Does Nutritional Importance Determine Element Uptake by Plants? Comparative Bioaccumulation and Translocation of S, Mo, and Li in Five Vegetable Crops

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Soil nutrient content is crucial for plant development. While macronutrients are essential, micronutrients are needed in lower concentrations. Non-essential elements exist, but their uptake and accumulation in plant organs remain poorly studied. Therefore, this study analyzed the concentrations of sulfur (S, a macronutrient), molybdenum (Mo, a micronutrient), and lithium (Li, a non-essential element) in the roots, stems, leaves, and fruits of tomato, cucumber, pepper, maize, and eggplant. Additionally, soil element concentrations were determined, and bioconcentration factor (BCF) and translocation factor (TF) values were calculated. The key findings were as follows: the highest S concentration was detected in tomato leaves (8620 ppm), while the highest Mo and Li concentrations were found in maize roots (18440 ppb and 17300 ppb, respectively). The highest TF values were recorded in tomato leaves for all three elements: S (8.39), Mo (1.20), and Li (0.75). The results demonstrate that S is intensively taken up from the soil and accumulates significantly in crop organs. In contrast, while Mo and Li are present in high concentrations in the soil, their accumulation in crop organs remains much more limited. Overall, these results were consistent with a hypothesis that crops take up soil elements primarily in the amounts they need as building blocks.

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INTRODUCTION

Plant development is primarily shaped by climatic (Cetin *et al*. 2018; Sevik *et al.* 2021) and edaphic (Shults *et al.* 2020; Cantürk *et al.* 2024) factors; in particular, nutrients in the soil play a vital function in plant development (Kravkaz Kuscu *et al.* 2018). For agricultural plants, H, C, O, P, N, K, Mg, Ca, and S are classified as macronutrients (Erdem *et al.* 2024), while Zn, Fe, Mn, B, Mo, Ni, Cu, and Cl are classified as micronutrients (Wedajo 2025). The presence of these elements in the soil directly affects plant

development. Since plants use these elements intensively, their concentration in the soil decreases. To replenish depleted nutrients, agricultural production uses fertilizers. Globally, P, K, Mg, and S are among the most commonly used fertilizers. These elements are absorbed by the plant and used in various organs. In contrast, elements such as Al, As, Ba, Be, Cd, Pb, and Li are non-essential for plant development (Baloch 2021).

In some plants, these elements accumulate in organs that are then consumed by humans and animals as food, whereas in others they are stored in other plant organs. Since these organs are not used in human and animal nutrition, they do not enter the food chain. Some of these elements are also essential nutrients for the human body and are found at different levels in plants that are used as human food (Demirci *et al.* 2026; Sevik 2026).

Three elements (S, Mo, and Li) were specifically selected for this study because of their distinct functional roles in plant nutrition and to compare their uptake levels. Sulfur (S) is a fundamental macronutrient in plant growth and development as a structural component of protein bonds, some amino acids, vitamins, cofactors, and chlorophyll (Narayan *et al.* 2022). This study aimed to investigate the bioaccumulation and translocation of macronutrients, micronutrients, and non-essential elements in plant organs. Therefore, it was deemed appropriate to select one element from each nutrient group: S from the macronutrient group, Mo from the micronutrient group, and Li from the non-essential nutrient group for plant development. Sulfur also plays a direct or indirect role in stress management (such as salinity, drought, and heavy metal exposure) in plants by increasing photosynthetic rates and plant and grain yields (Jia *et al.* 2024).

In contrast, molybdenum (Mo) is a micronutrient. It acts as a molybdenum cofactor in the active site of molybdoenzymes (such as nitrate reductase, xanthine dehydrogenase, sulfite oxidase, and aldehyde oxidase) in plants (Huang *et al.* 2021). These enzymes are involved in many vital biological processes such as nitrate assimilation, phytohormone biosynthesis, and sulfite detoxification. By synthesizing chlorophyll, Mo also contributes to photosynthesis (Oliveira *et al.* 2022).

Lithium (Li), in contrast, is thought to be an element that plants do not require. Although Li has been reported to have beneficial effects at low concentrations, such as promoting growth in various crops (maize, sunflower, and lettuce), it exhibits signs of toxicity at high concentrations. In terms of toxicity, Li has a similar effect to sodium (Na^+) (Garcia-Daga *et al.* 2025). However, studies indicate that Li utilizes different transport pathways than sodium and possesses unique molecular effects that directly interact with nucleic acids [*via* magnesium (Mg^{2+}) binding sites] (Garcia-Daga *et al.* 2025). Comparing these three elements (S, Mo, and Li) within the same study and in the same plant species offers a unique opportunity to test the decisive role of plants in the uptake of elements from the soil.

To establish a robust framework for comparing the elements S, Mo, and Li in the plants studied, the physiological requirements of these elements, their basic chemical forms in soil solutions, their dominant transport mechanisms, and their specific physiological functions are outlined in Table 1.

Table 1. Physiological Requirements, Chemical Specialization, Transport Pathways, and Empirical Roles of the Elements Used in the Study

Element	Nutritional Classification	Dominant Soil Chemical Speciation	Primary Plant Transport Pathway	Essential Physiological Function in Target Crops
Sulfur (S)	Macronutrient	Sulfate anion ($SO4^{2-}$) in soil solution	SULTR family active $H^+/SO4^{2-}$ symporters into root symplast	Constituent of Cys/Met, glutathione, ferredoxin, and proteins
Molybdenum (Mo)	Micronutrient	Molybdate anion ($MoO4^{2-}$) at pH > 5.5	MOT1 family high-affinity molybdate transporters	Cofactor (Moco) for nitrate reductase and sulfite oxidase
Lithium (Li)	Non-essential / Beneficial at trace levels	Monovalent cation (Li^+); highly soluble & weakly bound	Passive apoplastic flow & non-selective K^+/Na^+ channels	No essential biological role; toxic at high concentrations *via* Mg^{2+}/Na^+ competition

Table 1 details the physiological requirements (macro, micro, non-essential/ beneficial), dominant soil chemical speciation (SO_4^{2-}, MoO_4^{2-}, Li^+), primary plant transport pathways (SULTR active transporters, MOT1 transporters, K^+/Na^+ channels and apoplastic bypass) and cellular functions of the elements studied, S, Mo, and Li, in the target species (Schwarz and Mendel 2006; Huang *et al*. 2022; Narayan *et al.* 2023; Sarkar and Gogoi 2025; Garcia-Daga *et al.* 2025; Chen *et al.* 2025).

In this context, determining the levels at which nutrient elements are taken up from the soil by plants, and the levels of accumulation in organs, is vital, both for ensuring the healthy development of plants and for the effective use of plants in human nutrition. Although numerous studies have been conducted on this topic to date, the number of studies comparing the uptake and accumulation of different nutrient groups (macronutrients, micronutrients, and non-essential elements) within the same crops is quite limited. When the literature is reviewed, it is noticed that the research generally focuses on the accumulation of elements (both essential nutrients for plants and heavy metals that can be harmful to plants) in plant organs (Koç *et al*. 2026a; Öztürk Pulatoğlu *et al*. 2026) or on bioaccumulation or translocation related to their uptake rates from the soil (Erdem *et al*. 2026). In these studies, the accumulation of elements in plant organs is generally associated with their presence in the environment (Erdem *et al*. 2023; Kulac *et al*. 2025). However, even if some elements are present in the environment, their uptake by the plant and accumulation in its organs may vary depending on the plant's need for that element as a building block. However, the number of comprehensive studies on this subject is quite limited. Therefore, this study investigated the uptake and accumulation of macronutrient S, micronutrient Mo, and non-essential element Li from the soil in some of the most consumed vegetable crops worldwide. The main objective of this study is to determine whether the rates at which plants take up and store nutrients vary with the elements' necessity as building blocks for the plant. To this end, the main hypothesis of the study is that element uptake, bioaccumulation, and translocation of elements from the soil in plants vary depending on the plant's need for that element. Therefore, the accumulation and translocation values of the elements studied in plant organs are ranked as follows: S (macronutrient element) > Mo (micronutrient element) > Li (non-essential element).

EXPERIMENTAL

Material

The study was conducted in a field with clay loam soil texture in Düzce province, Türkiye (40°51′00″ N, 31°06′40″ E, and 135 m a.s.l.), close to an industrial area. Studies conducted in the study area determined that soil pH was 6.65 ± 0.90 in agricultural soils and 7.53 ± 1.24 in non-agricultural soils (Bozkurt and Sert 2026). The study area is a region where industrial facilities and agricultural areas are intertwined; therefore, due to the influence of factors such as traffic, urban areas, and industry, heavy metal pollution is at high levels, especially in soils and plants. Consequently, the concentrations of many non-essential elements in plants are also high in soil (Erdem *et al*. 2026; Sevik 2026). The purpose of this study was to examine the accumulation and translocation of the elements in question within the plant body despite their high levels in the soil. For this reason, this region was chosen as the study area. A wide variety of agricultural products are intensively cultivated in the region where the study was conducted. Five vegetable crop varieties were grown and evaluated in the study:

- Maize; *Zea mays* L. var. indentata Sturt.
- Eggplant; *Solanum melongena* L. 'Kemer'
- Pepper; *Capsicum annuum* L. 'Zıpkın F1'
- Cucumber; *Cucumis sativus* L. 'Beith Alpha'
- Tomato; *Solanum lycopersicum* L. 'Marmande'

Seeds were supplied by the Provincial Directorate of Agriculture and sown in small plastic bags. Seedlings were transplanted in mid-May into experimental plots situated on farmland within the industrial zone. The crops were established in separate experimental plots, with approximately 2.5 ± 0.5 m spacing between plots. Within each plot, plants were spaced 50 ± 5 cm apart. To minimize the influence of edge effects and root overlap from adjacent plants, only plants from the inner rows of each plot were selected for sampling. Routine watering and maintenance were performed, but no hormones, pesticides, or fertilizers were used. Harvesting took place in late August, when the plants had reached maturity. For each harvested plant, a soil sample was taken from the immediate root zone (root soil) after the roots of the target plant had been carefully separated from the surrounding soil, ensuring that each plant was directly paired with the soil in which it had actually grown. While the plot spacing and inner-row sampling were designed to reduce root interaction between neighboring plants, some degree of overlap under field conditions cannot be entirely excluded.

Methods

The experimental workflow in this study, including the preparation and analysis of plant and soil samples, is summarized in Fig. 1.

The crop roots were initially detached from the soil and thoroughly washed with tap water to remove any soil particles, then rinsed three times with deionized water. The crops were split into fruits, leaves, stems, and roots. The samples were positioned in Petri dishes and left undisturbed for 15 days in a well-ventilated room, shielded from direct sunlight, after which they were dried in an oven at 45 ± 2 °C for another two weeks.

Following the oven-drying process, the samples were ground into a powder with a stainless-steel blender, and 0.5 g of the powdered sample was transferred into microwave-compatible Teflon tubes (Ethos One, Milestone GmbH, Bargteheide, Germany). Then, 10 mL of 65% HNO_3 was added, and digestion was carried out in a microwave at 180 °C and 280 PSI for 20 min. After the cooling process, the digests were diluted to a final volume of 50 mL using deionized water and then filtered through Whatman No. 42 filter paper.

Soil samples were separated from the roots, air-dried at ambient temperature (20 ± 2 °C) for 7 days, and sifted through a 2-mm stainless steel sieve to remove stones and larger particles. The soils were subsequently ground in an agate mortar until they passed through a 0.15-mm sieve. For the digestion process, 0.5 g of the homogenized soil was measured into Teflon digestion vessels and treated with 10 mL of aqua regia ($HCl:HNO_3$, 3:1 by volume). The digestion was performed in the same microwave system at 280 PSI and 200 ± 5 °C for 30 minutes. After cooling, the digests were filtered through a filter paper (Whatman No. 42) and then diluted to 50 mL with deionized water.

The concentrations of S, Mo, and Li were measured using Inductively Coupled Plasma - Optical Emission Spectroscopy (GBC Integra XL-SDS-270 ICP-OES) from GBC Scientific Equipment Pty Ltd., Melbourne, Australia. Once dilution factors were applied, the final values were presented on a dry-weight (dw) basis. S was expressed in ppm, whereas Mo and Li were expressed in ppb for both plant and soil samples, so that the units used in the BCF calculations remained consistent. This procedure has been widely used in recent years for the elemental analysis of plant samples (Sevik *et al.* 2024; Yasar Ismail *et al.* 2025; Ismail *et al.* 2026).

Quality assurance and quality control (QA/QC) measures were utilized throughout the entire analytical procedure. Blank samples, created without any soil or plant components, were processed through all digestion and analysis stages to identify potential contamination. Calibration standards were reanalyzed following every 20 samples, and recalibration was conducted whenever deviations exceeded 5%. Calibration curves (using five points) were prepared from a certified 1000 mg/L stock solution (Merck, Germany), and the correlation coefficient (R^2) of all curves was above 0.997. Every sample was analyzed in triplicate.

A total of 100 biological specimens (5 crops × 5 plants × 4 organs) and 25 soil samples (5 crops × 5 plants) were used for S, Mo, and Li element analysis. Each biological sample was subjected to three technical replicates (300 plant and 75 soil analyses in total), and the average of these three readings was used as the statistical replicate for data analysis. The obtained data were analyzed using SPSS (version 21.0; IBM Corp., Armonk, NY, USA). Normality was first confirmed using the Shapiro-Wilk test, and then analysis of variance (ANOVA) was used to determine the F-value and error rate. When significant effects were detected ($\alpha = 0.05$), Duncan's test was used for post hoc pairwise comparisons.

Bioconcentration factors (BCF) and translocation factors (TF) were also computed in this analysis. Thus, this approach aimed to determine which species and organs accumulate the highest levels of S, Mo, and Li. The calculations were conducted using the following formulas (Sevik *et al.* 2026):

$$BCF = (\text{Element concentration in plant organ}) / (\text{Element concentration in soil}) \quad (1)$$

$$TF = (\text{BCF of the organ}) / (\text{BCF of the root soil}) \quad (2)$$

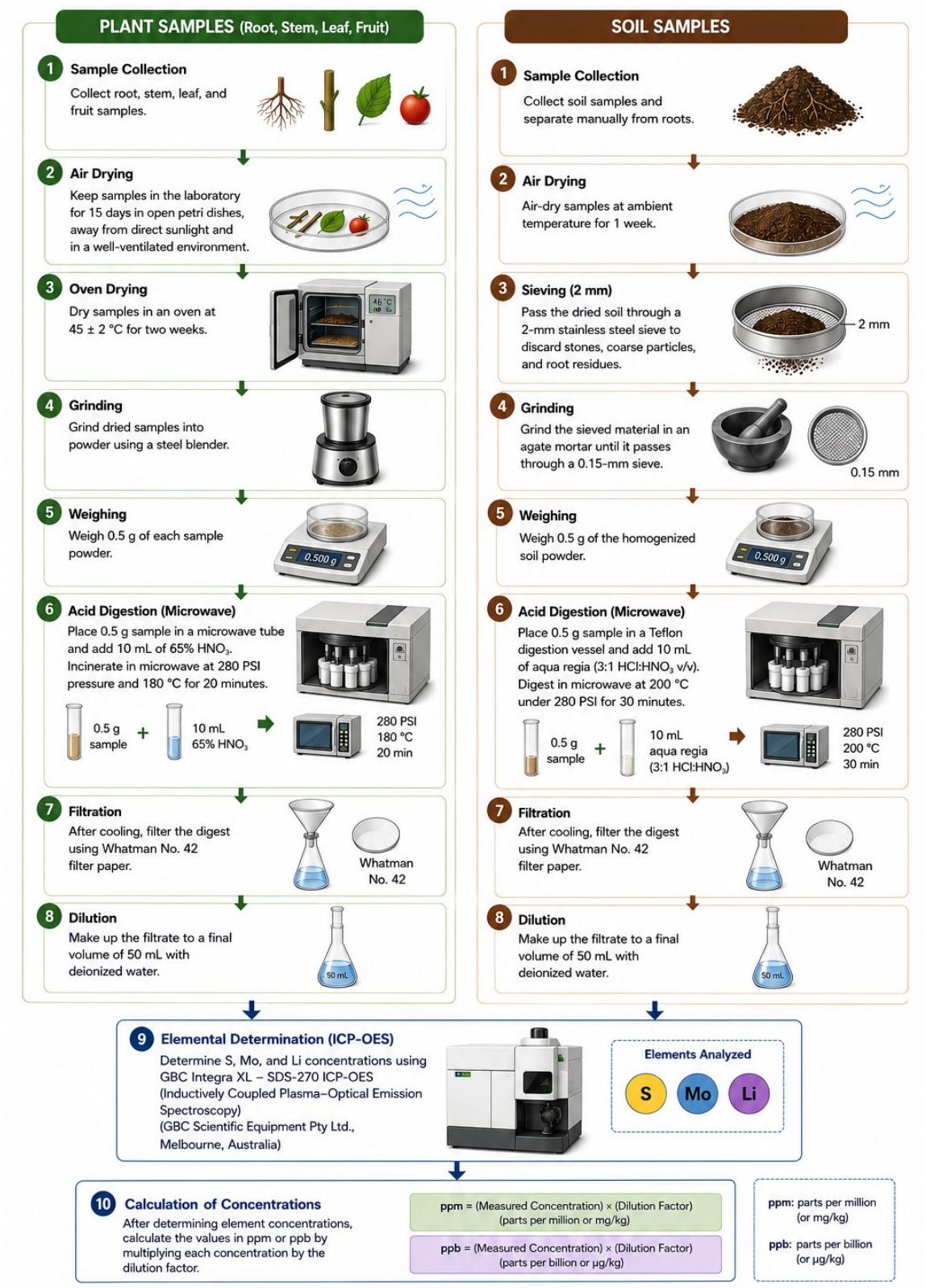


Fig. 1. Flowchart of plant and soil sample preparation, microwave digestion, and ICP-OES analysis for the determination of sulfur (S), molybdenum (Mo), and lithium (Li) concentrations

RESULTS AND DISCUSSION

Changes in Sulfur Concentration in Organs Across Crops

The average variation in S concentration in soil, crops, and crop organs, along with ANOVA and Duncan test results, is presented in Table 2. The variation was found to be statistically significant in all crops across each organ and in all organs across each crop ($P < 0.001$). Another noteworthy point in the table is that the leaf concentrations of all species were in the highest concentration group based on Duncan's test. The lowest values were obtained in the roots of cucumber and peppers, tomato fruit, and maize and eggplant stems. The highest values were observed in the leaves of all species.

In all organs, the values obtained in maize were in the group with the lowest concentration based on Duncan test results. The highest concentrations were observed in the stems of peppers, in the fruit of cucumbers, in the leaves of tomatoes, and in the roots of eggplants. According to the average values, the organs formed two groups: the stem, fruit, and root formed the group with the lowest concentration values, while the leaves formed the second-highest concentration group. Two groups were formed within the crops: maize and cucumber were in the low-concentration group, and tomatoes were in the high-concentration group; peppers and eggplants were in both groups. In the soils, S concentration was ranked as tomato < maize < eggplant < cucumber < pepper.

Table 2. Sulfur Concentration (ppm) in Organs Across Crops

Crops	Organ						
	Root	Stem	Leaf	Fruit	F value	Mean	Soil
Maize	669.41 ^{aB}	448.70 ^{aA}	1273.50 ^{aD}	685.76 ^{aC}	41100.7***	769.34 ^{a}	614.16 ^{b}
Eggplant	1648.66 ^{eC}	1195.06 ^{bA}	2540.90 ^{cD}	1259.46 ^{cB}	29373.7***	1661.02 ^{ab}	625.33 ^{c}
Pepper	1448.40 ^{dA}	2716.90 ^{dC}	3482.96 ^{dD}	1542.70 ^{aB}	59064.6***	2297.74 ^{ab}	934.20 ^{e}
Cucumber	681.63 ^{bA}	1200.36 ^{bB}	2120.23 ^{bD}	1358.43 ^{dC}	95222.4***	1340.16 ^{a}	678.25 ^{d}
Tomato	1026.63 ^{cA}	1817.30 ^{cC}	8619.69 ^{eD}	846.30 ^{bA}	47592.5***	3077.48 ^{b}	590.83 ^{a}
F value	138550.4***	72316.4***	34684.7***	24059.2***		3.712*	26154.7***
Mean	1201.33 ^{A}	1475.66 ^{A}	3607.46 ^{B}	1138.53 ^{A}	9.4***		

Mean concentration values with different letters differ statistically (Duncan's test, $P < 0.05$). Lowercase letters evaluate the crops in a vertical manner for each organ, whereas capital letters assess the organs horizontally for each individual crop. *, **, *** indicate significance at $P < 0.05$, 0.01, and 0.001, respectively. ns, not significant.

The change of BCF for S across crops and organs is shown in Table 3. According to the calculations, BCF values for the element S are quite high. The lowest value was obtained in maize stems (0.731), while all other values are above 1. The uppermost BCF values were calculated in tomato leaves (14.589), eggplant leaves (4.063), and pepper leaves (3.728). The very high values obtained in leaves are particularly noteworthy. Based on averages, the lowermost BCF values were computed for roots (1.604) as an organ and for maize (1.253) as a crop, whereas the uppermost values were computed for the leaf (5.516) and for tomato (5.209), with respect to organs and crops, respectively.

Table 3. Bioconcentration Factor Values for Sulfur

Crops	Organ				Mean
	Root	Stem	Leaf	Fruit	
Maize	1.090	0.731	2.074	1.117	1.253
Eggplant	2.636	1.911	4.063	2.014	2.656
Pepper	1.550	2.908	3.728	1.651	2.459
Cucumber	1.005	1.770	3.126	2.003	1.976
Tomato	1.738	3.076	14.589	1.432	5.209
Mean	1.604	2.079	5.516	1.643	2.711

The TF values computed for S are presented in Table 4. The observed TF values for S are quite high in peppers and cucumbers, with the TF value exceeding 1.0 in all organs in these species. The most unusual value was calculated in tomato leaves (8.394). In addition, the highest TF values were observed in cucumber leaves (3.110) and pepper leaves (2.405). The lowest values were recorded in maize stems (0.671) and eggplant stems (0.725).

Table 4. Translocation Factor Values for Sulfur

Crops	Organ			Mean
	Stem	Leaf	Fruit	
Maize	0.671	1.903	1.025	1.200
Eggplant	0.725	1.541	0.764	1.010
Pepper	1.876	2.405	1.065	1.782
Cucumber	1.761	3.110	1.993	2.288
Tomato	1.770	8.394	0.824	3.663
Mean	1.361	3.471	1.134	1.989

Changes in Molybdenum Concentration in Organs Across Crops

The average variation in Mo concentration in soil, crops, and crop organs, along with ANOVA and Duncan test results, is illustrated in Table 5. Similar to S, the variation in the element Mo was statistically significant in all crops across each organ and in all organs across each crop ($P < 0.001$).

The highest Mo concentration was observed in the stem and leaf of tomato, in the fruit of cucumber, and in the roots of maize. The lowest concentrations were observed in the cucumber stem, the pepper leaves, and the tomato fruit and roots. In terms of organs, across all crops except tomato, the stem values were in the first group based on Duncan's test. In the tomato, the minimum concentration was obtained in the fruit. In contrast, in all crops except tomato, the values obtained in the roots were in the highest group based on Duncan's test. In the tomato, the highest Mo concentration was found in the leaves. According to the average concentrations, each organ formed a separate group, and the Mo concentration in the organs was ranked as stem < fruit < leaf < root. Similarly, in soils, each species formed a separate group according to Duncan test results, and Mo concentration was ranked as: pepper < eggplant < tomato < maize < cucumber. There were no statistically significant differences between crops based on average values ($P > 0.05$).

Table 5. Molybdenum Concentration (ppb) in Organs Across Crops

Crops	Organ						
	Root	Stem	Leaf	Fruit	F value	Mean	Soil
Maize	18440.41^{eD}	3280.66^{dA}	3991.36^{cC}	3645.53^{cB}	34480.751***	7339.49	17935.66^{d}
Eggplant	5413.60^{bD}	2606.03^{bA}	3689.26^{bB}	4064.53^{dC}	6466.270***	3943.35	16440.25^{b}
Pepper	6166.29^{dD}	2847.20^{cA}	3515.26^{aC}	3386.76^{bB}	4166.728***	3978.88	7196.59^{a}
Cucumber	5535.56^{cD}	2354.86^{aA}	5251.00^{dC}	4643.06^{eB}	8219.464***	4446.12	18305.16^{e}
Tomato	4580.03^{aC}	4496.30^{eB}	5517.59^{eD}	3202.73^{aA}	2210.645***	4449.16	16603.25^{c}
F value	33859.7***	1084.0***	4152.7***	638.9***		2.419ns	178.164***
Mean	5423.87^{D}	3117.01^{A}	4392.90^{C}	3788.52^{B}	25.324		

Mean concentration values with different letters differ statistically (Duncan's test, $P < 0.05$). Lowercase letters evaluate the crops in a vertical manner for each organ, whereas capital letters assess the organs horizontally for each individual crop. *, **, *** indicate significance at $P < 0.05$, 0.01, and 0.001, respectively. ns, not significant.

The variation of BCF for Mo by crops and organs is given in Table 6. The values ranged from 0.129 (cucumber stem) to 1.028 (maize root). Based on calculations, the lowest values were acquired in tomato fruit and in the stems of other crops. The highest values were obtained in the leaves of tomatoes and in the roots of other species.

Table 6. Bioconcentration Factor Values for Molybdenum

Crops	Organ				Mean
	Root	Stem	Leaf	Fruit	
Maize	1.028	0.183	0.223	0.203	0.409
Eggplant	0.329	0.159	0.224	0.247	0.240
Pepper	0.857	0.396	0.488	0.471	0.553
Cucumber	0.302	0.129	0.287	0.254	0.243
Tomato	0.276	0.271	0.332	0.193	0.268
Mean	0.558	0.228	0.311	0.274	0.343

The TF values for Mo are summarized in Table 7. It is apparent that the TF for Mo was quite low in maize. In maize, TF values ranged from 0.178 (stem) to 0.217 (leaf), with an average of 0.197. The highest value was observed in tomato leaves at 1.203, the only TF value exceeding 1. In addition, the uppermost values were obtained in tomato stems (0.982), cucumber leaves (0.950), and cucumber fruits (0.841). Based on averages, TF values are ranked as stem < fruit < leaf in organs, while in species they are ranked as maize < pepper < eggplant < cucumber < tomato.

Table 7. Translocation Factor Values for Molybdenum

Crops	Organ			Mean
	Stem	Leaf	Fruit	
Maize	0.178	0.217	0.197	0.197
Eggplant	0.483	0.681	0.751	0.638
Pepper	0.462	0.569	0.550	0.527
Cucumber	0.427	0.950	0.841	0.739
Tomato	0.982	1.203	0.699	0.961
Mean	0.506	0.724	0.608	0.612

Changes in Lithium Concentration in Organs Across Crops

The average variation in Li concentration in soil, crops, and crop organs, along with ANOVA and Duncan test results, is illustrated in Table 8. The variation in the element Li was statistically significant in all crops across each organ and in all organs across each vegetable crop ($P < 0.001$). The lowest values were acquired in pepper stem (1910 ppb), maize leaf (1480 ppb), tomato (1790 ppb), eggplant (1910 ppb), and cucumber fruit (1520 ppb). The highest concentrations were again observed in the roots across all crops. By vegetable crops, the lowest concentrations were obtained in cucumber in the stem, fruit, and roots, and in maize in the leaves. The highest concentrations were received in tomato stems, pepper fruit, eggplant leaves, and maize roots. Notably, the calculated Li concentration in maize roots was much higher than in other organs. While there were no statistically significant differences between species based on average values, the lowest values at the organ level were obtained in stems and fruits, and the maximum values in roots. In soils, the lowest concentrations were found in peppers and eggplants, and the highest in other species (all other species were in the lowest group based on the Duncan test).

Table 8. Lithium Concentration (ppb) in Organs Across Crops

Crops	Organ						
	Root	Stem	Leaf	Fruit	F value	Mean	Soil
Maize	17319.41^{eD}	1894.30^{bC}	1479.33^{aA}	1729.70^{bB}	32486.220^{***}	5605.68	17691.33^{c}
Eggplant	5877.90^{dD}	2296.63^{cB}	4141.43^{dC}	1912.50^{cA}	4445.717^{***}	3557.11	16228.08^{b}
Pepper	3698.96^{bC}	1913.06^{bA}	2402.90^{bB}	1931.23^{cA}	422.709^{***}	2486.54	5097.06^{a}
Cucumber	3459.50^{aD}	1563.83^{aA}	2314.60^{bC}	1517.80^{aA}	322.120^{***}	2213.93	17427.50^{c}
Tomato	4132.10^{cD}	2311.66^{cB}	3094.33^{cC}	1789.16^{bA}	760.465^{***}	2831.81	17527.58^{c}
F value	27304.087^{***}	50.742^{***}	369.559^{***}	41.148^{***}		2.036^{ns}	1505.921^{***}
Mean	4292.11^{C}	1995.90^{A}	2686.52^{B}	1776.08^{A}	36.390^{***}		

Mean concentration values with different letters differ statistically (Duncan's test, $P < 0.05$). Lowercase letters evaluate the crops in a vertical manner for each organ, whereas capital letters assess the organs horizontally for each individual crop. *, **, *** indicate significance at $P < 0.05$, 0.01, and 0.001, respectively. ns, not significant.

The variation of BCF for Li by crops and organs is illustrated in Table 9. BCF for Li ranged between 0.084 (maize leaf) and 0.979 (maize root). The lowest values were obtained in the stem of pepper, the leaf of maize, and the fruit of other crops. The average BCF value rank was cucumber < tomato < eggplant < maize < pepper.

Table 9. Bioconcentration Factor Values for Lithium

Crops	Organ				Mean
	Root	Stem	Leaf	Fruit	
Maize	0.979	0.107	0.084	0.098	0.317
Eggplant	0.362	0.142	0.255	0.118	0.219
Pepper	0.726	0.375	0.471	0.379	0.488
Cucumber	0.199	0.090	0.133	0.087	0.127
Tomato	0.236	0.132	0.177	0.102	0.162
Mean	0.500	0.169	0.224	0.157	0.263

As shown in Table 10, the Li TF values ranged from 0.086 (maize leaves) to 0.750 (tomato leaves). The lowest values were consistently found in maize, with TF values ranging between 0.086 and 0.109. Notably, no organ exhibited a TF value exceeding 1.0. The highest TF values were recorded in the leaves of tomato (0.750), eggplant (0.704), and cucumber (0.668).

Table 10. Translocation Factor Values for Lithium

Crops	Organ			Mean
	Stem	Leaf	Fruit	
Maize	0.109	0.086	0.100	0.098
Eggplant	0.392	0.704	0.326	0.474
Pepper	0.517	0.649	0.522	0.563
Cucumber	0.452	0.668	0.437	0.519
Tomato	0.559	0.750	0.432	0.580
Mean	0.406	0.571	0.363	0.447

The S concentration ranged from 449 ppm (maize stem) to 8620 ppm (tomato leaves). The approximately 19-fold difference between these two values is noteworthy. Based on average values, S concentrations in leaves were significantly higher than in other organs. In fruits, S concentration ranged from 686 ppm (maize) to 1540 ppm (pepper). The S concentration was 590 ppm in tomato-growing soils and 935 ppm in pepper-growing soils. It was also found that Mo concentration ranged from 2360 ppb (cucumber stem) to 18400 ppb (maize root). The variation of Mo at the organ level was more limited compared to S. Soil Mo concentrations ranged from 16400 ppb (eggplant) to 18300 ppb (cucumber) for species other than pepper (7200 ppb). The variation in Mo concentration in the soils of vegetable crops other than peppers was limited. Li concentration varied similarly to Mo concentration. Unlike the values in the organs, the element concentrations in the soil varied within a narrow range. This small variation indicates that the uptake and accumulation of S by crops from soil were not directly related to soil S concentration. Similar results have been obtained in different studies for different elements, showing that both plant species (Guney *et al.* 2023; Koç *et al.* 2024; Dışbudak *et al.* 2026) and organs (Isinkaralar *et al.* 2022a; Sevik *et al.* 2024; Ozturk Pulatoglu *et al.* 2025) have been found to be determining factors in element accumulation.

The main objective of this study was to compare the uptake and accumulation of three different elements classified as macronutrients, micronutrients, and non-essential nutrients by crops. The results showed that translocation factor (TF) values for S were quite high in cucumbers and peppers, exceeding 1.0 in all organs of these species. The TF value was calculated as 8.394 in tomato leaves. The highest values were acquired in the leaves of cucumber (3.110) and pepper (2.405). The average TF value was above 1.0 in all species and organs. For Mo, the TF value exceeded 1.0 only in tomato leaves (1.203), whereas it remained below 1.0 in all other organs. For Li, the TF value did not exceed 1.0 in any organ of any species. The mean TF values were calculated as 1.989 for S, 0.612 for Mo, and 0.447 for Li. The TF value serves as a critical indicator of a species' capacity to accumulate elements. Generally, higher TF values correspond to greater accumulation potential in the relevant organ (Wang *et al.* 2019). Some researchers suggest that species with a TF value greater than 1.0 can be classified as strong accumulators of the elements in question (Takarina and Pin 2017). However, it is generally considered that a TF value greater than 1 alone is not sufficient to prove that a plant is a strong accumulator. This is because studies

have supported a positive correlation between many elements' concentrations in the soil and their concentrations within the plant's organs (Gómez-Oquendo *et al.* 2026).

According to this study, S accumulation in crop organs was considerably higher, and Mo concentrations and TF values in plant organs are also higher than those of Li. However, the Mo and Li concentrations in the soil were similar. These patterns indicate that crops intensively absorb macronutrients, such as S, from the soil and accumulate them in their organs. In contrast, the intensity of uptake is lower for micronutrients, such as Mo, and much lower for non-essential elements, such as Li. Indeed, similar results have been obtained in studies on the subject. Ergül (2025) determined that the TF values for S in plants grown in the same environment could reach 3.75 in the bark and 2.80 in the leaves of *Pinus nigra*, and 2.19 in the bark and 2.74 in the leaves of *Pinus sylvestris*. It was determined that the TF values for macronutrients were very high, reaching 4.32 for P, 11.1 for K, and 5.79 for Ca. However, within the same species, the TF values for micronutrients were computed as averages of 0.639 for Mo in wood, 0.902 for bark, and 0.733 for leaves. Similarly, the average TF values for Li were below 1 in all organs (Ergül 2025). In a study of crops, TF values in organs ranged from 0.389 to 0.598 for Sb and from 0.429 to 0.638 for Se (Sevik 2026). However, in another study, the average TF values for Cd in fruits and leaves were 0.635 and 0.894, respectively, and for Cr, 0.690 and 1.149, respectively (Demirci *et al.* 2026). In another study on vegetable crops, it was determined that the average TF values in organs could reach 0.243 for Ti and 0.723 for Au, while TF values could reach 3.59 for P, 4.63 for K, and 8.29 for S (Demirci 2026). Ogori *et al.* (2023) reported TF values of 4.00 for Ni and 5.00 for Zn across distinct crop organs.

However, the uptake and accumulation of elements by plants can differ significantly across vegetable crops and organs, and many other factors are also involved in this process. Studies indicate that environmental element concentrations are among the determining factors in the accumulation of certain elements, particularly heavy metals, in plant organs (Ghoma *et al.* 2023; Koc *et al.* 2024; Ergül and Kravkaz Kuşçu 2025; Gültekin *et al.* 2025). This is because roots are not the only pathway for elements entering the plant. Elements can also enter the plant through stomata in the leaves or directly through the stem sections. In this case, the entry of atmospheric elements into the plant and their accumulation in various organs is expected (Koc *et al.* 2025; Kulac *et al.* 2025).

In addition to these, plant phenotypic characteristics, including the potential to absorb and accumulate elements, are shaped by the interaction between genetic structure and environmental conditions (Key *et al.* 2023; Özel *et al.* 2025; Koç *et al.* 2026b). Studies have shown that the accumulation of different elements in organs varies widely across species and organs within plants grown in a similar environment (Du *et al.* 2025; Isinkaralar *et al.* 2025; Sevik *et al.* 2025). Similarly, in vegetable crops, the concentration of elements in different organs can differ depending on various aspects such as the structure of the element, the relationship between the plant and the element, and even weather conditions (*e.g.*, air humidity) (Isinkaralar *et al.* 2022b; Key *et al.* 2022). Research demonstrates have element accumulation in plants is shaped by the combined effect of numerous environmental factors. Factors such as pH, oxidation-reduction potential (ORP), moisture content, and electrical conductivity are among these.

Furthermore, it has been determined that these factors are spatially heterogeneous and interact with each other. In this context, element uptake from the soil is regulated not only by solubility parameters but also, in particular, by the surface properties and distribution coefficients of reactive mineral phases such as Fe, Mn, and Al oxides. These oxides, owing to their high specific surface areas and variable surface charges, can

immobilize elements by binding them through microscopic mechanisms such as adsorption, complexation, and surface precipitation. However, changes in environmental conditions (such as a decrease in pH or reduced redox conditions) can weaken these bonds, releasing the elements back into the soluble phase. Consequently, these microscopic processes directly affect soil solution element concentrations, thereby determining their uptake by crops through the root system (Wu *et al.* 2026a). In this process, pH, mineral phase balance, complexation processes, and other environmental variables shape element mobility (Wu *et al.* 2026b).

The adsorption and desorption of elements in soil are highly complex, nonlinear processes influenced by the interactions among multiple physicochemical properties (*e.g.*, initial concentration, ionic strength, and solid-liquid ratio). Numerous and unstable factors can be involved in this process. For example, ion exchange capacity (IEC) has a significant effect. IEC controls the amount of element ions adsorbed onto biomaterials (Hubbe *et al.* 2011). For every mole of divalent element adsorbed, one mole of Ca is displaced (Crist *et al.* 2003). In other words, based on the valence of the elemental species, each adsorbed ion is expected to exchange with other ions, such as sodium or hydrogen (Hubbe 2013). Therefore, the presence and concentration of other elements in the soil can significantly affect plant uptake of these elements (Hubbe *et al.* 2022; Şevik 2026). Anthropogenic factors such as fertilization also contribute to this process. For example, it has been determined that the leaf phosphorus (P) content in eggplants can be significantly increased with organic fertilizers such as compost tea and humic acid (Moursy *et al.* 2021). Fruit P content, however, can vary depending on the type of fertilization. It has been determined that chemical fertilizers, such as NPK combined with urea and potassium sulfate, can increase the P content of fruits by approximately 25–27 mg per 100 g of fresh matter, compared with some organic applications (Théodore *et al.* 2021). Indeed, studies have shown strong correlations between numerous elements within the plant (Şevik *et al.* 2024).

Studies also show that even when plants are grown under the same conditions, their elemental content can vary depending on their genetic structure (Guo *et al.* 2025; Li *et al.* 2025; Onat *et al.* 2026). For example, it has been determined that P levels in eggplant fruits differ significantly among genotypes (Bidaramali *et al.* 2020; Joseph *et al.* 2025). In addition, it is stated that stress levels are also determinants of both morphological, phenotypic, and anatomical characteristics, as well as element uptake in plants (Yildiz *et al.* 2014; Koç and Nzokou 2023; Kulac *et al.* 2025). For example, salinity stress has been shown to reduce P content in both leaves and fruits, whereas moderate salt stress can improve P uptake (Mady *et al.* 2023). This interplay occurs because the element uptake and accumulation potential of plants, like all other phenotypic characteristics, is shaped by the interaction between genetic structure and environmental conditions (Koç 2022; Arıcak *et al.* 2024). In this process, it can be considered a natural state for the plant to take up structurally necessary elements in greater quantities than other elements.

Based on the results, it can be said that the hypothesis (that the uptake, bioaccumulation, and translocation of elements from the soil in plants vary depending on the plant's need for that element; therefore, the bioaccumulation and translocation values of the elements in plant organs are ranked as S (macronutrient element) > Mo (micronutrient element > Li (non-essential element)) is generally supported. However, it would be incorrect to draw definitive conclusions, as the results may also be attributable to other factors. For example, the binding constant with functional groups such as the carboxylate group found in plants is quite low (Inouhe *et al*. 2024; Garcia-Daga *et al*. 2025). In contrast, Mo is generally present as the molybdate ion (two negative charges);

therefore, its adsorption behavior is expected to differ markedly (Rana *et al*. 2025; Sarkar and Gogoi 2025). In addition, the Mo element has a much higher polarizability compared to Li; therefore, van der Waals contributions may also be present. It is expected to be much larger (Chen *et al*. 2024). Similarly, S has a highly complex chemistry and is likely to occur in various ionic or non-ionic forms (Narayan *et al*. 2023). To truly support the theory that "plants tend to take up more of the elements they need," it will be necessary to compare many more elements whose speciation (depending on pH, concentration, and redox potential) is well known. Therefore, in order to validate the results obtained in this study, future studies on this subject should include:

a) conducting chemical speciation and fractionation analysis, using advanced analytical techniques such as X-ray absorption near-edge structure (XANES) spectroscopy and sequential chemical extraction to identify the precise chemical species of Li, Mo, and S elements found in plant organs (roots, leaves, fruits) and rhizosphere soil pore water,

b) characterizing and determining a broader element matrix and molecular carriers; expanding the scope to include other alkali metals, micronutrients, and toxic, non-essential trace elements, and, if possible, allowing researchers to study molecular transporter kinetics (SULTR, MOT1, HKT/AKT channels) separately from soil matrix interactions,

c) conducting rhizosphere geochemistry and soil-plant modeling, investigating the effects of dynamic rhizosphere parameters such as pH fluctuations, redox potential, root exudates, and organic matter complexation, and

d) It is recommended that the chemical species of elements found in plants (and soil-associated water), including Li (if possible), Mo, and S, be included in the research during these studies.

CONCLUSION AND SUGGESTIONS

1. This study has compared elements with varying nutritional values. The results indicate that nutrient requirements can be a determining factor in a plant's uptake of soil nutrients. Therefore, the extent to which a crop utilizes certain elements as building blocks, such as heavy metals, may be a determining factor in their accumulation within the plant. Further detailed studies on this topic are recommended.
2. The results from this study indicate that the amount of S accumulated in the crop was significantly higher than that of the other two macronutrients, whereas the corresponding soil sodium concentration was much lower. This variation suggests that plants absorb macronutrients such as sodium in large amounts from the soil. Therefore, determining which plant accumulates which nutrient at high concentrations, then determining the concentrations of macronutrients in the soil, and supplementing with the necessary elements through fertilization could be crucial for plant development and, consequently, crop yield.
3. The sulfur (S) accumulation in crops was lowest in the fruit and highest in the leaves. The lowest S concentration in leaves (1273.50 ppm) was found in maize, and the highest S concentration (8619.69 ppm) was found in tomatoes. While maize leaves can sometimes be used as animal feed, the leaves of other species are not economically valued; only the fruits are consumed as food. However, the results show that S concentrations in these organs are very high. This elevated concentration indicates that the potential for using these organs, which are economically undervalued, as organic

fertilizers is quite high. When these organs are converted into compost and used as fertilizer, they can significantly promote plant growth and significantly lower fertilizer costs. A similar situation is likely to apply to other macronutrients as well. Therefore, further studies on this subject are recommended.

4. It was found that Mo and Li had very low concentrations in crop organs and very low TF (Translocation Factor) values. However, Mo and Li concentrations in the soil were found to be quite high. Numerous studies on this subject have shown that some non-essential elements (especially harmful heavy metals) accumulate to high levels in plant organs. This can be concluded as meaning that the uptake of these non-essential elements from the soil is limited, and that a large portion of these elements enters the plant's system from the air. In production activities in areas with elevated metal pollution, greenhouse-like environments can be used to limit the entry of airborne metals into the plant's system.

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DATA AVAILABILTY

The dataset used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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