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Assessment of Macro-Mineral Bioavailability in Medicinal Plants and Corresponding Soils of Punjab, Pakistan: Implications for Human Health and Daily Intake

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Article Details

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ABSTRACT

This study investigated the concentrations of essential macrominerals, sodium (Na), calcium (Ca), potassium (K), and magnesium (Mg), in soils and six medicinal plants collected from two distinct locations in Punjab, Pakistan. Significant site-wide variations in mineral uptake and soil availability were recorded via ANOVA, with fluctuating trends observed across locations and species. The sodium concentrations in soils (59.09-59.77 mg/kg) and plants (0.026-0.61%) were below critical levels, indicating a potential deficiency that may affect both plant productivity and dietary sufficiency. Notably, Peganum harmala presented the greatest accumulation of Na, whereas Withania somnifera presented the lowest accumulation. The calcium content ranged from 72.90-84.51 mg/kg in soils and 0.191-0.391% in plants, with Solanum nigrum showing the highest uptake. Despite being above the critical soil level (71 mg/kg), the plant Ca concentrations were insufficient to meet the recommended daily intake (350–1100 mg/day). The potassium levels in the soils ranged from 68.53--83.73 mg/kg, and those in the plants ranged from 0.59-1.15%, yet most values were below the 0.8% critical threshold, indicating K deficiency. The bioaccumulation factor (BCF) for K was remarkably high (127.03-155.52), suggesting metal sensitivity in certain species, such as Adhatoda vasica. The magnesium level remained consistently below the soil critical value of 9.10 mg/kg, whereas the plant Mg content ranged from 0.093-0.196%, approaching or slightly exceeding the 0.1% threshold. The calculated daily intakes from plant consumption revealed insufficient contributions of Na and K but relatively adequate Mg, supporting its therapeutic relevance. Correlation analysis revealed weak or nonsignificant relationships between the soil and plant mineral contents, indicating metal-specific uptake mechanisms and possible antagonistic interactions. These findings underscore the need for soil amendment strategies and the informed use of medicinal herbs in dietary formulations to ensure adequate macromineral intake.

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INTRODUCTION

Pakistan boasts a diverse range of wild plants, many of which are used medicinally and aromatically. While some of these plants' therapeutic characteristics and traditional applications are widely known in local communities and among end users, a large number are yet to be investigated for their medicinal potential (Shinwari, 2000). More than 1,000 plant species with healing powers have been reported in Pakistan, and they are widely used by marginalized people to treat a variety of diseases (Mushtaq *et al.*, 2009). This massive stock of botanical resources holds enormous promise for the identification of new bioactive chemicals and the development of plant-derived medicines.

Several ethnobotanical research have been conducted in Pakistan, demonstrating the country's growing interest in preserving indigenous plant knowledge (Sheikh and Hussain, 2008). Like many other countries, Pakistan is making rapid progress in the subject of ethnobotany. The country has over 5,700 medicinal plant species, 372 of which are commonly utilized and widely dispersed. Notably, 456 of these species are commercially traded and used as raw materials in the manufacture of over 350 medicinal formulations used to treat a variety of health issues. However, one major problem is the possibility of heavy metal contamination of medicinal plants during growth, harvesting, or subsequent processing. This pollution endangers not only human health, but also the efficacy and safety of herbal treatments.Therefore, assessing the accumulation of heavy metals in these plants is critical.Whereas many metallic and non-metallic elements are very important for human growth and health within permissible limits, their excess can pose health risks. Consequently, determining the elemental composition of medicinal plants is vital for evaluating both their therapeutic value and safety.

High levels of some heavy metals in the human body might offer major health hazards (WHO, 2005). Calcium is an important structural component of bones and teeth, and it regulates membrane permeability, enzyme activity, and blood pressure. Sodium (Na+) and potassium (K+) are essential electrolytes for several physiological functions, such as fluid balance, neuronal transmission, and muscle contraction. Sweating is the primary source of sodium loss, but diarrhoea and vomiting can also deplete Na^+ and K^+ levels.Tea, fruits, vegetables, and coffee contain significant amounts of these nutrients. The recommended daily intake is 2.4 g sodium and 3.5 g potassium (Baysal, 2002). Globally, the importance of critical minerals in illness prevention is becoming more widely recognised. Mineral concentrations, whether deficient or excessive, have a profound impact on the health of plants and animals and should be closely monitored to preserve ecological and physiological balance.

Excessive mineral concentrations can have serious health and developmental consequences in both plants and animals. Mineral-related illnesses are typically difficult to diagnose due to their intricacy and the time required to identify particular symptoms. Furthermore, deficiencies involving multiple minerals are extremely difficult to detect and interpret (Suttle and Brebner, 1990). The current study aimed to evaluate the mineral profiles of various medicinal plants collected from various locations in the Kallar Kahar region of District Chakwal. Understanding the mineral makeup of these medicinal plants is critical for developing safe and effective herbal remedies. This knowledge will be useful not only for improving public health and local flora health, but also for pharmaceutical firms that produce herbal formulations.

MATERIALS AND METHODS

PLANT SELECTION AND AREA OF STUDY

The current study was carried out in Kallar Kahar, a subdivision and union council of Chakwal District, Punjab, Pakistan. Kallar Kahar, located around 25 kilometres southwest of Chakwal and 125 kilometres from Rawalpindi via the road, is a popular tourist attraction known for its scenic beauty, peacocks, and saline lake. The valley is located at the district's eastern edge, between 32°26′ 11″ to 32°41′ 18″ N latitude and 71°50′ 33″ to 72°30′ 07″ E longitude. The experiment was carried out over an area of about 200 acres, which was rich in floristic diversity. *Dodonaea viscosa*, *Withania somnifera*,*Solanum nigrum*, *Calotropis procera*, *Mentha spicata*, *Peganum harmala*, *Cannabis sativa*, and *Adhatoda vasica* are some of the medicinal plant species typically found in this region.

The area is part of the Pothohar Plateau and has a semi arid environment with hot and dry summers, moderate winters, and irregular rainfall, which occurs primarily during the monsoon season and sometime all over the year. The soil is usually calcareous and moderately fertile, supporting both native fauna and flora. The region's diverse microclimates provide a unique ecological environment that promotes the growth of a wide range of medicinal and commercial plants. The natural topography and low agricultural disturbance make it an ideal location for researching plant-soil interactions and heavy metal buildup in wild flora

MAP OF STUDY SITE, KALLAR KAHAR, CHAKWAL, PUNJAB, PAKISTAN

SAMPLES COLLECTION

In the current study, 24 sites were randomly selected from two distinct locations, with each site approximately 8.3 acres apart for soil sample collection. 24 soil samples were taken from each location. To ensure partial representation of all soil layers, dirt was dug at each site to a depth of 12-15 cm with a stainless steel auger (Sanchez, 1976). Samples were air-dried, labelled, sealed in brown paper bags, and incubated at 60°C for 15 days to guarantee good preservation.

To reduce the danger of cross-contamination, plant samples were obtained from the same places as soil samples, using sterilized instruments. The medicinal plant species chosen for the study were *Dodonaea viscosa*, *Withania somnifera*, *Solanum nigrum*, *Calotropis procera*, *Mentha spicata*, *Peganum harmala*, *Cannabis sativa*, and *Adhatoda vasica* (Table 1). One representative plant specimen was gathered at each site, for a total of 24 samples from Location I and 24 from Location II. To remove adherent dust and probable surface contaminants, all samples were washed with distilled water first, then rinsed in 0.1 N hydrochloric acid to remove weakly bound metal ions.

After cleaning, samples were air-dried under shade to prevent photodegradation of active compounds. They were then transferred to a hot-air oven at 50°C for 15 days to ensure complete desiccation. The dried plant material was then pulverized with a stainless steel grinder and stored in airtight plastic containers for additional chemical analysis. This standardized approach ensured uniform sample preparation for determining heavy metal accumulation and mineral content in each plant species.

TABLE 1: FORAGE SPECIES WITH ABBREVIATIONS AND SOIL SAMPLES AT DIFFERENT SITES AT KALLAR KAHAR CHAKWAL

Symbols	Forage species	Symbols	Soil samples
PS1	*Dodonaea viscose*	S1	Rhizosphere *of Dodonaea viscose*
PS2	*Withania somnifera*	S2	Rhizosphere *of Withania somnifera*
PS3	*Solanum nigram,*	S3	Rhizosphere *of Solanum nigram,*
PS4	*Calotropis Procera*	S4	Rhizosphere *of Calotropis procera*
PS5	*Mentha spicata*	S5	Rhizosphere *of Mentha spicata*
PS6	*Paganum hermala*	S6	Rhizosphere *of Paganum hermala*
PS7	*Cannabis sativa*	S7	Rhizosphere *of Cannabis sativa*
PS8	*Adhatoda vasica*	S8	Rhizosphere *of Adhatoda vasica*

SAMPLES PREPARATION

After incubation, soil samples were digested using Vukadinović and Bertić's (1988) wet digestion procedure. One g of soil sample was placed in a digestion flask and treated with 4 mL of pure H_2SO_4 and 8 mL of H_2O_2. The mixture was cooked in a digestion chamber for around 30 minutes. Once fumes stopped, remove the flask and add 2 mL of H_2O_2. The sample was warmed and the process was repeated until the digest was colourless, indicating that all organic materials had been oxidized. The digested solution was then filtered using Whatman paper, and the final volume was increased to 50 mL by adding double-distilled water. The produced solutions were placed in labelled plastic bottles for further analysis. The samples were taken to the Department of Botany, University of Sargodha, Sargodha, Pakistan.

After complete dehydration, the plant samples were taken from the incubator. One g of each dried plant sample was placed in a digestion flask and treated with 2 mL of concentrated H_2SO_4 and 4 mL of H_2O_2. The mixture was cooked in a digesting chamber for thirty minutes. Once fumes stopped, remove the flask and add 2 mL of H_2O_2. The sample was reheated, and the procedure was repeated until the solution turned colourless, signifying complete digestion. The digested material was diluted with double-distilled water, filtered through Whatman No. 42 filter paper, and adjusted to a final volume of 50 mL. The produced solutions were stored in labelled plastic bottles for further investigation.

INSTRUMENTATION

MINERAL ANALYSIS

Following wet digestion of the soil, relative plant samples were subjected to mineral analysis using an Atomic Absorption Spectrophotometer Perkin-Elmer AAS-5000 (Perkin-Elmer Corp., 1980). The analysis was carried out using an AASP (Atomic Absorption Spectrophotometer) in accordance with Lindsay and Norvell's (1978) guidelines to determine the concentration of minerals in soil and medicinal plants commonly used by rural populations. The heavy metals studied included sodium (Na), potassium (K), calcium (Ca), and magnesium (Mg) from the soil samples collected from two locations and 8 different sites

BIOCONCENTRATION FACTOR (BCF)

The BCF index was used to measure the amount of metal that was transported from the soil to the edible portion of the vegetables. It is influenced by Cui *et al.*'s (2004) formula:

BCF = Metal value in the edible part/metal value in the soil

DAILY INTAKE OF METALS

The DIM was employed to determine how much metal an individual might consume by eating vegetables.

$$\mathbf{DIM} = \frac{M \times F \times V}{W}$$

where M = the concentration of metal in the vegetables.

F=Conversion factor of 0.085.

V= Vegetable consumption per person per day for humans was 0.345 kg

W= 60 kg is the average human body weight for an adult

STATISTICAL ANALYSIS

After the collection of soil and plant samples from the two locations and eight differernt sites the data for various attributes were statistically analyzed using the SPSS software for correlation and one-way analysis of variance was calculated. Steel and Torrie (1980) suggested that statistical significance between the means be tested at the 0.05, 0.01, and 0.001 levels of probability.

GRAPHICAL ABSTRACT FOR THE ASSESSMENT OF MACRO-MINERAL BIOAVAILABILITY IN MEDICINAL PLANTS

RESULTS

SOIL ANALYSIS AT DIFFERENT STUDY SITES

SODIUM ANALYSIS FOR SOIL AND PLANT

The analysis of variance revealed that site I had no significant influence ($p<0.001$) on soil salt concentration, while location II did (Table 1). The soil sodium mean values were highest in S1 at location I and lowest in S3 at location II (Figure 1A). The soil salt level ranged from 59.32 to 59.50 mg/kg at location I and 59.09 to 59.77 mg/kg at location II.

ANOVA analysis of sodium (Na) concentration found a significant effect of site ($P < 0.05$) on all medicinal plant species studied at Location I (Table 1). The mean Na concentration ranged from 0.026% to 0.61%, with the highest level found in *Peganum harmala* and the lowest in *Withania somnifera*. The ANOVA results for Location II showed no significant effect ($P > 0.05$) of site on Na concentration (Table 1). Na levels in this location ranged from 0.060% to 0.110%, with *Mentha spicata* having the highest concentration and *W. somnifera* having the lowest (Figure 1B). Overall, Na concentrations at all sites fell below the critical threshold of 0.06%.

Sodium is a vital mineral in the human body, helping to regulate fluid volume and maintain acid-base balance. Abnormally low sodium levels (hyponatraemia) can lead to major health consequences such as seizures and coma, while excessively high levels (hypernatraemia) can also cause convulsions and perhaps deadly effects. In plants, sodium is often found in low amounts and may not be sufficient to support human nutritional needs; in some situations, it may even pose health problems if polluted. The bioconcentration factor (BCF) for sodium from soil to plants in the current study ranged from 0.11 to 0.9 mg/kg, while the estimated daily intake (EDI) ranged from 0.03 to 0.9 mg/kg/day (Figure 1C). Soil-plant ratio of BCF was lower than the permissible limits.

The lowest value was observed in P1, indicating that metal bioavailability is low in this plant. It could be owing to the antagonistic impact of other metals. The greater bio concentration rate was detected in P2, indicating the plant's sensitivity. Na revealed a non-significant positive ($r=0.198$) correlation between soil and plant in both locations (Table 2). This demonstrated a close relationship between soil and plants.

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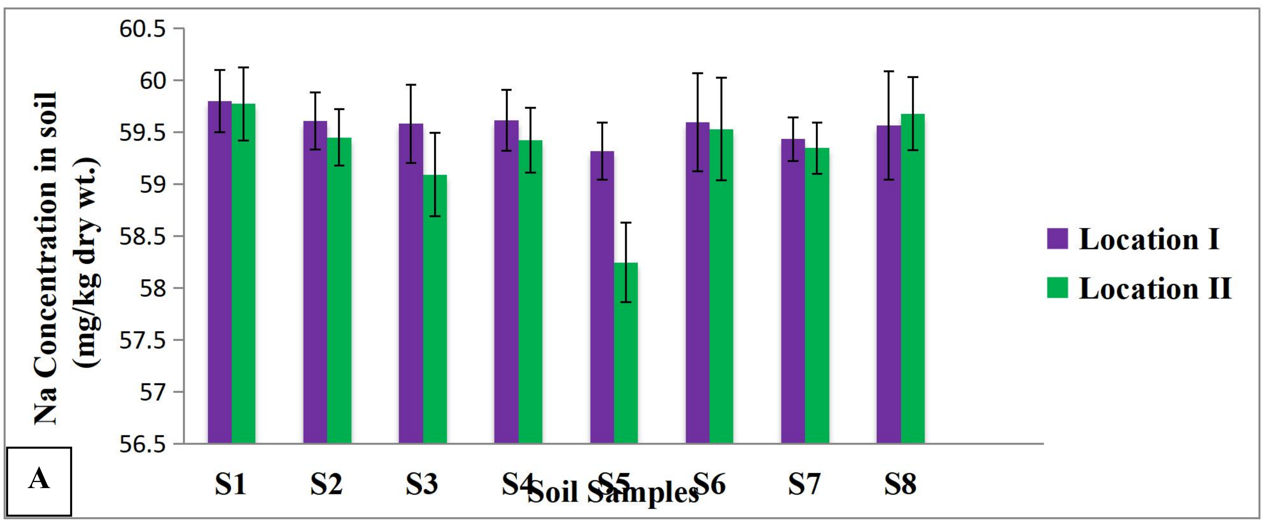
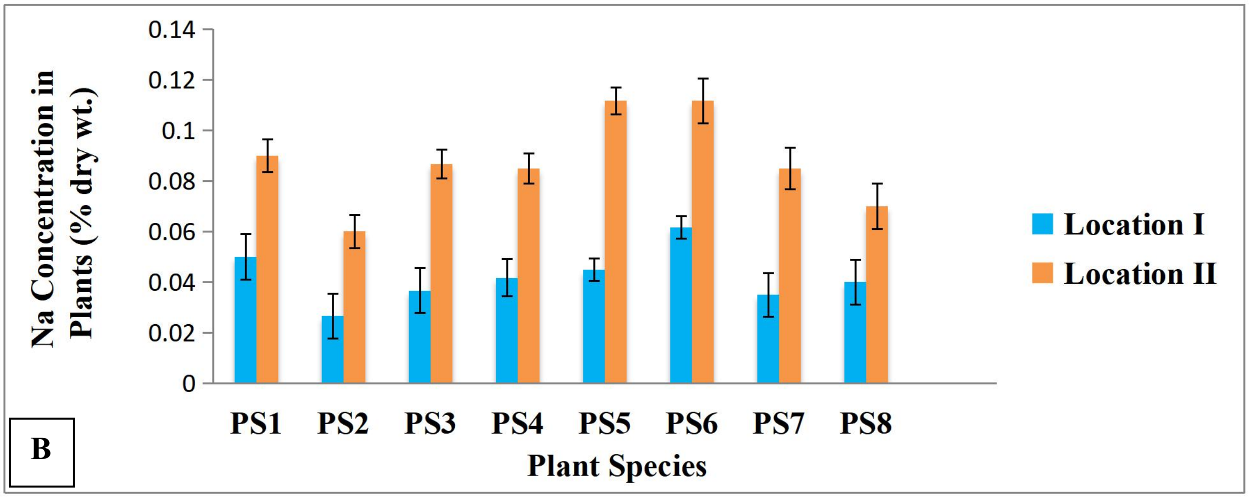
TABLE 2: ANALYSIS OF VARIANCE FOR SODIUM (NA) CONCENTRATIONS IN SOIL AND PLANTS AT DIFFERENT STUDY SITES AT KALLAR KAHAR

Source of Variation (S.O.V)	Degrees of Freedom (df)	Mean Squares			
		Soil		Plant	
		Location-I	Location-II	Location-I	Location-II
Sites	7	0.059ns	0.691**	0.001**	0.005ns
Error	16	0.075	0.198	0.005	0.005

=significant at 0.01 level, **ns= non-significant





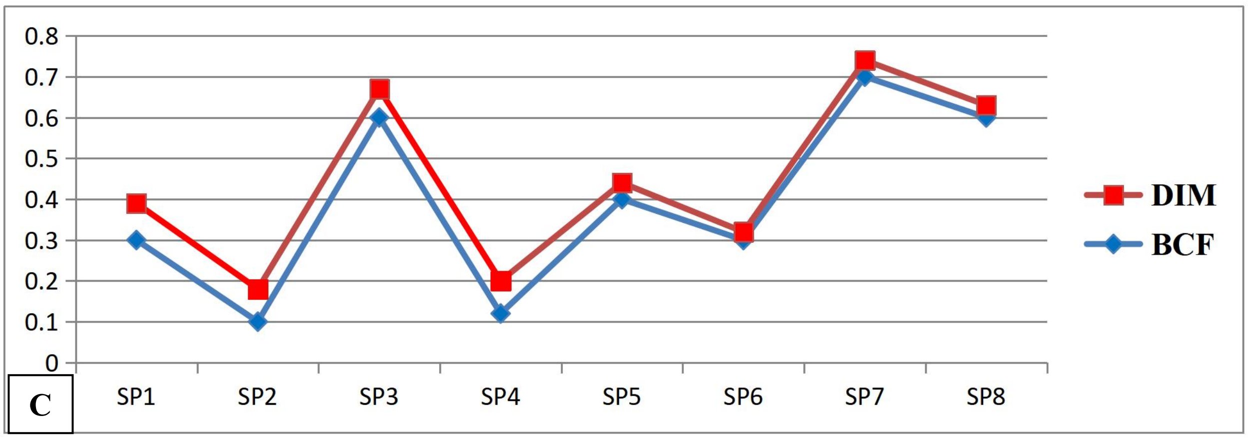


FIGURE 1 (1A-1C):SODIUM LEVEL IN SOIL (A) AND PLANTS (B), BIOCONCENTRATION FACTOR (BCF) AND DIM (C) AT TWO DIFFERENT LOCATIONS AND EIGHT DIFFERENT STUDY SITES (S-P = SOIL TO PLANT)

CALCIUM (CA) ANALYSIS FOR SOIL AND PLANTS

Analysis of variance (ANOVA) showed no significant effect ($P < 0.001$) of location on soil calcium (Ca) concentration. Despite the absence of statistical significance, mean soil calcium levels varied between sampling sites, ranging from 72.90 to 84.47 mg/kg at Location I and 77.10 to 84.51 mg/kg at Location II. Ca concentrations varied between the sites, indicating an uneven pattern. The soil Calcium concentration was the lowest at Site S3 in Location I, and the highest recorded at Site S3 in Location II compared to other sites (Figure 2.1). Overall, the soil's mean calcium concentration exceeded the necessary level of 71 mg/kg, according to McDowell (1983). Calcium is a secondary macronutrient required for plant growth and metabolism that regulates soil pH and metabolic processes and improves nutrient uptake.Additionally, calcium amendments are

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known to stimulate microbial activity in soil ecosystems.

All plant species at Location I showed a significant effect of site on calcium (Ca) concentration ($P < 0.05$). The average Ca concentration in plant samples at this location ranged from 0.241% to 0.391%, with *Solanum nigrum* having the highest concentration and *Peganum harmala* having the lowest (Figure 2A). Calcium concentrations at Location II differed substantially among sites ($P < 0.001$) in the examined plant species (Table 3). The mean values ranged from 0.191% to 0.381%, with *S. nigrum* showing the highest Ca concentration and *P. harmala* the lowest (Figure 2B).

The bioconcentration factor (BCF) for calcium (Ca) from soil to plants ranged from 0.3 to 0.9 mg/kg, whereas the daily metal intake (DIM) ranged from 0.01 to 0.07 mg/kg (Figure 2C). The BCF value was highest in plant sample P6, and lowest in P3. The variation among species reflects their different calcium absorbing capabilities. A lower BCF implies potential resistance to calcium buildup, whereas a higher bioconcentraion factor indicates increased sensitivity or absorption efficiency. A significant high negative correlation ($r = -0.521$) was found between soil and plant Ca concentrations in both locations (Table 2), demonstrating a mild inverse link between soil Ca availability and plant uptake in the current investigation.

TABLE 3: ANALYSIS OF VARIANCE FOR CA CONCENTRATIONS IN SOIL AND PLANTS AT DIFFERENT LOCATIONS AT KALLAR KAHAR

SOURCE OF VARIATION	DEGREES OF FREEDOM (DF)	MEAN SQUARES			
		Soil		Plant	
		Location-I	Location-II	Location-I	Location-II
Locations	7	36.152ns	18.492ns	0.011***	0.007**
Error	16	20.986	19.052	0.001	0.001

=significant at 0.01 level, **ns= non-significant

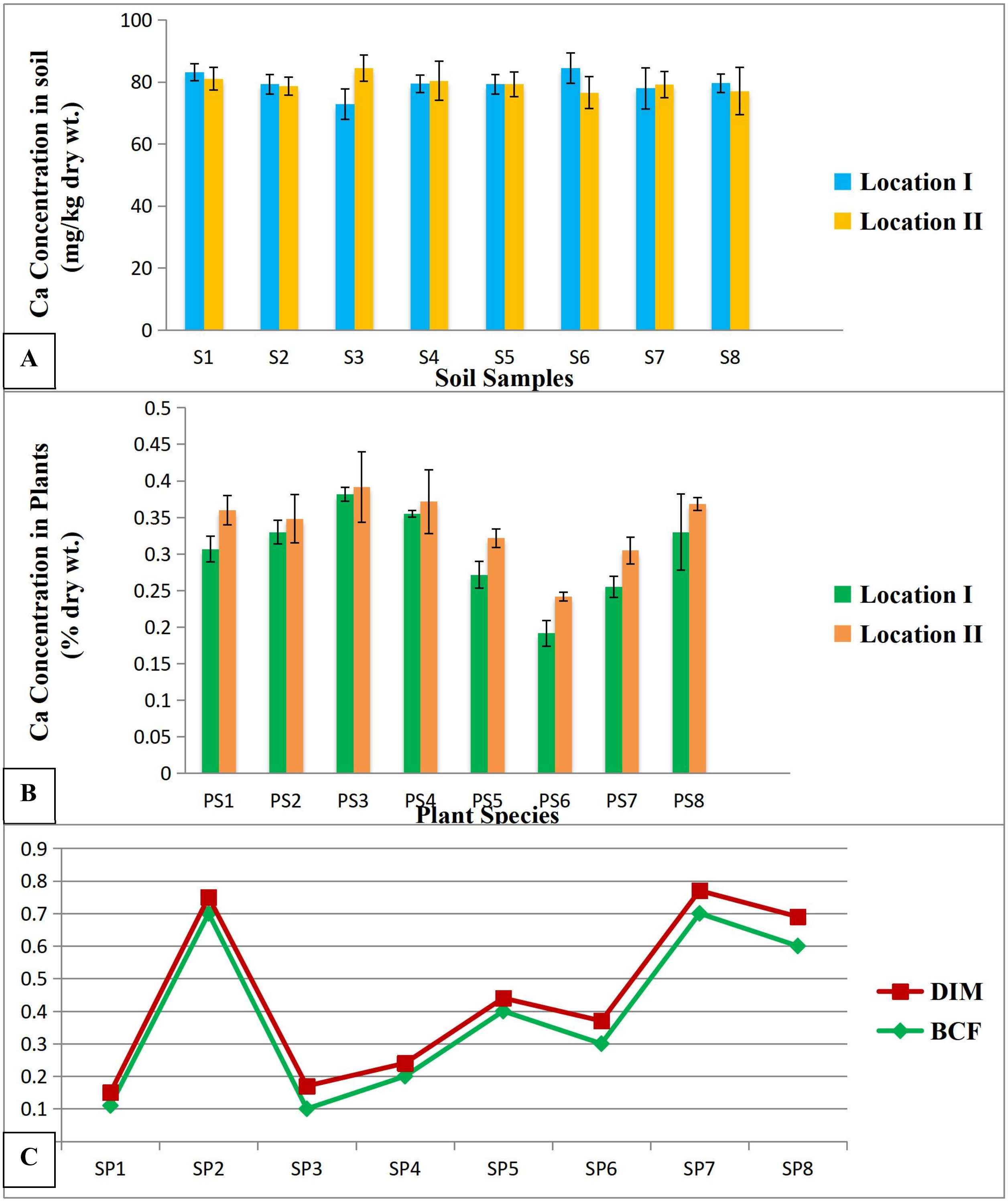


FIGURE 2 (2A-2C):CALCIUM (CA) LEVEL IN SOIL (A) AND PLANTS (B), BIOCONCENTRATION FACTOR (BCF) AND DIM (C) AT EIGHT DIFFERENT STUDY SITES (S-P = SOIL TO PLANT)

POTASSIUM (K^+) ANALYSIS FOR SOIL AND PLANTS

The analysis of variance revealed no significant effect ($P < 0.001$) of sampling sites on soil potassium (K^+) concentrations in both locations. Soil K^+ levels varied from 68.53 to 80.36 mg/kg at Location I and 75.68 to 83.73 mg/kg at Location II (see Table 4). The highest mean concentration was found at Site S5, and the lowest at Site S4, both in Location II. Overall, soil potassium levels matched the essential threshold of 80 mg/kg.

The analysis of variance for potassium (K) concentration in plants found no significant effect ($P > 0.05$) of site at Location I. The mean K content ranged from 0.59% to 0.73%, with the highest amount found in Cannabis sativa and the lowest in *Mentha spicata* (Figure 3A). Similarly, at Location II, K concentrations did not vary significantly across sites ($P > 0.05$) (Table 1). The average value ranged from 0.86% to 1.15%, with *Adhatoda vasica* having the highest concentration and *Calotropis procera* having the lowest (Figure 3A).

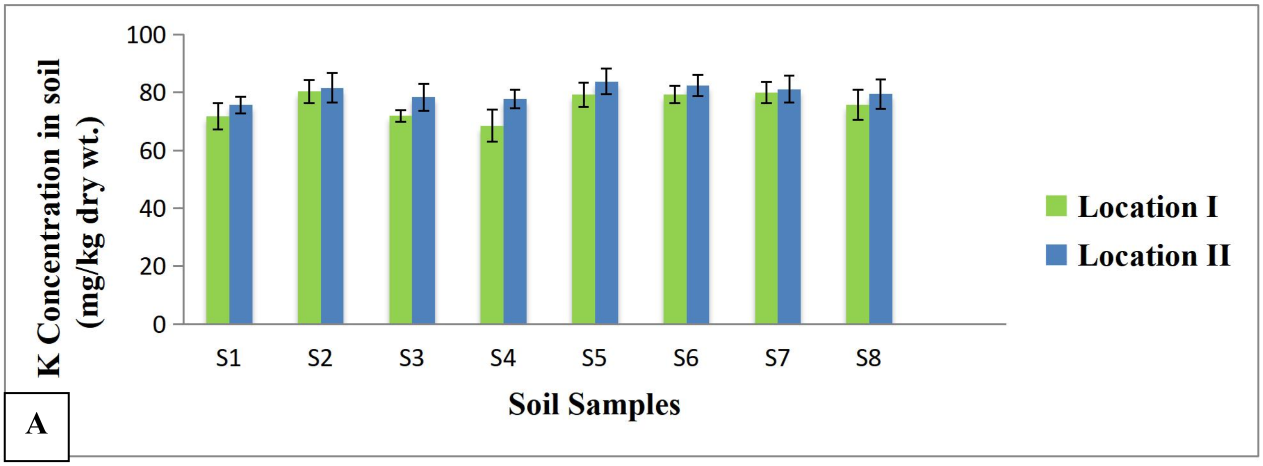
The current study shows a potassium (K) deficiency in the studied area, which could be attributed to the antagonistic effects of other metals that interfere with K uptake. The bioconcentration factor (BCF) for K from soil to plants ranged from 127.03 to 155.52 (Figure 3B). The maximum BCF was detected in plant sample P3, while the lowest was found in P4. A high BCF indicates that the plant is very sensitive to K absorption, and excessive buildup may cause physiological imbalances or toxicity. In contrast, a low BCF may indicate resistance to K uptake, possibly due to competition with other metal ions in the soil. A slight negative association ($r = -0.090$) was found between soil and plant K contents at both locations.This showed a strong relation of soil to plants. These results showed the mineral imbalance of K among soil and plant.The bio concentration factor for potassium concentration from soil to plants was varied from 0.1 to 0.12 mg /kg and DIM from 0.02 to 0.09 mg/kg/day (Figure 3C).

TABLE 4: ANALYSIS OF VARIANCE FOR POTASSIUM (K^+) CONCENTRATIONS IN SOIL AND PLANTS AT DIFFERENT LOCATIONS AT KALLAR KAHAR

SOURCE OF VARIATION (S.O.V)	DEGREES OF FREEDOM (DF)	MEAN SQUARES			
		Soil		Plant	
		Location-I	Location-II	Location-I	Location-II

Locations	**7**	62.380**	21.589ns	0.005ns	0.024ns
Error	**16**	24.757	15.589	0.002	0.012

=significant at 0.01 level, **ns= non-significant



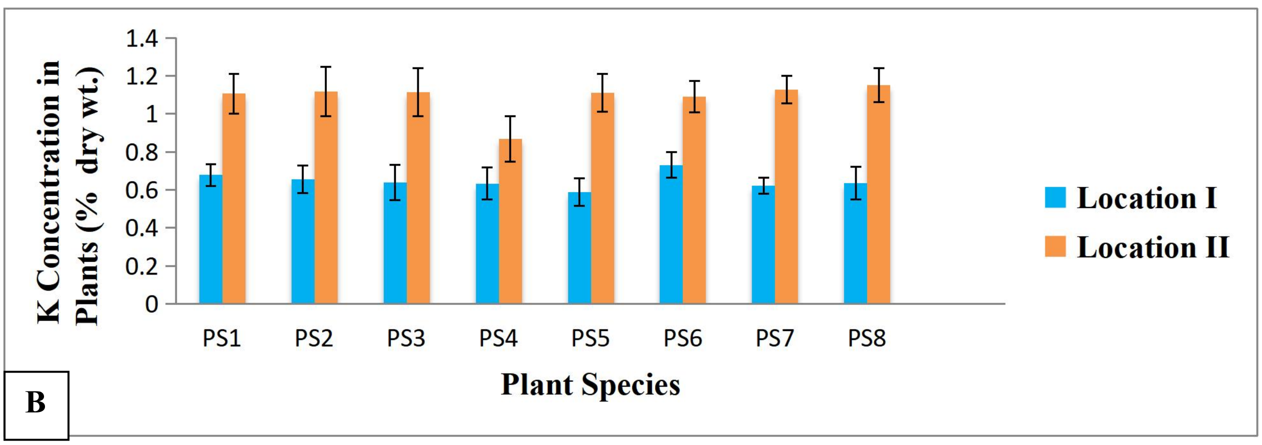


FIGURE 3 (3A-3C):POTASSIUM (K) LEVEL IN SOIL (A) AND PLANTS (B), BIOCONCENTRATION FACTOR (BCF) AND DIM (C) AT EIGHT DIFFERENT STUDY SITES (S-P = SOIL TO PLANT)

MAGNESIUM (MG)ANALYSIS FOR SOIL AND PLANTS

The analysis of variance revealed a non-significant effect ($P > 0.001$) of site on magnesium (Mg) concentration in soil samples at Location I, but a significant effect at Location II. Soil Mg concentrations showed inconsistent patterns of increase and decrease across sampling sites in both locations. Mean Mg concentrations at Location I ranged from 5.65 to 6.48 mg/kg, while at Location II they ranged from 5.63 to 7.71 mg/kg (Table 5). The lowest Mg content was found at Site S6, and the highest at Site S1, both in Location II (Figure 4A).

The results indicate that the site had no significant effect ($P > 0.05$) on magnesium content in all plant species at Location I (Table 5). Mean Mg concentrations in plant samples at this location ranged between 0.093% and 0.121%, with *Withania somnifera* having the highest value and Cannabis sativa having the lowest (Figure 4B). Similarly, at Location II, Mg concentrations varied non-significantly across sites ($P>0.05$), ranging from 0.161% to 0.196% (Table 1). At Location II, *Mentha spicata* had the lowest Mg concentration, while *W. somnifera* had the highest compared to other sites (Figure 4B).

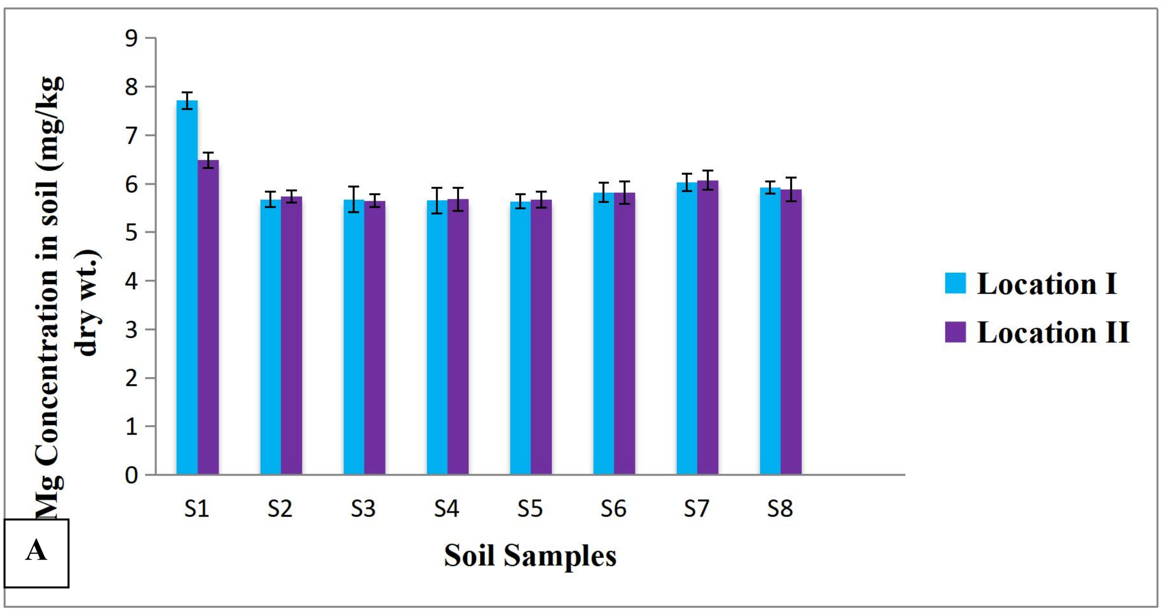
The bioconcentration factor (BCF) for magnesium (Mg) from soil to plants ranged from 227.82 to 334.75, with plant sample P3 showing the highest uptake and P1 having the lowest. Plants' metal uptake is mostly determined by the element's bioavailability in the soil. Lower accumulation may be due to antagonistic interactions with other metals that inhibit Mg uptake.

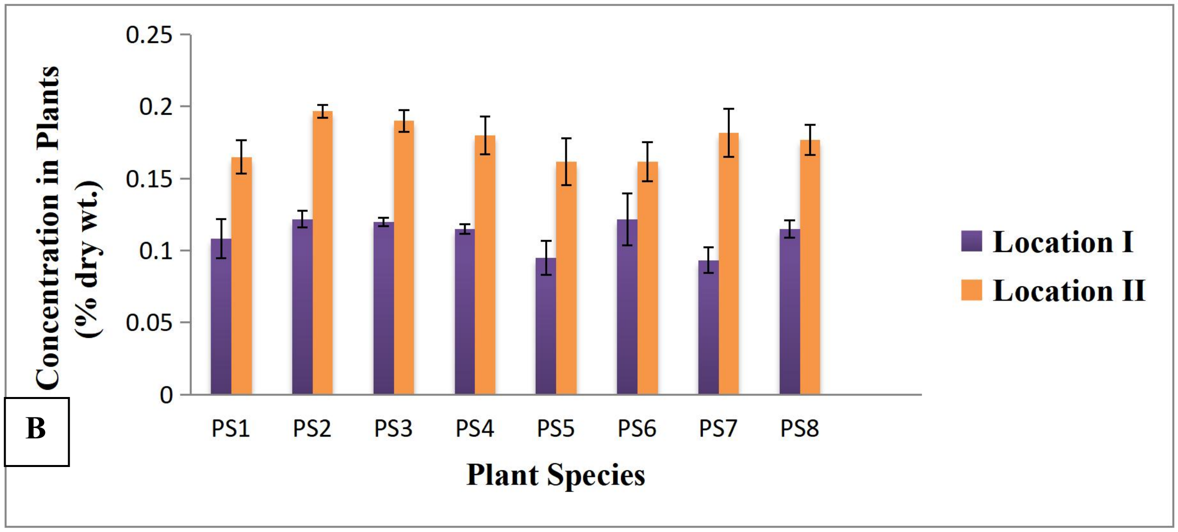
Table 5 shows a poor connection (r = -0.028) between soil Mg contents and plant absorption at both locations. Furthermore, the BCF for Mg, expressed in mg/kg, ranged from 0.12 to 0.3, while the estimated daily intake (DIM) was 0.03 to 0.08 mg/kg/day (Figure 4C).

TABLE 5: ANALYSIS OF VARIANCE FOR MAGNESIUM (MG) CONCENTRATIONS IN SOIL AND PLANTS AT DIFFERENT LOCATIONS AT KALLAR KAHAR

SOURCE OF VARIATION	DEGREES OF FREEDOM (DF)	MEAN SQUARES			
		SOIL		PLANT	
		Location-I	Location-II	Location-I	Location-II
Locations	**7**	1.471^{ns}	0.242**	0.004^{ns}	0.001^{ns}
Error	**16**	0.750	0.078	0.002	0.002

=significant at 0.01 level, **ns= non-significant





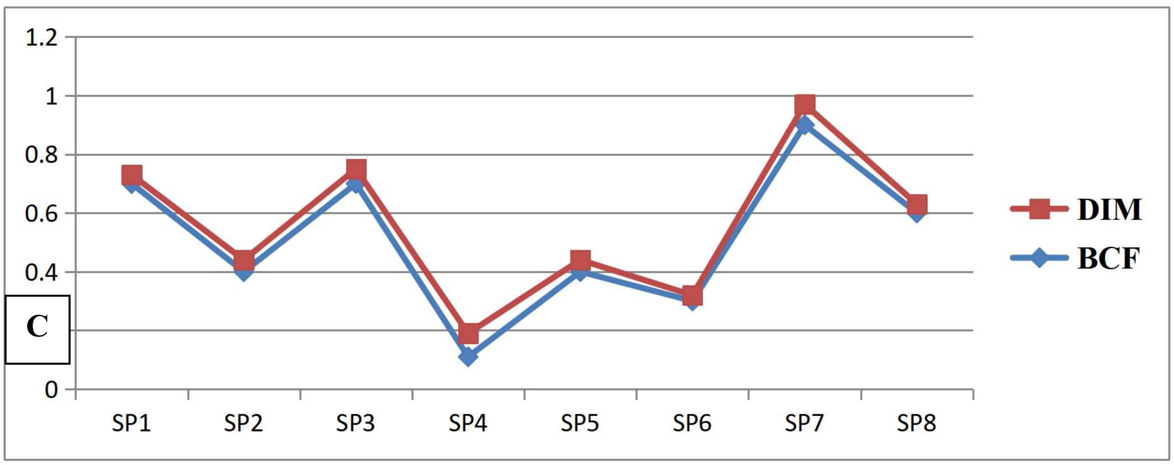


FIGURE 4 (4A-4C):MAGNESIUM (MG) LEVEL IN SOIL (A) AND PLANTS (B), BIOCONCENTRATION FACTOR (BCF) AND DIM (C) AT EIGHT DIFFERENT STUDY SITES (S-P = SOIL TO PLANT)

DISCUSSION

SODIUM (NA) DYNAMICS IN SOIL AND PLANTS

In studied soilall sampling sites had mean sodium (Na^+) values below the critical threshold of 62 mg/kg, as determined by Rhue and Kidder (1983). Espinoza *et al.* (1991a) observed similar low Na^+ values. Sodium deficiency is regarded as one of the most common mineral deficiencies affecting livestock worldwide, especially in underdeveloped nations (Singh and Malik, 2025). This study represents that applying Na^+ containing fertilizers could improve soil fertility in different studied location and sites. In contrast, Wenhai *et al.* (2025) found the much greater soil Na^+ concentrations in a ranch in southwestern Punjab, Pakistan.

The results show that soil sodium concentrations stayed below the crucial threshold of 62 mg/kg established by Rhue and Kidder (1983) in both research locations. Although the levels were statistically insignificant at location I, there was significant fluctuation at position II. Plants accumulated Na^+ despite soil constraints, with *P. harmala* exhibiting the highest amount and *W. somnifera* continuously displaying the lowest. The current Na concentration results were greater than those reported by Martins *et al.* (2008) in various locations of the world.

According to the National Research Council (NRC, 1984), the critical threshold for sodium (Na^+) in plants is 0.06%. The study found that most plant species had Na^+ concentrations below the recommended threshold, suggesting a probable sodium deficit. Sodium is essential for plant osmotic management and nutrient delivery, as well as for fluid balance, neuronal function, and overall health in animals and humans (Underwood & Suttle, 1999). Rhue and Kidder (1983) found widespread Na^+ deficit in emerging locations, including Nigeria. According to these findings, the use of sodium-based fertilizers may be required to improve soil fertility and promote sustainable agriculture in the examined region.

CALCIUM (CA^2) ACCUMULATION AND SOIL-PLANT RELATIONSHIP

The calcium (Ca) concentrations measured in this investigation were lower than those reported by Li *et al.* (2024). Prolonged calcium insufficiency has been linked to osteoporosis, which is characterized by bone degradation and an increased risk of fractures. The recommended daily calcium intake is between 350 and 1100 mg (Ahmed *et al.*, 2024). The average Ca concentrations in plants measured in this study were significantly lower than those previously reported in Pakistan by Gatasheh *et al.* (2025) and Abbas *et al.* (2023), as well as the findings of Ajasa *et al.* (2004). Calcium is required for the formation and maintenance of bones and teeth, as well as muscle function and cardiac activity (Rashkh, 2020).High concentrations of Ca are important because of its role in bones, teeth, muscles system and heart functions (Raskh, 2020) and studied plants show satisfactory level of Ca accumulation.

Soil calcium levels above the required level of 71 mg/kg (McDowell, 1985), indicating good availability. Plant Ca^{2+} levels varied greatly between sites and species at both locations. *S. nigrum* showed the greatest Ca^{2+} levels, whereas *P. harmala* had the lowest. A substantial negative correlation ($r = -0.521$) was discovered between soil and plant Ca^{2+} contents, indicating complicated soil-plant interactions mediated by metal antagonism or selective ion absorption.

Plants require calcium (Ca^{2+}) to stabilize cell walls, regulate enzyme activity, and maintain membrane permeability (Yan *et al.*, 2024). In humans, chronic calcium insufficiency is linked to osteoporosis, cardiovascular dysfunction, and reduced muscle performance (Shlisky *et al.*, 2022). This study found lower calcium concentrations in plants than previously described in Pakistan (Saqib *et al.*, 2020), underlining the necessity for closer monitoring of Ca^{2+} dynamics within local agroecosystems to promote both plant health and human nutrition.

POTASSIUM (K) VARIABILITY AND UPTAKE PATTERNS

Soil potassium (K) values ranged from 68.53 to 83.73 mg/kg, staying close to the crucial threshold of 80 mg/kg set by Warncke and Robertson (1976). Unlike sodium (Na) and calcium (Ca^2), potassium (K) levels did not differ significantly between sampling sites. Plant K^+ concentrations varied by species, with Cannabis sativa and *Adhatoda vasica* showing the highest accumulation. Despite this, all plant K^+ levels were below the threshold concentration of 0.8% (Lima *et al.*, 2020), indicating a potential potassium deficit, potentially due to competitive suppression by other cations such as Mg^{2+} and Na^+.

The potassium levels observed in the current study were lower than those reported by Slaton *et al.* (2021) in Florida and Abbas *et al.* (2023) in Pakistan, who studied similar agro-ecosystems in southwestern Punjab. The reduced soil K^+ levels may be attributed to leaching losses, a known factor in potassium depletion (Espinoza *et al.*, 1991a). Despite low soil K^+, the examined plant species had relatively high potassium content, which aligns with recent studies on therapeutic herbs (Luo *et al.*, 2021). Potassium absorption may be affected by antagonistic interactions with other metal ions as Mg^{2+}, Na^+, and Cu^{2+}. This could explain the difference. Potassium is usually absorbed by plants from the soil, especially when potassium-rich fertilizers are used.In humans, potassium is essential for normal kidney function and plays a critical role in heart health, skeletal and smooth muscle contraction, and overall digestive and muscular function (Ozcan, 2004). However, all mean plant K^+ concentrations were lower than the critical level of 0.8 % (Tang *et al.*, 2020).

Potassium is required for stomatal control, photosynthesis, and enzyme activity (Marschner, 1998). Its deficiency reduces growth and stress tolerance. Soil-plant correlations were weakly negative (r = -0.090), indicating antagonistic interactions or restricted mobility in Punjab's alkaline soils.

MAGNESIUM (MG^2) CONCENTRATION AND PLANT RESPONSE

Soil magnesium levels were very low, falling below the 9.1 mg/kg threshold (Zandybay *et al.*, 2024), particularly in location II. Plant samples, particularly *W. somnifera*, had higher Mg^{2+} content, indicating efficient uptake. Magnesium is essential for chlorophyll formation and ATP activation in plants, and deficiency reduces photosynthetic capacity (Chaudhry *et al.*, 2021). Mg^{2+} is important for about 300 enzymatic pathways in humans, and deficits can lead to cardiovascular and neuromuscular problems (Kumar *et al.*, 2024; Fiorentini *et al.*, 2021). Plants may accumulate Mg^{2+} even in poor soils, suggesting possibilities for biofortification and phytoremediation.

Magnesium (Mg) shortage in humans can cause muscle spasms and has been associated to hypertension, cardiovascular disease, diabetes, and osteoporosis. The Mg levels measured in plants during this study were lower than those reported by Kumar *et al.* (2024). Mazza *et al.* (2025) propose a daily dosage of 350 mg for men and 300 mg for women. The average Mg concentration in plants was near to the crucial threshold of 0.1%, indicating marginal sufficiency. However, potential antagonistic interactions with other elements such as Fe, Na, K, and Mn could have altered Mg uptake. Furthermore, all soil samples contained Mg levels below than the essential limit of 9.10 mg/kg, indicating widespread insufficiency in the study area.In the present study soil Mg concentration was lower than those reported earlier (Tien *et al.*, 2022). This soil requires amendment with fertilizers containing Mg to overcome its deficiency in soil. The results indicated that the studied herbal plants showed a high content of Mg.

BIOCONCENTRATION FACTOR (BCF)

The bioconcentration factor (BCF), which measures a plant's ability to accumulate minerals from the soil, differed significantly between the four examined elements and plant species. Sodium (Na^{+}) had a BCF range of 0.11 to 0.90, indicating limited bioavailability and inadequate translocation from soil to plant tissues (Ding *et al.*, 2021). *P. harmala* had the highest BCF, whereas *W. somnifera* had the lowest, indicating that Na^{+} uptake efficiency varies by species. Calcium (Ca^{2+}) had a BCF range of 0.3 to 0.9, with S. nigrum showing the highest accumulation, indicating efficient Ca^{2+} uptake mechanism. Potassium (K^{+}) presented unusually high BCF values ranging from 127.03 to 155.52, especially in species such as *A. vasica* and *C. sativa*. Although these values indicate a strong affinity for K^{+} accumulation, they also raise concerns about possible mineral imbalances or toxicity under high soil K^{+} exposure (Debela, 2020).

Magnesium (Mg^{2}) displayed the highest BCF among all elements, ranging from 227.82 to 334.75, with *W. somnifera* being the most effective accumulator. These results suggest that despite the overall low availability of Mg^{2+} in soil, some plant species are highly capable of mobilizing and sequestering this element, likely through specialized physiological pathways (Prajapati, 2021). The wide variation in BCF across species and elements underscores the importance of plant genotype in mineral uptake and the potential utility of certain species in phytoremediation or nutrient enhancement applications.

DAILY INTAKE OF MINERALS

The daily intakes of minerals values, which estimate the potential human exposure to minerals through plant consumption, were found to be lower than the recommended nutritional thresholds for all four elements. Sodium intake via plants contributes minimally to dietary sodium requirements, demonstrating the mineral's poor solubility in the local medicinal flora. Calcium levels varied from 0.01 to 0.07 mg/kg/day, which is much lower than the recommended daily requirement of 350-1100 mg (Gao *et al.*, 2021), indicating both low plant accumulation and the need for dietary supplementation from other sources.

Potassium daily intake varied between 0.02 and 0.09 mg/kg/day, which, despite high BCF values, remain insufficient to meet the human requirement for potassium (K), possibly due to low plant tissue concentration and antagonistic effects from other metals such as magnesium and sodium. Magnesium intake from these plants ranged from 0.03 to 0.08 mg/kg/day, again below the recommended 300-350 mg/day, although certain species such as *W. somnifera* showed relatively higher values (Nyero *et al.*, 2023). Overall, the daily intake analysis reveals that the studied medicinal plants, while exhibiting species-specific accumulation capabilities, contribute only modestly to daily mineral intake and may not serve as reliable sources of essential nutrients without soil amendments or mineral-rich dietary diversification.

CONCLUSION

This study highlights distinct patterns of mineral availability and uptake in medicinal plants across different sites in the Sargodha region. While calcium is generally sufficient in soil, sodium, potassium, and magnesium are below critical levels, posing potential limitations for plant growth and nutritional value. Weak soil–plant correlations suggest that mineral uptake is strongly influenced by species-specific traits and potential antagonistic interactions. Among the studied plants, *Solanum nigrum* and *Withania somnifera* presented greater accumulation of calcium and magnesium, respectively, suggesting their suitability for targeted phytoremediation or nutritional supplementation. These findings underscore the need for region-specific soil amendments, especially Na^{+}, K^{+}, and Mg^{2+}, to improve soil fertility and plant health. Future work should explore the impacts of micronutrients and trace metals and assess their long-term ecological and health implications.

DECLARATIONS

CONSENT FOR PUBLICATION

Not applicable

AVAILABILITY OF DATA AND MATERIALS

The data will be available from author on reasonable request

COMPETING INTEREST

All authors declare that there are no competing interests.

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