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Assessment of Molybdenum, Arsenic, and Selenium Bioaccumulation in Medicinal Plants: Implications for Human Health Across Diverse Agro-Ecological Zones

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Article Details

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ABSTRACT

This study evaluated the concentration, mobility, and plant uptake of three trace elements, Molybdenum (Mo), Arsenic (As), and Selenium (Se) in soils and selected medicinal plants across two locations and eight different sites. Mo concentrations in soil were below the critical threshold (1 mg/kg), but plant Mo levels above safe limits (>6 mg/kg), particularly in Calotropisgigantea and Cannabis sativa, indicating a risk of bioaccumulation. Arsenic levels in soil were safe (<20 mg/kg), but most plants above the WHO's allowed limit for therapeutic use (1.0 mg/kg), with Menthaspicata and C. sativa having the highest levels. Selenium concentrations in soils and plants ranged within or just over safe levels, with C. gigantea accumulating the most Se. Bio-concentration factors (BCFs) varied greatly, indicating differential absorption capability among species. All soil-to-plant transfer linkages were found to be weak or non-significant using correlation analysis. These findings suggest potential elemental risks associated with medicinal plant consumption and highlight the need for site-specific monitoring and metal management strategies in plant-based therapeutic applications

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INTRODUCTION

Medicinal plants are utilized across almost every region of the world for the treatment of a wide range of health conditions. These plants possess active constituents that are used in the formulation of herbal therapies (Pengelly, 2020). Compounds present in medicinal plants show antioxidant effects due to the existence of polyphenols, which are used to combat diseases (Sun et al., 2023). The presence of such compounds in medicinal plants has been observed in the body of the ice man, who was preserved in ice in the Swiss Alps for over 5300 years (Huffman, 2003). The demand for plant-based medicine has risen in recent times owing to its affordability and minimal adverse effects compared to traditional allopathic drugs (Shakya, 2016).

Minerals are inorganic elements that exist within all biological tissues and bodily fluids, and their presence is vital for maintaining various physicochemical activities crucial to life. These minerals are chemical elements that perform multiple roles in the human body. Though they do not provide energy, they are involved in essential physiological processes (Miller, 2017; Awiuchi, 2020). With only a few exceptions, the majority of toxic metals are located in the d and f blocks of the periodic table. These toxic metals are identified by having densities greater than 5 gm/cm^3. They include elements from the transition group, lanthanides, actinides, and specific metalloids (Jann, 2004; Hutchings et al., 2003). While toxic metals in limited quantities carry out critical roles in all living organisms due to their involvement in various biochemical pathways required for survival, the necessity for these metals varies depending on the species (Vijver et al., 2001).
The issue of toxic metals entering the soil and subsequently accumulating in medicinal plants has become a major concern for both agriculture and public health, since these metals can be taken up by plants in harmful quantities and eventually reach humans through the food chain. At higher concentrations and within a restricted range, heavy metals exhibit toxicity (Barany-Kevei&Kaszala, 2005). For these reasons, many individuals are turning toward herbal treatments for their health problems, and this trend, along with growing market demand, has sparked scientific interest in researching medicinal plants.

Arsenic (As) disrupts the process of cellular respiration by blocking mitochondrial enzymes and interrupting oxidative phosphorylation. Arsenic also affects the Krebs cycle by suppressing pyruvate dehydrogenase. It damages various tissues, including the nerves (causing peripheral polyneuropathy and axonal damage), gastrointestinal tract, and skin (Ling, 2001). This research was carried out to evaluate the mineral content of various medicinal plants collected from several sites within the KallarKahar region of District Chakwal. The information gathered from the mineral analysis of medicinal plants can be applied in the formulation of herbal

medicines to support public health, and such data can also assist herbal medicine manufacturers.

The current study focused on the levels, mobility, and uptake of trace elements such as molybdenum (Mo), arsenic (As), and selenium (Se) in both soils and medicinal plants gathered from eight separate locations in KallarKahar, Chakwal, Pakistan. Although Mo content in soil samples remained below toxicity thresholds, its concentration in plant samples, especially in *Calotropisgigantea* and *Cannabis sativa*, regularly exceeded the safety limit of 6 mg/kg, indicating a high potential for accumulation. Arsenic concentrations in soil were within permissible boundaries (<20 mg/kg), yet numerous plant samples surpassed the WHO safety guideline of 1.0 mg/kg, with *Menthaspicata* and *C. sativa* showing the highest levels. Selenium values were generally within or slightly above recommended limits in both soil and plant materials.

MATERIALS AND METHODS

STUDY AREA

This investigation was carried out in KallarKahar, which is a subregion of the Chakwal District located in Punjab, Pakistan. The area lies about 25 kilometers southwest of Chakwal city and nearly 125 kilometers from Rawalpindi. Renowned for its scenic landscapes, saline lake, and rich biodiversity, KallarKahar is positioned on the eastern boundary of the region, within the geographical coordinates of 32°26'11" to 32°41'18" N latitude and 71°50'33" to 72°30'07" E longitude. The total experimental area spanned 200 acres and was home to a variety of medicinal plant species including *Dodonaeaviscosa*, *Withaniasomnifera*, *Solanumnigrum*, *Calotropisgigantea*, *Menthaspicata*, *Peganumharmala*, *Cannabis sativa*, and *Adhatodavasica.*

SAMPLE COLLECTION

SOIL SAMPLING

The research incorporated 24 soil sampling points selected randomly from two separate regions, maintaining an approximate distance of 8.3 acres between each site. At each location, 24 soil samples were obtained using a stainless steel auger, penetrating the soil to a depth of 12-15 cm to ensure representative sampling of all soil horizons (Sanchez, 1976). These samples were then air-dried, labeled, enclosed in brown paper bags, and incubated at a temperature of 60 °C for 15 days to fully remove residual moisture.

PLANT SAMPLING

Plant samples were taken from the identical sites as the soil samples, employing sterilized tools to avoid contamination. The plant species gathered consisted of *Dodonaeaviscosa*, *Withaniasomnifera*, *Solanumnigrum*, *Calotropisgigantea*, *Menthaspicata*, *Peganumharmala*, *Cannabis sativa*, and *Adhatodavasica.* From each location, 24 plant samples were obtained. These were

initially washed with distilled water followed by a dilute HCl solution to eliminate surface dust and other contaminants. Afterward, the samples were air-dried and placed in an incubator at 50 °C for a duration of 15 days to ensure complete moisture removal.

SAMPLE PREPARATION

SOIL PREPARATION

Once removed from the incubator, soil samples were subjected to digestion using the wet digestion technique (Vukadinović and Bertić, 1988). A 1-gram portion of soil was treated with 4 mL of H_2SO_4 and 8 mL of H_2O_2 in a flask, and the mixture was heated inside a digestion chamber for approximately 30 minutes. After the cessation of fume emission, the sample was taken out of the chamber. An additional 2 mL of H_2O_2 was added, and the mixture was reheated until the solution turned colorless. The digested sample was then filtered using Whatman No. 42 filter paper, diluted to a final volume of 50 mL with double-distilled water, and stored in labeled plastic containers for further analysis.

MEDICINAL PLANT PREPARATION

Following full dehydration, the plant samples were taken out from the incubator, and exactly one gram of each was transferred into a flask. These samples were digested by adding 2 mL of H_2SO_4 along with 4 mL of H_2O_2 and heating the mixture in a digestion chamber for 30 minutes. The digestion process was paused once the emission of fumes from the flask stopped, at which point the sample was removed from the chamber. Subsequently, an additional 2 mL of H_2O_2 was introduced, and the mixture was reheated by placing it back into the digestion chamber. This cycle was repeated until the solution lost its color completely. The fully digested sample was then taken from the chamber, diluted with double-distilled water, and passed through Whatman No. 42 filter paper to a final volume of 50 mL. The filtered solutions were stored in clearly labeled plastic containers.

INSTRUMENTATION

MINERAL ANALYSIS

Once wet digestion was completed, both soil and associated plant samples were analyzed for their mineral contents using an Atomic Absorption Spectrophotometer (AAS), model Perkin-Elmer AAS-5000 (Perkin-Elmer Corp., 1980). The methodology was based on procedures described by Lindsay and Norvell (1978) using AASP to determine the mineral concentrations. The selected medicinal plant species, commonly used by rural populations, were tested for the presence of heavy metals including Molybdenum (Mo), Arsenic (As), and Selenium (Se).

STATISTICAL ANALYSIS

The data obtained for various parameters were analyzed statistically using SPSS software. Correlation and one-way analysis of variance (ANOVA) were conducted. Differences among mean values were tested for statistical significance at probability levels of 0.05, 0.01, and 0.001, as outlined by Steel and Torrie (1980).

BIOCONCENTRATION FACTOR (BCF)

The bioconcentration factor was applied to estimate the transfer of metals from soil to the edible portion of the plants. This value was calculated using the formula developed by Cui et al. (2004):

BCF = Metal concentration in edible plant part / Metal concentration in soil

DAILY INTAKE OF METALS (DIM)

The DIM index was used to assess the estimated quantity of metal intake through vegetable consumption:

$$\textbf{DIM} = M \times F \times V / W$$

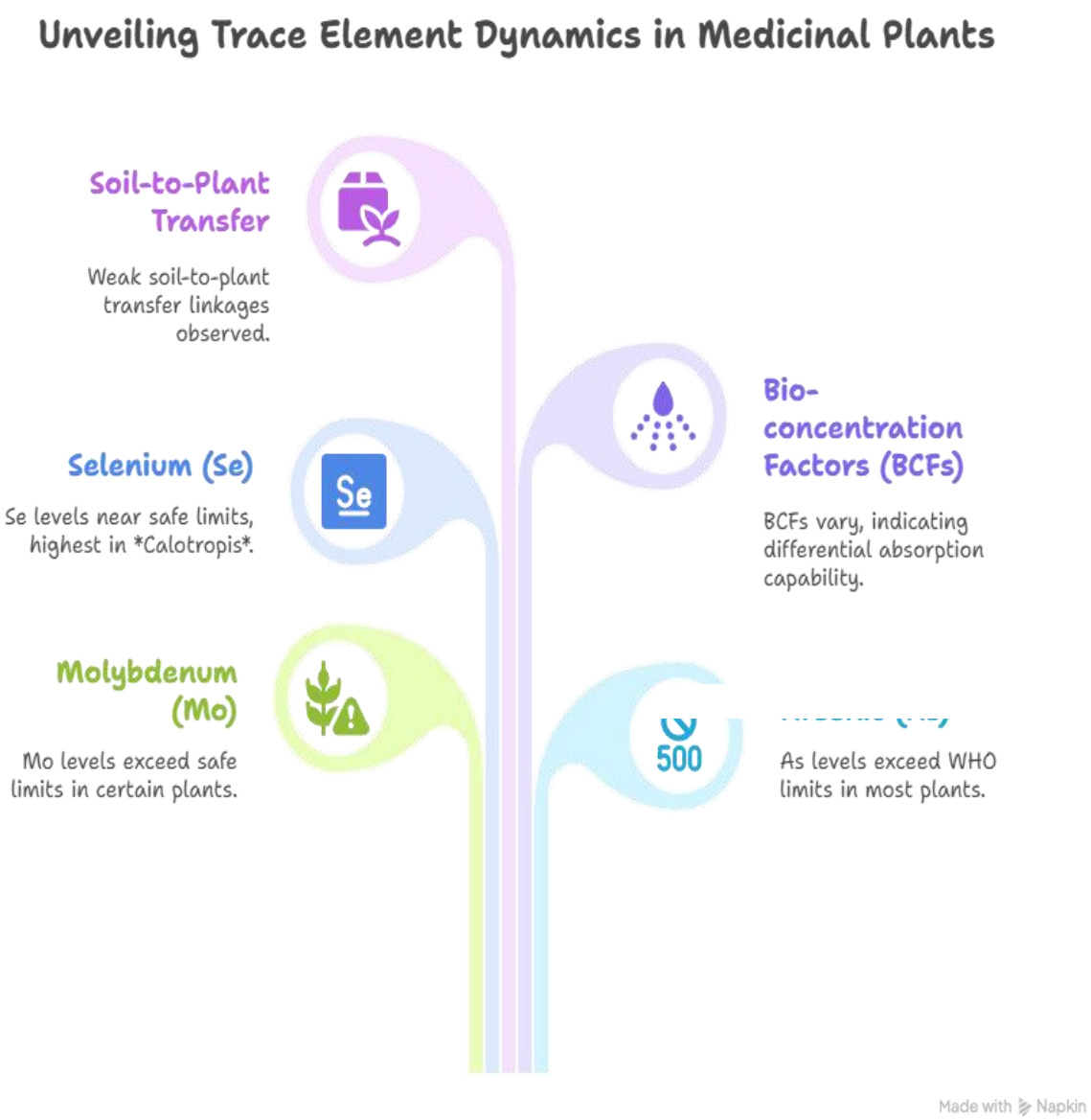
where:

M = concentration of metal in the vegetable

F = conversion factor = 0.085

V = average daily vegetable intake = 0.345 kg

W = average adult body weight = 60 kg



GRAPHICAL REPRESENTATION OF DIFFERENT HEAVY METALS AND THEIR IMPACTS ON HUMAN HEALTH

RESULTS AND DISCUSSION

MOLYBDENUM (MO)

SOIL

The analysis of variance indicated that the influence of sampling sites on Mo levels in the soil was statistically non-significant ($p>0.001$) across both locations. The lowest Mo concentration was detected at site S4, whereas the highest level was recorded at site S8 in location-I (Fig. 1a). The trend of Mo concentrations across all sampling points showed irregular fluctuations. In location-I, the Mo values ranged from 0.768 to 1.08 mg/kg, and in location-II, they ranged from

0.836 to 0.993 mg/kg (Table 1).

Average Mo levels found were lower than the critical value of 1 mg/kg as described by O'Connor (2001). According to Anjum et al. (2015), optimal Mo concentrations in soil fall between 1-2 mg/kg, levels which can lead plants to accumulate Mo in quantities ranging from 10 to 20 mg/kg, much higher than the values observed in this study. Mo deficiency in soil may result from specific conditions such as low organic matter, high acidity, sandy texture, and elevated iron content. Mo deficiency can be corrected using commercial fertilizers applied either as seed treatments or foliar applications (Cardoso et al., 2020). No indicators of Mo toxicity in animals were noted during the study.

PLANTS

In location-I, Mo content in different plant species exhibited statistically non-significant differences ($p>0.05$). Mo concentration ranged between 7.08 to 8.80 mg/kg. The highest accumulation occurred in *Calotropisgigantea*, whereas*Withaniasomnifera* exhibited the lowest Mo uptake in this region (Fig. 1a). Similarly, Mo levels across all plant samples in location-II also showed non-significant variation ($p>0.05$) (Table 1).

Overall, Mo concentrations in plant species ranged from 7.80 to 10.03 mg/kg. The lowest Mo level was seen in *Withaniasomnifera* and the highest in *Cannabis sativa* at location-II (Fig. 1b). The mean Mo concentrations observed were above the critical threshold of 6 mg/kg reported by Xia et al. (2016), indicating elevated Mo accumulation. These values exceed those documented in previous literature. The findings correspond well with the study by Florida Hornick et al. (1977), which noted similar plant Mo accumulation. Mo uptake is greatly influenced by soil Mo availability and soil pH; generally, lower pH levels enhance Mo absorption by plants (Anke, 2004).

High soil moisture and organic matter can enhance Mo bioavailability in plants consumed by animals (Murphy, 2015). The bioconcentration factor (BCF) for Mo from soil to plants ranged between 8.120 and 10.712 (Fig. 1b). The highest BCF was noted in P4, and the lowest in P6. Elevated BCF values suggest higher sensitivity of certain plant species to Mo, potentially leading to toxicity. Conversely, lower BCFs may be linked to antagonistic interactions with other metals, reducing Mo uptake. Correlation analysis between Mo in soil and plants yielded non-significant negative values across locations (Table 1), indicating a weak relationship between Mo levels in soil and plant tissues.

The biplot illustrates the multivariate association of plant-soil samples (PS1–PS8) collected from both locations. Arrows (vectors) show the strength and direction of correlations among variables.

Mo and BCF strongly impacted PS7 and PS8, revealing higher metal accumulation and possible environmental implications at these sites. DIM was more associated with PS6, PS1, and PS2, suggesting a greater risk of human exposure. PS4 was influenced mainly by BCF but showed minimal alignment with Mo or DIM, implying selective uptake behavior. PS3 and PS5, situated in the lower-left quadrant, had low values across all measured parameters. These findings reveal spatial variability in metal dynamics and plant uptake, helping to pinpoint high-risk areas (Fig. 1c).

TABLE 1: ANALYSIS OF VARIANCE FOR MO CONCENTRATIONS IN SOIL AND PLANTS AT DIFFERENT LOCATIONS

Source of Variation (S.O.V)	Degrees of Freedom (df)	Mean Squares			
		Soil		Plant	
		Location-I	Location-II	Location-I	Location-II
Locations	7	0.028ns	0.013ns	0.951ns	1.692ns
Error	16	0.018	0.021	0.395	0.703

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

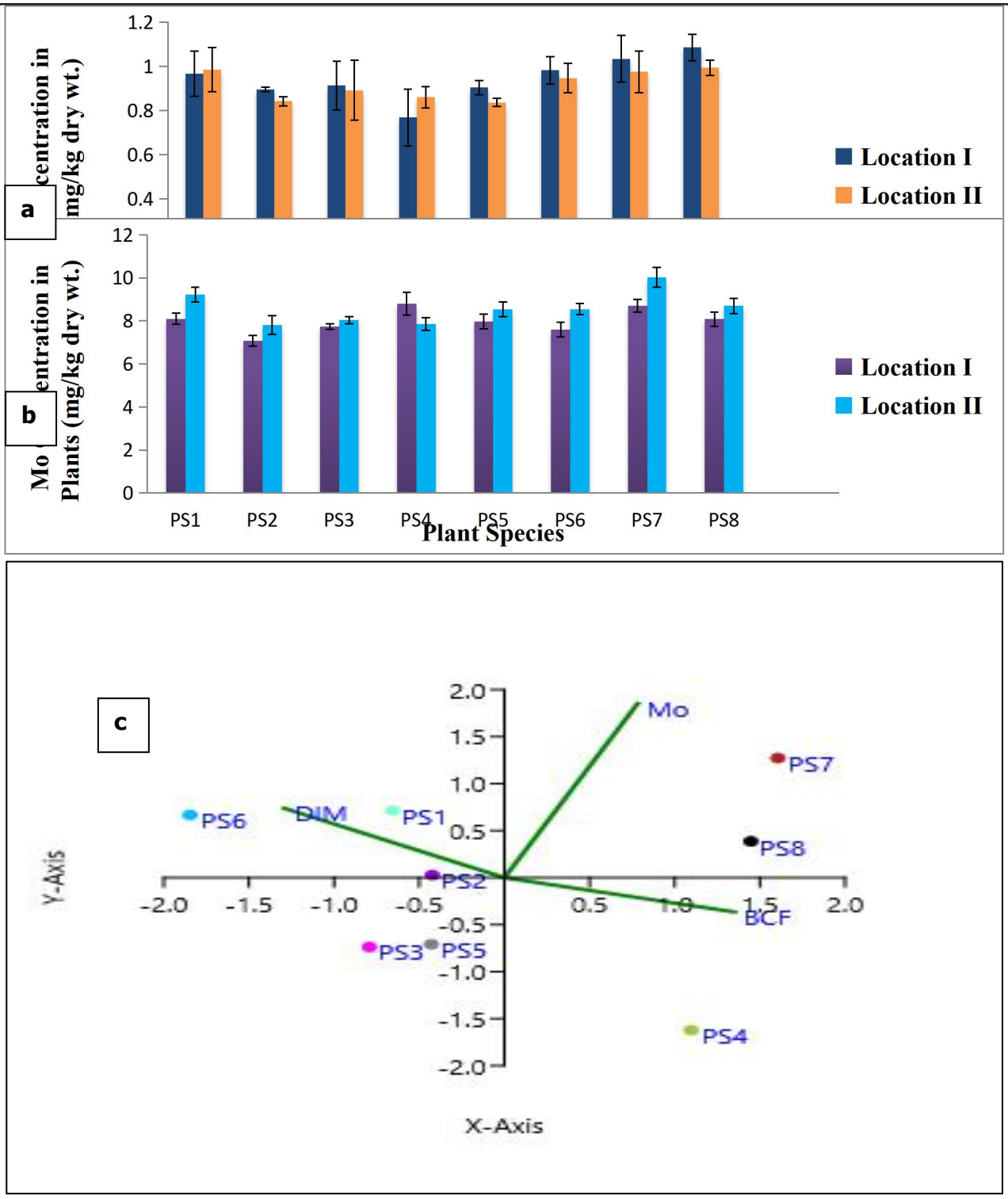


FIG. 1 (1A-1C):MOLYBDENUM (MO) LEVEL IN SOIL (A) AND PLANTS (B), BIOCONCENTRATION FACTOR (BCF) AND DIM BIPLOT(C) AT TWO DIFFERENT LOCATIONS AND EIGHT DIFFERENT STUDY SITES (S-P = SOIL TO PLANT; BCF, BIOCONCENTRATION FACTOR;DIM, DAILY INTAKE OF METALS)

ARSENIC (AS)

SOIL

Analysis of variance found no significant effect ($p>0.001$) of sampling site on soil arsenic concentrations across both locations. Arsenic levels varied between 4.07 and 4.55 mg/kg in location-I, and between 4.04 and 4.57 mg/kg in location-II. The lowest As concentration was found at site S2, and the highest at site S4 in location-II (Fig. 2a). These arsenic values remain under the critical threshold of 20 mg/kg defined by O'Neill (1995). Compared to the findings of Nazir et al. (2015), the current values were considerably lower. Factors like iron, aluminum, and phosphorus concentrations influence arsenic mobility in soils. In addition, soil pH and composition also play roles in arsenic movement (Caporale, 2016). According to Mamuzdar (2015), lower pH levels combined with increased folic acid result in higher arsenic leaching. Arsenic concentrations in the soils studied here are considered safe for animals raised in the area.

PLANTS

Variance analysis showed significant site-based differences ($p<0.05$) in arsenic concentrations in plants at location-I (Table 2). Arsenic levels ranged from 3.19 to 3.60 mg/kg across all plant species. The highest As accumulation was seen in *Menthaspicata*, while the lowest was recorded in *Dodonaeaviscosa* (Fig. 2b). However, at location-II, plant As levels did not vary significantly ($p>0.05$) among sites (Table 2). The highest average As level in this region was found in Cannabis sativa, and the lowest in *Dodonaeaviscosa*, with values ranging from 3.31 to 3.61 mg/kg (Fig. 2b). All recorded As levels exceeded the critical limit of 3.0 mg/kg as noted by O'Neill (1995). The WHO (1992) suggests a maximum permissible arsenic concentration in dried medicinal plants of 1.0 mg/kg, which is substantially lower than what was found in this study.

WHO also specifies that the acceptable daily intake of arsenic is 128 µg for a 60 kg adult (Tchounwou et al., 2019). A report from Taiwan recorded a maximum arsenic level of 8.78 ppb in medicinal plant samples. Most earlier studies report higher arsenic levels in medicinal plants than the current findings. In a recent analysis by Khute et al. (2024), arsenic contamination ranged between 0.173 and 15.62 µg/g in medicinal plant species. Arsenic presence in soil has been associated with inhibited plant growth.

The bioconcentration factor for As transfer from soil to plants ranged between 0.729 and 0.866 (Fig. 2b). The highest BCF was observed in P2, indicating that this species may be sensitive to arsenic, potentially affecting its survival. In contrast, P6 exhibited the lowest BCF, suggesting resistance to As uptake. Reduced uptake may result from competitive inhibition by other metals in the soil, which can interfere with arsenic absorption. Correlation between As

levels in soil and plants was a non-significant negative at both sampling locations (Table 2), reflecting a weak relationship between soil and plant arsenic content.

The biplot analysis demonstrates the correlation of plant-soil samples (PS1-PS8) with key indicators such as arsenic concentration, bioconcentration factor (BCF), and daily metal intake (DIM). The arrows reflect both the direction and strength of these variables. PS2 and PS5 showed high alignment with arsenic and BCF vectors, indicating strong accumulation and uptake capability at these points. DIM had a stronger association with PS1, PS4, and PS6, suggesting higher dietary risk from plant consumption in these areas. PS7 and PS8 appeared in the negative quadrant, representing low arsenic-related values and minimal risk. PS3 was positioned closer to As but indicated only moderate influence. The visualization emphasizes the spatial differentiation in metal bioavailability and plant uptake, highlighting the need for targeted site-specific evaluations and regulatory controls (Fig. 2c).

TABLE 2: ANALYSIS OF VARIANCE FOR AS CONCENTRATIONS IN SOIL AND PLANTS AT DIFFERENT LOCATIONS

Source of Variation (S.O.V)	Degrees of Freedom (df)	Mean Squares			
		SOIL		PLANT	
		Location-I	Location-II	Location-I	Location-II
Locations	**7**	0.094^{ns}	0.072^{ns}	0.059^{**}	0.035^{ns}
Error	**16**	0.089	0.152	0.012	0.014

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

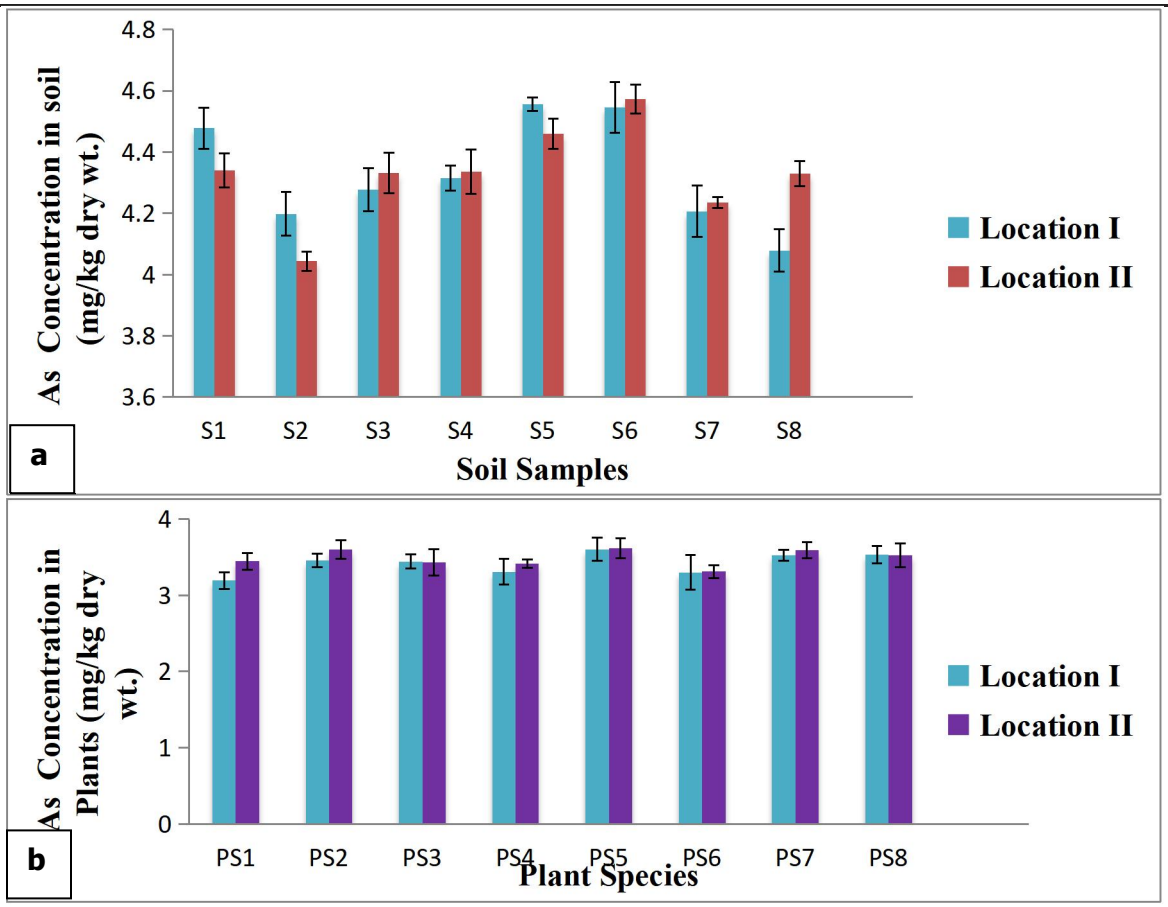


FIG. 2 (2A-2C):ARSENIC (AS)LEVEL IN SOIL (A) AND PLANTS (B), BIOCONCENTRATION FACTOR (BCF) AND DIM (C)BIPLOTAT TWO DIFFERENT LOCATIONS AND EIGHT DIFFERENT STUDY SITES (S-P = SOIL TO PLANT; BCF, BIOCONCENTRATION FACTOR; DIM, DAILY INTAKE OF METALS)

SELENIUM (SE)

SOIL

The analysis of variance indicated that selenium concentrations in soil showed a statistically non-significant effect ($p>0.001$) across sampling sites in location-I, whereas the opposite was observed in location-II, where site differences were significant. At location-I, mean soil Se values ranged between 0.591 and 0.673 mg/kg, while at location-II, values varied from 0.593 to 0.681 mg/kg (Fig. 3a). Throughout all sample points, Se levels showed gradual variation. The lowest concentration was observed at site S8 in location-I, while the highest was found at site S5 in location-II. These selenium levels are within the critical threshold of 0.5 mg/kg established by Ryabova et al. (2024).

Comparable low selenium levels have also been previously reported by Khan et al. (2005) from livestock farms in a different region of Punjab, Pakistan. The current findings indicate lower soil Se content than those reported by Hadrup et al. (2019). Selenium deficiency or excess in soil can directly affect animal health, as the amount of Se consumed is linked to its availability in plants (Wan et al., 2017). Adequate plant uptake of bioavailable Se is, therefore, crucial to maintaining optimal dietary levels in animals.

PLANTS

At location-I, the influence of sampling sites on selenium levels in plant species was found to be statistically non-significant ($p>0.05$) (Table 2). The average Se concentrations in plants ranged from 0.0866 to 0.120 mg/kg. Among all species, *Dodonaeaviscosa* recorded the lowest mean Se concentration, while *Calotropisgigantea* showed the highest (Fig. 3a). Likewise, at location-II, the effect of different sites on Se content in plants was also statistically non-significant ($p>0.05$) (Table 3). Se values ranged from 0.095 to 0.131 mg/kg, with *Cannabis sativa* showing the lowest accumulation and *Calotropisgigantea* again registering the highest levels at this location (Fig. 3a).

The mean Se content in plants observed during this study exceeded the critical limit of 0.1 mg/kg recommended by Zwolak (2020). These values also surpassed those reported by El-Boshy et al. (2015). The Se^{2+} concentrations observed were consistent with earlier studies conducted under similar environmental conditions in Colombia (Pastrana et al., 1991) and Pakistan (Shinwari, 2000), but lower than the levels reported by Lee et al. (2016) for the West Indies.

The bioconcentration factor (BCF) for selenium transfer from soil to plants ranged from 0.149 to 0.190 (Fig. 3b). The lowest BCF value was recorded in P7, while the highest was found in P4. This variation in Se uptake suggests that bioconcentration is closely linked to the

bioavailability of Se in soil. A higher BCF may reflect increased uptake efficiency by specific plant species. The correlation between soil and plant selenium concentrations was non-significant but positive, indicating a weak yet direct relationship across both study areas (Table 3).

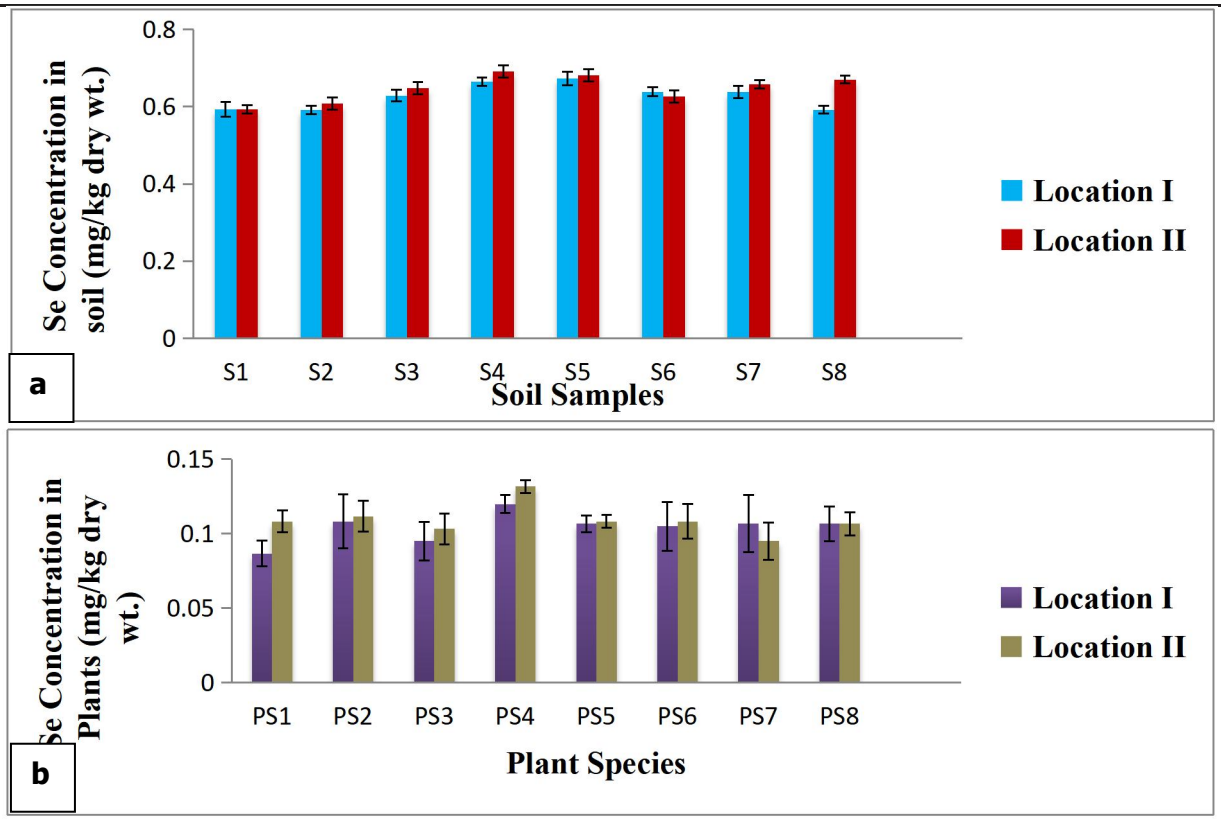
MULTIVARIATE RELATIONSHIPS

The biplot graphically represents the spatial distribution of plant-soil samples (PS1-PS8) and their associations with key variables, Bioconcentration Factor (BCF) and Daily Intake of Metals (DIM), at both locations. Vectors on the plot show that BCF is strongly correlated with PS7 and PS6, indicating a high capacity for selenium accumulation at these sites. DIM is closely associated with PS4, PS5, and PS8, pointing to a greater potential health risk through dietary intake from these locations. PS2 displays moderate alignment with both BCF and DIM, while PS3 lies at the center, indicating a balanced influence from both variables. PS1 and PS3 appear distant from all variable vectors, implying a minimal role in Se accumulation or related health risks. This multivariate analysis offers valuable insights into selenium dynamics and highlights areas needing targeted intervention and monitoring (Fig. 3c).

TABLE 3:ANALYSIS OF VARIANCE FOR SE CONCENTRATIONS IN SOIL AND PLANTS AT DIFFERENT LOCATIONS

Source of Variation (S.O.V)	Degrees of Freedom (df)	Mean Squares			
		Soil		Plant	
		Location-I	Location-II	Location-I	Location-II
Locations	7	0.003*	0.004*	0.000ns	0.000ns
Error	16	0.001	0.001	0.001	0.000

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



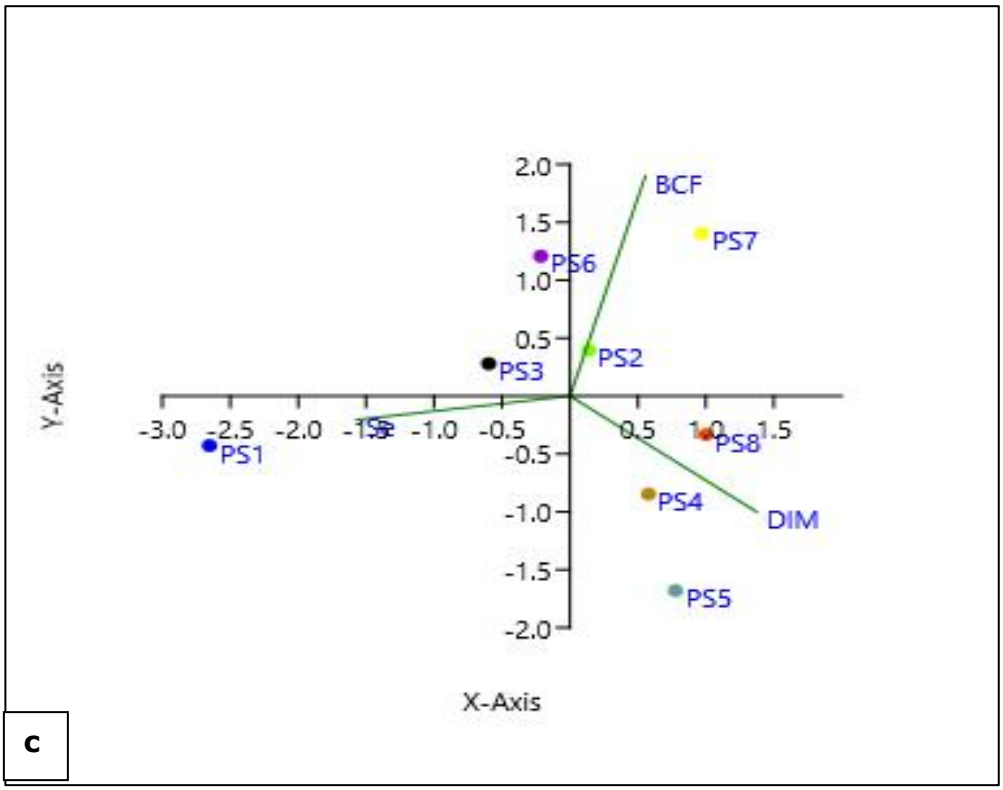


FIG. 3 (3A-3C):SELENIUM (SE)LEVEL IN SOIL (A) AND PLANTS (B), BIOCONCENTRATION FACTOR (BCF) AND DIMBIPLOT (C) AT TWO DIFFERENT LOCATIONS AND EIGHT DIFFERENT STUDY SITES (S-P = SOIL TO PLANT)

CORRELATION OF SOIL-PLANT INTERACTION AND METALS

The correlation analysis of Molybdenum (Mo), Bioconcentration Factor (BCF), and Daily Intake of Metals (DIM) at two and eight sites indicates changeable connections that reflect the dynamics of metal uptake from soil to plants, as well as possible human exposure. A modest positive association between Mo and BCF indicates that elevated Mo concentrations in soil are marginally associated with increased plant uptake, implying the involvement of other environmental or biological factors such as soil pH, organic matter, or plant species. In contrast, a moderate to severe negative association between BCF and DIM suggests that as plant accumulation grows, the estimated daily intake falls, presumably due to changes in consumption rates or metal dilution within plant tissues. A modest positive association between Mo and DIM adds to the argument that, while soil Mo content contributes to human intake via the food chain, its influence is not dominant. These associations highlight the complexities of trace metal transmission in agroecosystems and the importance of integrated monitoring to better understand exposure concerns (Fig. 4a).

The correlation matrix for arsenic (As), bioconcentration factor (BCF), and daily intake of metals (DIM) between two and eight sites demonstrates the interrelationships between soil contamination, plant uptake, and potential human exposure. A substantial positive connection exists between As and BCF, demonstrating that elevated arsenic levels in soil are strongly linked to increasing accumulation in plant tissues, implying effective uptake and transfer from soil to plant. The connection between BCF and DIM is relatively positive, indicating that when arsenic accumulates in plants, the estimated daily intake rises, however the relationship is not exactly linear and may be influenced by eating patterns or plant biomass. Interestingly, a slight negative connection between As and DIM implies that even when soil arsenic levels are elevated, daily intake does not always increase correspondingly, presumably due to limited translocation within edible plant parts or decreased bioavailability (Abdullayev et al., 2025). These findings highlight the importance of carefully monitoring arsenic levels in agricultural systems to reduce the risks associated with food chain transfer and human exposure (Fig. 4b).

The correlation matrix for Selenium (Se), Bioconcentration Factor (BCF), and Daily Intake of Metals (DIM) at two and eight sites indicates distinct patterns in Se behaviour from soil to human exposure. A substantial positive connection between Se and BCF shows that increased selenium concentrations in soil increase plant absorption, showing effective transfer across the soil-plant interface. Interestingly, Se has a moderate to strong negative connection with DIM, showing that more Se in the soil does not necessarily transfer into elevated daily

intake by humans, potentially due to restricted accumulation in edible plant parts or variances in consumption rates.

Similarly, a modest negative association between BCF and DIM suggests that even when plants store more Se, the estimated daily intake does not increase correspondingly, emphasizing potential physiological or metabolic constraints in Se translocation within plants (Zhang et al., 2023). These findings indicate that, while selenium is easily absorbed by plants from the soil, its bioavailability and contribution to human intake are influenced by a variety of circumstances, necessitating site-specific risk assessment and dietary consideration (Fig. 4c).

Analysis of variance indicated no significant changes in Mo concentration between sites, although bioconcentration factors (BCFs) differed significantly, indicating species-specific absorption behavior (Abdullayev et al., 2025). Correlation study revealed weak or non-significant relationships between soil and plant metal concentrations, emphasizing the importance of soil pH, organic matter, and metal interactions over soil content. Biplot analysis revealed spatial variability, with some plant-soil samples (e.g., PS7, PS8) exhibiting elevated Mo and BCF (Zhang et al., 2023), levels while others (PS6, PS1, PS2) were more related with DIM, exposing areas of possible ecological and health danger. These findings highlight the importance of species selection and site-specific monitoring in medicinal plant harvesting, as trace metal bioaccumulation, even at safe soil levels, can pose substantial health concerns if not controlled effectively.

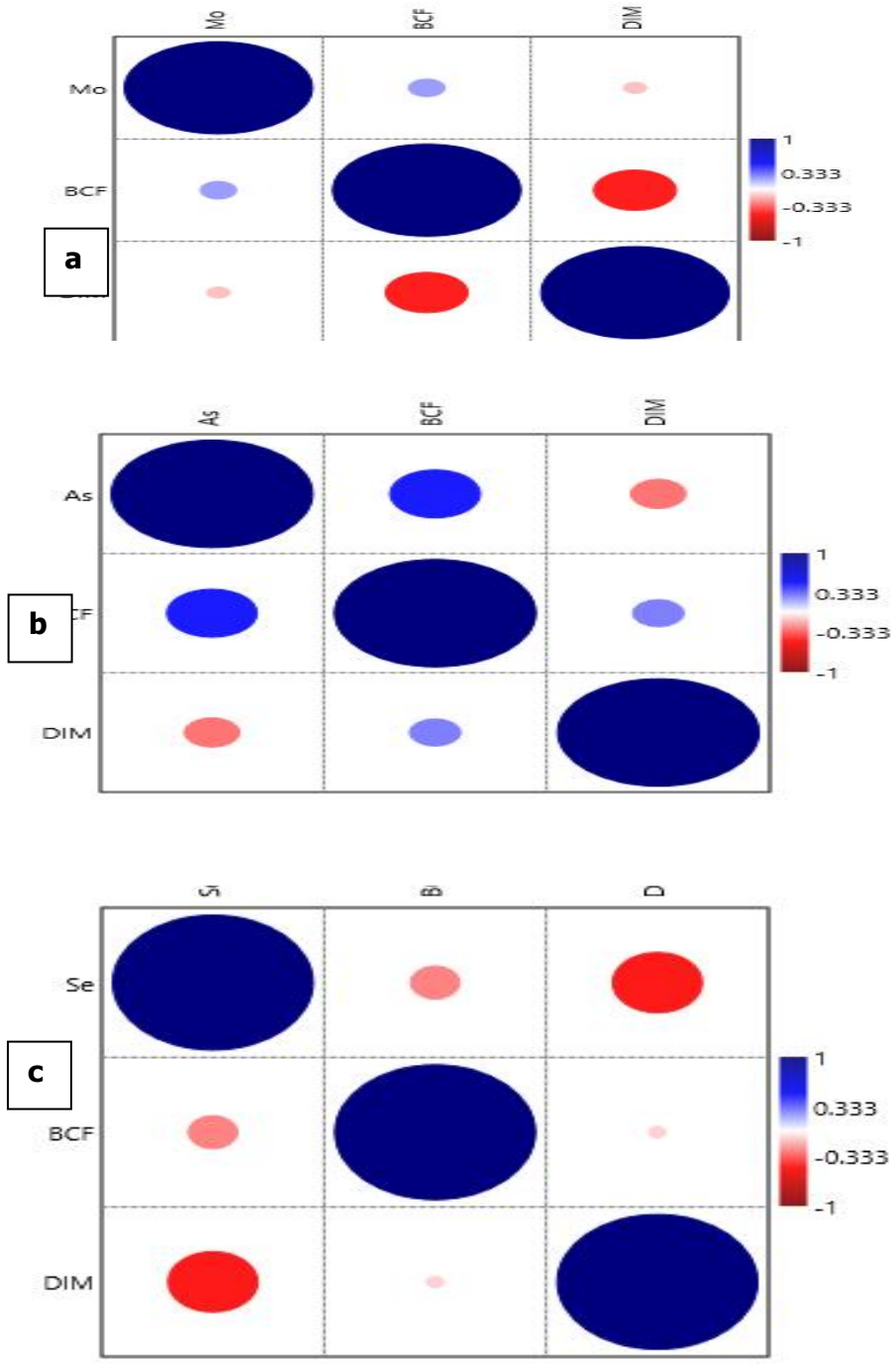


FIG. 4 (4A-4C): CORRELATION OF SOIL-PLANT INTERACTION AMONG MOLYBDENUM (MO), BCF AND DIM (A), ARSENIC (AS), BCF AND DIM (B), MOLYBDENUM (MO), BCF AND DIM (C).

CONCLUSION

The elemental profile of soils and medicinal plants found that, whereas soil levels of Mo, As, and Se were mostly safe or crucial, their accumulation in plants, particularly Mo andAs, frequently

surpassed suggested values. This disparity highlights the possibility of bioaccumulation despite seemingly safe soil conditions. Species such as *Calotropisgigantea*, *Cannabis sativa*, and *Menthaspicata* have a higher propensity for trace metal uptake, which could represent toxicity hazards if used medicinally without thorough screening. The limited connections between soil and plant metal concentrations suggest that uptake is influenced by more complex elements than soil content, such as pH, organic matter, and metal interactions. Regular monitoring and management of medicinal plants from metal-contaminated regions is advised to protect human and animal health.

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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