under field conditions [32].

The internal cycling and re-assimilation of elements within plants are also considered an important scientific issue. Li et al. showed that the application of nitrogen and zinc, as well as agrotechnical measures (harvesting), alters the resorption efficiency of nutrients in plants [33]. In addition, anthropogenic factors, particularly irrigation with wastewater, significantly affect the elemental composition in the soil–plant system. Nasirpour et al. identified changes in the concentrations of heavy metals and essential elements in soil, leaves, and fruits under the influence of urban wastewater [34].

Microelements also directly affect the secondary metabolism and productivity of plants. Jariyal et al. showed that microelements modulate biomass and essential oil composition in aromatic plants grown in the Western Himalayas [35]. In addition, Arif et al.

substantiated that the synergistic effect of zinc and boron enhances plant growth, stress resistance, and tolerance to heavy metals [36].

The analyzed scientific studies show that microelements play a decisive role not only in the biogeochemical cycling within the soil–plant system, but also in plant physiology, stress resistance, and productivity. However, these works have mainly been conducted within the framework of individual elements or local ecological conditions, and the need for a comprehensive and integrative analysis of macro- and microelement dynamics in the context of vertical and horizontal zonality remains.

2 Research object and methods

The object of this study was a set of scientific sources related to the distribution, bioaccumulation, and biogeochemical cycling processes of macro- and microelements in the soil–plant system under conditions of vertical (altitudinal) and horizontal (landscape and geographical) zonality. The subject of the research was to identify the patterns of element migration, their assimilation by plants, and the variability arising under the influence of ecological factors in different soil-climatic conditions.

This study was carried out in the form of a semi-systematic literature review and was aimed at generalizing the dynamics of macro- and microelements in the soil–plant system under conditions of vertical and horizontal zonality. As the research object, a collection of scientific articles published in international scientific databases was selected.

The data were searched in Scopus, Web of Science, and Google Scholar platforms based on the following keywords: "soil–plant system", "macroelements", "microelements", "vertical zonation", "horizontal zonation", "biogeochemical cycling". The search covered the period from 2025 to 2026.

The selection criteria included peer-reviewed articles directly related to the topic and written in English; duplicate and irrelevant sources were excluded. A total of 36 articles with high scientific significance were included in the final analysis.

In data analysis, thematic and comparative analysis methods were applied, and the results were generalized according to element type, soil properties, zonality factors, and plant characteristics. As a result, the main patterns and factors influencing the dynamics of macro- and microelements were identified.

3 Results

Within the framework of this study, the comprehensive literature analysis conducted confirmed that the distribution, bioaccumulation, and biogeochemical cycling of macro- and microelements in the soil–plant system are multifactorial and complex processes. The results of the analysis were systematized across several key directions.

The analyzed Scopus-indexed studies indicate that the dynamics of macro- and microelements in the soil–plant system are shaped by the interaction of vertical and horizontal zonality, the physicochemical properties of the soil, biological characteristics of plants, and anthropogenic factors. According to the general findings, the mobility and biological assimilation of elements are directly related to pH, salinity, organic matter content, soil texture, and moisture regime. In particular, microelements are more sensitive to spatial variability compared to macroelements, and their transfer from soil to plants is regulated by redox conditions, microbiological activity, and processes occurring in the rhizosphere environment [1, 9, 21].

Under conditions of vertical zonality, with increasing altitude, climatic factors—particularly temperature, precipitation, and the rate of decomposition of organic matter—change. This leads to differences in the accumulation, leaching, and assimilation of elements within soil layers. In high mountain and alpine zones, the accumulation of certain microelements, the slowing of nutrient cycling, and the strengthening of selective uptake strategies by plants are observed [8]. Slope exposure and degree of inclination further complicate these differences through their influence on solar radiation, soil moisture, and erosion processes.

Under conditions of horizontal zonality, the distribution of elements is determined by soil type, landscape position, hydrological conditions, and land-use intensity. In arid and semi-arid regions, salinization and the relative accumulation of elements prevail, whereas in humid regions, leaching processes intensify, leading to the migration of mobile elements into deeper soil layers. The differentiation of element content by soil depth also serves as an important criterion in assessing soil fertility and plant nutrition [29]. Irrigation, fertilization, and other agrotechnical measures modify the effects of natural zonality, creating additional anthropogenic pressure in element cycling [13, 18].

The literature analysis shows that the soil–plant system is not a passive medium in element movement, but rather functions as an active biogeochemical filter. Plant species, genotype, root system, physiological state, and rhizosphere microorganisms regulate the selective uptake, translocation, and bioaccumulation of elements. Some studies have reported that plant genotype determines the level of accumulation of essential and hazardous elements, while in contaminated areas the bioaccumulation of potentially toxic elements in plant organs increases [4, 5]. Microbiological factors, particularly rhizobacteria and mycorrhizal systems, enhance the assimilation of nutrient elements and increase plant adaptability under stress conditions [23, 32].

Anthropogenic factors exert a dual influence on element dynamics. On the one hand, irrigation with wastewater, industrial waste, and the application of mineral and organic fertilizers increase the risk of excessive accumulation of heavy metals and other elements in the soil–plant system [34]. On the other hand, biofertilizers, biofortification, nano-fertilizers, and modified materials are considered promising tools for managing element cycling, reducing microelement deficiencies, and increasing plant productivity [19, 31]. However, the long-term ecological consequences of these technologies have not yet been sufficiently studied in a systematic manner.

The above results show that the dynamics of macro- and microelements in the soil-plant system are formed as a result of the complex interaction of vertical and horizontal zonality, soil properties, plant biology, and anthropogenic factors. A comprehensive analysis of these processes makes it possible to identify the general patterns of element cycling and apply them in the sustainable use of land resources.

4 Conclusion

This comprehensive literature review demonstrates that the variability and distribution of macro- and microelements in soil–plant systems are governed by a tightly coupled set of biogeochemical processes operating across vertical (altitudinal) and horizontal (landscape–geographical) zonation gradients. The synthesis of recent high-impact studies reveals three consistent patterns. First, spatial variability of element availability is primarily controlled by soil physicochemical properties (pH, salinity, organic matter, and texture), which regulate element mobility and bioavailability, thereby determining plant uptake efficiency. Second, vertical zonation imposes climate-mediated constraints (temperature, precipitation, and weathering intensity) that modify element pools and cycling rates, whereas horizontal zonation structures element distribution through soil type heterogeneity, land use, and hydrological regimes. Third, plant-mediated processes-species traits, genotypic differences, and rhizosphere interactions-act as key regulators of selective uptake, translocation, and bioaccumulation, often amplified by microbiome activity and management interventions.

Importantly, the review identifies a robust link between elemental diversity and ecosystem functioning, indicating that balanced macro- and microelement composition enhances productivity, resilience, and temporal stability of ecosystems. At the same time, anthropogenic drivers-including irrigation practices, fertilization regimes, wastewater use, and emerging nano- and bio-based amendments-significantly alter element cycling pathways, sometimes improving nutrient use efficiency but also increasing risks of imbalance and contamination.

Despite substantial progress, a critical research gap persists: existing studies remain fragmented across scales, species, and environmental contexts, lacking an integrated, cross-scale framework that simultaneously captures vertical and horizontal zonation effects on element dynamics. There is a notable absence of comparative analyses linking edaphic variability, plant functional traits, and microbiome interactions within a unified biogeochemical model.

From a practical perspective, these findings underscore the necessity of site-specific nutrient management strategies that account for zonation-driven heterogeneity in soil–plant systems. Incorporating spatial variability into fertilization planning, biofortification programs, and sustainable land-use practices can substantially improve nutrient efficiency and ecological stability.

Future research should prioritize: (i) multi-scale monitoring of element fluxes across contrasting zonation gradients; (ii) integration of soil-plant-microbiome interactions using systems-based approaches; (iii) assessment of climate change impacts on element mobility and cycling; and (iv) development of predictive models linking biogeochemical variability with ecosystem services. Advancing these directions will enable a more precise understanding of element dynamics and support the transition toward resilient and sustainable agroecosystems.

Author Contributions: All authors contributed equally to the conceptualization, literature review, methodology, data interpretation, writing of the original draft, and review and editing of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding and was funded by the authors.

Institutional Review Board Statement: This research did not include any experiments involving human participants or animals, so Institutional Review Board (IRB) approval was not necessary.

Informed Consent Statement: This study did not involve human subjects; therefore, informed consent was not required.

Data Availability Statement: All data is shared in this manuscript.

Acknowledgments: The authors sincerely thank the editorial team and anonymous reviewers for their valuable comments and suggestions, which helped improve the quality of this manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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