

Assessment of contamination pattern of medicinal plants with heavy metals in polluted soils

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Abstract

This study investigated the accumulation patterns of heavy metals, i.e., Cr, Ni, Cu, As, Pb, and Cd, from heavily polluted agricultural soil with 23 medicinal plant species commonly used in traditional Indian medicine. The bark, leaf, and fruit samples, along with corresponding soils, were collected from 45 locations in central India's Ambagarh Chowki district, Chhattisgarh state, and analyzed via ICP–MS. Plant parts (bark, leaves, mesocarps and seeds) presented distinct accumulation patterns of these heavy metals (10.4–58.4, 20–144, 8.8–74.4 and 11.2–113.7 mg kg⁻¹), with the highest total concentrations found in *Bauhinia racemosa* (BR) barks, *Careya arborea* (CA) leaves, *Tamarindus indica* (TI) mesocarps, and *Terminalia arjuna* (TA) seeds. Selective element enrichment was observed, varying significantly among species. Statistical analysis revealed strong correlations between soil composition and plant accumulation patterns. Family-specific accumulation trends emerged, with *Lecythidaceae* accumulating more heavy metals. While most species were within safe ranges, some exceeded safety thresholds for As, Cd, and Pb, particularly in areas with high soil contamination. These results establish important baselines for medicinal plant safety in contaminated regions and identify promising candidates for phytoremediation, suggesting the need for location-specific monitoring protocols in traditional medicine practices.

Introduction

As important sources of both traditional and modern medicines, medicinal plants play crucial roles in human cultural development (Saleh et al., 2015). Approximately 10% of vascular plants (n ≈ 350,000) are used as medicinal plants and are cultivated for pharmaceutical purposes (Salmerón-Manzano et al., 2020). These plants have been used for centuries because of their rich mineral and phytochemical contents, as well as their antimicrobial properties. Compared with conventional treatments, they are employed to address several health concerns, including weight management, liver function enhancement, wound healing, and disease prevention, which are often associated with fewer reported side effects (Fatemeh et al., 2018). Furthermore, medicinal plants serve as valuable resources for the extraction of modern medicines (Chen et al., 2016).

The bark of medicinal trees contains beneficial phytochemical constituents that protect the plant from damage and water loss and has been found to be useful in treating conditions such as asthma, skin diseases, and diabetes (Aye et al., 2019). Plants have been identified as bioindicators of environmental pollution because of their ability to accumulate contaminants from air, water, and soil (Nouchi, 2002; Zaghloul et al., 2020). Research groups worldwide have reported heavy metal contamination in medicinal plants and its potential implications for human health, including studies from Brazil, China, Ghana, India, Pakistan, South Africa, Romania, and the United Arab Emirates (Asiminicesei et al., 2020; Chen et al., 2021; Dghaim et al., 2015; Luo et al., 2021; Meng et al., 2022; Okem et al., 2014; Paula et al., 2020; Soomro et al., 2021; Vinogradova et al., 2023).

Aegle marmelos (L.) Corrêa possesses laxative, febrifuge, and expectorant properties, and its extract is used to treat various conditions, including ophthalmia, inflammation, and diabetes (Baliga et al., 2013). *Syzygium cumini* (L.) Skeels, *Diospyros melanoxylon* Roxb., and *Schleichera oleosa* (Lour.) Oken are multipurpose trees whose fruits are edible and are used for treating inflammation, ulcers, and diarrhea (Rathore et al., 1972; Sarkar et al., 2022; Swami et al., 2012). *Buchanania lanzan* Spreng seeds are used in traditional food preparations and as remedies for various health issues, including headache, respiratory disorders, mouth ulcers, cough, and constipation, with all parts of the plant having medicinal applications (Elias et al., 2021).

Murraya koenigii (L.) Spreng. is an aromatic plant with antioxidant, antidiabetic, anti-inflammatory, anticancer, and neuroprotective properties and is considered an essential ingredient in cuisine (Mahalik and Mandal, 2021). *Moringa oleifera* Lam. is a versatile tropical tree rich in minerals and bioactive compounds and is used in folk medicine to treat inflammation, joint pain, and cancer (Ercan et al., 2021). *Phyllanthus emblica* L. is an important medicinal plant used to cure many diseases because it is rich in phytochemicals, vitamins, and minerals (Saini et al., 2022). *Lawsonia inermis* L. is a globally recognized medicinal plant with ethnobotanical, medicinal, and cosmetic applications (Abdulfatai & Ayotunde, 2022).

Plants such as *Terminalia* species, *Cassia fistula* L., *Albizia odoratissima* (L.f.) Benth., *Albizia lebbek* (L.) Benth., *Acacia nilotica* (L.) Willd. ex Delile, *Hibiscus rosa-sinensis* L., *Ficus benghalensis* L., and *Ficus religiosa* L. are medicinal trees with documented therapeutic applications (Das et al., 2020; Fatima et al., 2021; Issoufou et al., 2020; Kajaria, 2015; Khristi and Patel, 2017; Murugesu et al., 2022; Mwangi et al., 2017; Venkanna et al., 2017). *Azadirachta indica* A. Juss. possesses antimicrobial properties, and its extract is used to enhance body immunity and treat skin disorders (Abbas et al., 2020).

Medicinal plants accumulate, biomonitor, and phytoremediate minerals, including nutrients, heavy metals, and rare earth elements (Dar et al., 2020; Liu et al., 2022; Sahu et al., 2022; Zhang et al., 2023). Among these, heavy metals associated with these plants can cause serious health hazards (Asiminicesei et al., 2020; Hlihor et al., 2022).

Therefore, in this work, we studied the phytoaccumulation potential of medicinal plants, including *A. marmelos*, *Careya arborea* Roxb., *S. cumini*, *L. inermis*, *M. koenigii*, *M. oleifera*, *P. emblica*, *Terminalia arjuna* (Roxb.) Wight & Arn., *Terminalia bellirica* (Gaertn.) Roxb., *Terminalia chebula* Retz., *Tamarindus indica* L., *A. odoratissima*, *A. nilotica*, *A. lebbek*, *A. indica*, *Bauhinia racemosa* Lam., *B. lanzan*, *C. fistula*, *H. rosa-sinensis*, *D. melanoxylon*, *F. benghalensis*, *F. religiosa*, and *S. oleosa* toward various heavy metals (Cr, Ni, Cu, As, Pb, and Cd). The transport mechanisms, toxicity, and health hazards of these metals in various plant parts (bark, leaf, and fruit) are discussed.

Materials and methods

Sample collection

Twenty-three plant species with known therapeutic properties belonging to the families Ebenaceae, Malvaceae, Lecythidaceae, Moringaceae, Phyllanthaceae, and Combretaceae were selected for this study and collected in duplicate (Table S1).

Field surface soil samples (1.0 kg, 0–10 cm depth) and medicinal plant samples (in duplicate) were collected from 45 locations (Fig. 1) in June 2021 from the Ambagarh Chowki district (20.59° N 80.75° E), Chhattisgarh, India.

Circular bark samples (50 mm diameter) were collected at a height of 2.0 m via a belt punch and hammer, with a 5 mm hole made in the center. Species details and collection dates were recorded. Approximately 1.0 kg each of the bark, leaf, and fruit samples were collected from 2.0 m above ground level. The bark samples were washed thoroughly with ultradeionized water three times.

Sample preparation

All the samples were sun-dried for one week. Leaves and fruits (mesocarps and seeds) were separated and ground into a fine powder and then sieved to obtain particles ≤ 0.1 mm in size. The samples were transferred to colored glass bottles and dried overnight in a hot air oven at 50°C. The dried samples were sent to France (LU Nancy) for ICP–MS analysis.

Powdered soil samples (10 g) were mixed with 20 mL of deionized water in 250 mL conical flasks, shaken, and left overnight at room temperature ($30 \pm 2^\circ\text{C}$). The pH value of the soil extract was measured via an LI-120 pH meter (Elico Ltd., Hyderabad, Telangana, India).

The samples (0.2 g) were mixed with HNO_3 (3.5 mL, 65%, AR, Optima) and H_2O_2 (1 mL, 35%, AR, Optima) in 5 mL Teflon tubes and digested in a microwave oven. The cooled solutions were filtered through quartz filters (1 μm) and diluted to 25 mL with ultrapure water for ICP–MS analysis.

Analysis of elements

An ICP–MS (X Series II Model, Thermo Fischer Scientific, Waltham, MA, USA) was used for elemental analysis. An internal standard solution of In (10 mg L^{-1}) was spiked into the standard and working solutions. The detection limits (DLs) and quantification limits (QLs) for the elements in the soil samples ranged from 0.05–53.03 and 0.16–384.52 $\mu\text{g g}^{-1}$, respectively. For the plant samples, lower limits were observed (0.007–2.252 and 0.012–3.494 $\mu\text{g g}^{-1}$). The samples were analyzed in duplicate, and the mean values are reported.

Indices evaluation

The soil and plant indices, including the contamination factor (C_f), enrichment factor (E_f), pollution load index (PLI), and transport factor (T_f), were evaluated following established methods (Barbieri et al., 2015; Gruszecka-Kosowska, 2019; Rudnick and Gao, 2003):

$$C_f = [M_s]/[M_{cr}]$$

$$E_f = [M_s/Al_s]/[M_{cr}/Al_{cr}]$$

$$PLI = (C_{f1} \times C_{f2} \times C_{f3} \times \dots \times C_{fn})^{1/n}$$

$$T_f = [M_p]/[M_s]$$

where M_s , M_{cr} , M_p , Al_s , and Al_{cr} represent analyte concentrations in the soil, the Earth's crust, and plant tissue, Al in the soil, and Al in the Earth's crust, respectively.

Exposure assessment

Given the widespread use of medicinal plants in traditional medicine and the pharmaceutical industry, and considering that heavy metals are among the most dangerous contaminants due to their toxicity, quality control of these plants with respect to heavy metal contamination is essential to ensure consumer safety. Health-related parameters, including estimated daily intake (EDI, $\text{mg kg}^{-1} \text{ day}^{-1}$), hazard quotient (HQ), hazard index (HI), and cancer risk (CR), were computed following Luo et al. (2021):

$$EDI = [C \times IRD] / BW$$

$$HQ = [C \times IR \times Ef \times EDI \times t] / [AT \times BW \times RfD]$$

$$CR = [C \times IR \times Ef \times EDI \times t \times SFO] / [AT \times BW]$$

$$HI = \sum HQ$$

where C, IRD, BW, IR, Ef, and AT represent the concentration (mg kg^{-1}), daily ingestion rate (0.01 kg day^{-1}), body weight (60 kg), daily dosage of herbal medicine or ingestion rate (0.5 kg day^{-1}), exposure frequency (90 days per year), and average lifetime ($365 \text{ days} \times 70 \text{ years}$), respectively. The parameter t represents the transfer rate of heavy metals to herbal detection: 14% for Cd, Cu, and Pb and 35% for As. RfD refers to the oral reference dose ($\text{mg kg}^{-1} \text{ day}^{-1}$), which is 0.0035 for Pb, 0.0005 for Cd, 0.0003 for As, 0.0003 for Hg, and 0.04 for Cu. SFO ($\text{mg kg}^{-1} \text{ day}^{-1} \text{ bw}^{-1}$) is the oral slope factor indicating cancer

severity, with proven values for three heavy metals: 6.1 for Cd, 1.5 for As, and 0.0085 for Pb, while 10^{-6} is the conversion factor (USEPA 1989, 2009, 2012; Liu et al., 2013; Farmer et al., 2019).

Quality assurance/quality control (QA/QC) analysis

Blank samples (where the concentration of the metal of interest was below the detection limit) were included. Several standards with values matching the practical range of grades in the actual samples were employed. Certified reference materials, including Oriental soil and Basma tobacco leaves (INCT-OBTL-5, LGC Promochem, Molsheim, France), were used for instrument standardization.

Statistical analyses

The average values ($n = 2$) of the elements in the soil and plant samples are presented. The Kruskal–Wallis H test was applied to determine variations in the concentrations of the elements present in various parts of the plants, i.e., the bark, leaves, and seeds. Factor analysis was performed via IBM (Armonk, NY, USA) SPSS 20.0 to identify trace element sources in the collected leaf and bark samples. Varimax rotation with Kaiser normalization was selected, and elements with commonalities higher than 0.61 were retained.

Results

Geology and concentration in soil

The geological relationships in the region are complex. The different metamorphic and geochemical processes that these rock types have undergone during their formation and settlement have led to their enrichment in rare earth elements. The formation of other rare earth elements, particularly arsenic, is controlled by this lithology and structure. Therefore, understanding the geology, chronostratigraphic sequence, and structural history is crucial for understanding rare earth element formation behavior in the region.

The study area comprises four geological types: the Dongargarh granite, Bailadila, Nandgaon Bijli Rhyolite, and Nandgaon Pitepani groups (Fig. 1). The Chowki area of the Rajnandgaon district is part of the Indian shield and falls within the Central India craton. Regionally, the area forms part of the Dongargarh–Kotri rift zone and is surrounded by Paleo-Proterozoic Dongargarh Batholithic granites in the west, the Meso-Proterozoic platform sequence of the Chhattisgarh Supergroup in the northeast, and the Paleo-Proterozoic Supra-Crustal sediments of the Iron ore series in the south.

The area is situated within one of India's most significant mineralization provinces, where Dalli Rajhra Iron ore deposit, Malajkhanda porphyry copper deposit, Chandi-Dondri fluoride-lead deposit, Kotri Gold prospect, and Bodal uranium prospects are already being exploited, while base metal prospecting in the nearby area is ongoing. The rocks in the area have a regional strike in the N–S to NW–SE direction with subvertical to vertical dips, suggesting antiform or synforms. The rock types are represented by rhyolite, rhyolite porphyries, basalts, and thin sheets of mildly ultrabasic (tremolite schists) rocks.

The Dongargarh granite batholith was emplaced into or formed comagmatically with the rhyolite sequence. The metamorphism is low-grade greenschist to epidote amphibolite facies. The sheared rock and metamorphism are considered due to the emplacement of the epizones Dongargarh granite batholith (Krishnamurthy et al., 1988), which deposited fine veins containing disseminated uranium, fluoride, and sulfide minerals during the hydrothermal phase. On the basis of the lithological characteristics of the region, Bhata (Entisol), Matasi (Inceptisol), Dorsa (Alfisol), and Kanhar (Vertisol) soils are common (Krishnamurthy et al., 1988). The concentrations of Cr, Cu, Ni, As, Cd and Pb were in the following ranges: 17.9–1100, 12.4–55.8, 11.4–325, 0.03–0.58 and 11.1–54.5, with average values of 170 ± 211 , 36.8 ± 9.9 , 82 ± 60 , 77.2 ± 70.0 , 0.12 ± 0.10 and 24.1 ± 7.5 mg kg⁻¹, respectively. Among these elements, a several-fold higher concentration of As than the background level of 5.0 mg kg⁻¹ was detected in the agricultural soil of this region (Patel et al., 2023).

Distribution of elements in the bark samples

Bark is a source of bioactive compounds with various medicinal properties, including anti-inflammatory, antioxidant, antidiabetic, and antimicrobial activities, and is used in the preparation of various formulations in the Indian system of medicine (Pásztor et al., 2016). The distribution of elements in the bark samples is shown in Table 1. The concentrations of Cr, Ni, Cu, As, Cd, and Pb in the bark of the 23 plants were in the 3.45–42.5, 0.27–3.02, 1.57–17.4, 0.022–0.461, and 2.70–37.6 mg kg⁻¹ ranges, respectively, with maximum values in *T. indica* (TI), *C. arborea* (CA), *A. marmelos* (AM), *D. melanoxylon* (DM), *S. oleosa* (SO), and *M. oleifera* (MO) bark, respectively. These results suggest potential applications for the phytoremediation of heavy metal contamination.

Table 1
Elemental composition of bark samples from medicinal plants (mg kg⁻¹, dry weight).

Bark	Cr	Ni	Cu	As	Cd	Pb
AM	8.10	1.16	17.44	0.93	0.022	3.53
CA	16.25	3.02	10.10	1.36	0.039	8.40
EJ	5.04	0.96	3.14	1.32	0.059	7.00
LI	7.57	1.83	5.75	0.60	0.300	8.04
MK	5.94	0.76	3.74	0.88	0.197	7.12
MO	10.73	1.20	3.18	2.45	0.039	37.63
PE	3.63	0.27	1.66	0.54	0.219	4.09
TA	3.45	0.63	1.57	1.58	0.036	3.69
TB	4.38	0.36	3.22	0.84	0.215	2.70
TC	4.62	1.09	2.84	2.49	0.042	7.34
TI	42.46	1.81	10.36	0.80	0.047	3.41
AO	6.03	1.08	2.37	3.20	0.050	6.96
AN	4.87	1.06	2.23	2.25	0.033	5.44
AL	5.11	0.82	2.07	1.82	0.023	9.20
AI	3.57	1.17	3.16	2.02	0.027	5.75
BR	10.79	2.27	4.37	6.70	0.173	34.15
BL	4.23	0.73	1.67	0.45	0.031	13.47
CF	3.55	0.77	2.08	0.58	0.303	3.97
HR	4.63	0.87	2.21	4.25	0.136	7.35
DM	7.83	1.53	6.05	7.24	0.034	7.15
FB	5.13	1.12	2.66	2.89	0.050	6.90
FR	6.09	1.50	3.61	2.87	0.031	4.39
SO	5.35	0.71	4.97	1.57	0.461	4.59

Values represent means of duplicate analyses. Plant species abbreviations: AM: *Aegle marmelos*, CA: *Careya arborea*, EJ: *Eugenia jambolana*, LI: *Lawsonia inermis*, MK: *Murraya koenigii*, MO: *Moringa oleifera*, PE: *Phyllanthus emblica*, TA: *Terminalia arjuna*, TB: *Terminalia bellirica*, TC: *Terminalia chebula*, TI: *Tamarindus indica*, AO: *Albizia odoratissima*, AN: *Acacia nilotica*, AL: *Albizia lebbeck*, AI: *Azadirachta indica*, BR: *Bauhinia racemosa*, BL: *Buchanania lanzan*, CF: *Cassia fistula*, HR: *Hibiscus rosa-sinensis*, DM: *Diospyros melanoxylon*, FB: *Ficus benghalensis*, FR: *Ficus religiosa*, SO: *Schleichera oleosa*.

Distribution of elements in the leaf samples

Leaves are readily available in large quantities for medicinal uses and are sources of minerals and phytochemicals (Rathor, 2021). The distributions of heavy metals are shown in Table 2. The total concentration of these elements varied from 20 to 144 mg kg⁻¹, with the highest value in *C. arborea* (CA) leaves. The highest phytoremediation potential of metals, i.e., Cr, Ni, As, and Pb, was detected in the CA tree leaf. These findings suggest the potential for rhytofiltration applications.

Table 2
Elemental composition of leaf samples from medicinal plants (mg kg⁻¹, dry weight).

Leaf	Cr	Ni	Cu	As	Cd	Pb
AM	5.5	6.65	75.7	0.48	0.022	2.93
CA	38.1	23.13	53.9	8.54	0.074	20.34
SC	3.2	2.82	11.4	1.69	0.017	8.66
LI	28.9	12.92	21.3	7.14	0.202	14.29
MK	3.4	3.51	22.0	1.14	0.068	4.12
MO	5.9	3.46	18.4	5.34	0.052	6.45
PE	4.5	4.60	7.90	0.97	0.047	3.69
TA	3.2	2.49	25.4	3.84	0.039	5.22
TB	13.6	7.43	7.80	2.22	0.144	7.47
TC	4.8	10.78	34.9	4.54	0.044	6.73
TI	8.2	5.57	72.7	1.28	0.043	7.64
AO	3.8	2.31	21.8	2.01	0.023	3.07
AN	2.8	3.70	21.3	0.35	0.014	2.10
AL	6.1	3.18	14.8	1.29	0.017	7.27
AI	3.8	2.42	14.5	0.98	0.032	4.09
BR	6.2	5.33	11.5	1.72	0.092	9.33
BL	7.5	15.53	3.90	0.78	0.053	6.02
CF	8.0	2.06	112.2	0.32	0.267	2.79
HR	3.8	3.30	22.9	5.79	0.488	5.97
DM	5.4	5.12	32.8	4.74	0.258	5.43
FB	3.9	1.85	5.70	3.22	0.033	5.33
FR	3.4	1.90	13.9	1.84	0.038	4.54
SO	3.6	2.96	22.6	0.51	0.205	3.33
Values represent means of duplicate analyses. Plant species abbreviations as in Table 1.						

Distribution of elements in the mesocarp and seed samples

Fruits provide key vitamins, bioactive compounds, fiber, and minerals to the human body (Karasawa et al., 2018). The distribution of elements in the edible mesocarp of seven fruits is summarized in Table 3. The total concentration of heavy metals ranged from 8.8–74.4 mg kg⁻¹, with maximum values in the *S. oleosa* fruit mesocarp.

Table 3
Elemental composition of mesocarp samples from selected medicinal plants (mg kg⁻¹, dry weight).

Mesocarp	Cr	Ni	Cu	As	Cd	Pb
AM	9.38	10.52	13.0	3.23	0.018	8.13
EJ	18.97	11.26	14.5	1.08	0.009	3.55
MO	2.71	1.86	9.2	0.55	0.018	1.31
TI	4.27	2.77	61.1	0.18	0.009	6.07
AI	3.14	2.04	10.7	0.30	0.014	1.21
DM	3.08	1.98	2.7	0.15	0.005	0.90
SO	7.22	7.98	42.3	2.02	0.328	8.59
Values represent means of duplicate analyses. Plant species abbreviations as in Table 1						

Seeds of medicinal plants are sources of valuable and active metabolites that are beneficial for medicine and pharmaceuticals (Kumar et al., 2021). The distributions of the 6 elements in the 15 seeds are presented in Table 4. Their total concentrations varied from 11.2–113.7 mg kg⁻¹, with the maximum value

occurring in *T. arjuna* tree seeds. These TA plant parts, i.e., the bark, leaves, and seeds, could be used as bioabsorbents for the remediation of air and water pollutants.

Table 4
Elemental composition of seed samples from medicinal fruits (mg kg⁻¹, dry weight).

Seed	Cr	Ni	Cu	As	Cd	Pb
AM	3.9	9.71	12.4	0.72	0.009	3.3
CA	15.8	12.47	23.0	0.98	0.009	4.0
EJ	3.1	2.29	4.5	0.15	0.005	1.2
LI	17.0	13.67	24.7	1.03	0.060	4.6
TA	12.4	10.56	73.0	1.91	0.035	15.8
TB	4.4	4.23	13.2	0.57	0.090	2.0
TC	4.8	7.65	9.9	2.66	0.016	2.6
TI	3.1	2.90	20.9	0.19	0.006	2.9
AO	14.0	13.69	20.2	1.33	0.028	15.8
AN	2.5	10.39	14.4	0.11	0.014	1.1
AL	3.1	6.09	12.4	0.68	0.004	0.8
AI	2.3	1.94	19.6	0.07	0.008	0.3
BL	8.9	5.49	13.7	1.00	0.370	2.6
CF	3.4	4.71	14.5	0.12	0.264	2.2
SO	2.5	5.42	36.2	0.63	0.146	1.2
Values represent means of duplicate analyses. Plant species abbreviations as in Table 1.						

Discussion

Soil characteristics

The soil of Ambagarh Chowki, Chhattisgarh, is neutral (pH = 6.77 ± 1.21) and ranges from blackish to black in color, containing alluvium and colluvium materials. High concentrations of crustal element oxides (Al, Fe, Mg, and Ca) have been observed (Verma et al. 2025). The total concentrations of 6 elements (Cr, Cu, Ni, As, Cd, and Pb) in the surface soil samples (n = 45) ranged from 124–1394 mg kg⁻¹ (Table S2). In terms of the mean concentration, the elements in the soil decreased in the following order: Cr (170) > Ni (81.9) > As (77.2) > Cu (36.8) > Pb (24.1) > > Cd (0.12 mg kg⁻¹).

The soil pollution indices are listed in Table S3. Ni, Cr, Cu, Cd, and Pb were moderately enriched (≥ 3–≤6), and As was strongly enriched (≥ 6) in the field soil of Ambagarh Chowki. The C_f and PLI values were closely related (r = 0.99). Among these elements, As was found to significantly contaminate the soil (Patel et al., 2023).

Transfer factor

The metals are absorbed by the plant through the root, transported to the xylem, and translocated to the shoot. They form chelates with organic acids, i.e., citric acid, oxalic acid, etc., in cells and move within cells. They may be deposited in the cell walls to reduce mobility and toxicity.

The transfer factors (T_f) of the elements from the soil to the bark and leaves are presented in Tables S4–S5. The transfer factors of Cr, Ni, Cu, As, Cd, and Pb from the soil to the bark varied over the 0.02–0.21, 0.02–0.23, 0.18–1.18, 0.01–0.2, 0.07–4.7, and 0.1–1.53 ranges, respectively with maximum values in BR, DM, BL, BR, SO, and MO, respectively. Similar Tf values from soil to leaf for were observed Cr, Ni, Cu, As, Cd and Pb, in the 0.02–0.21, 0.02–0.23, 0.18–1.18, 0.01–0.20, 0.07–4.7 and 0.10–1.53 ranges, with maximum values of TI, HR, BR, TI, FR and MK, respectively.

Uptake of minerals from the bark to the leaves, mesocarp, and seeds

Minerals are responsible for regulating plant metabolism and the ecosystem functions of plants (Li et al., 2023). The concentration ratios of Cr, Ni, Cu, As, Cd and Pb from the bark to the leaf were in the following ranges: 0.19–3.82, 0.38–9.29, 0.11–12.5, 0.15–11.9, 0.21 7.6 and 0.17–2.8, with maximum values in the LI, BL, CF, LI, DM, and TB, respectively (Table S6). Generally, lower uptake of heavy metals from the bark to the mesocarp and seeds was observed (Tables S7-8).

On average, higher concentrations of Cr, Cd, and Pb were observed in the bark, ranging from 3.5–42.5, 0.022–0.461, and 2.7–37.6 mg kg⁻¹, respectively. Relatively high concentrations of As, Ni, and Cu were detected in leaves, ranging from 0.32–8.54, 1.85–23.1, and 3.9–112 mg kg⁻¹, respectively.

Effect of plant taxonomy

The taxonomy of the plants strongly influenced the concentrations of elements in the bark, leaves, and seeds (**Table S9**). In the bark samples, the maximum concentrations of the elements were distributed among the plant families as follows: As in Ebenaceae; Cr and Cu in Lecythidaceae; Pb in Moringaceae; and Ni and Cd in Rutaceae and Sapindaceae, respectively.

A different pattern of element concentration maxima was observed in leaves: Cr, Ni, Cu, Zn, As, and Pb were highest in Lecythidaceae, and Cd was highest in Malvaceae. Similarly, the maximum concentrations of elements in seeds were distributed among families as follows: Cr and Ni were highest in Lythraceae; Pb was highest in Lecythidaceae; Cu was highest in Sapindaceae; and Cd was highest in Anacardiaceae.

Source apportionment

Three factors explaining 73.97% of the total variance were selected for interpretation (**Table S10**). The KMO value (Bartlett's test < 0.001) was 0.67.

Factor 1, which explained 41.15% of the total variance, presented high loadings for As and rare earth elements, which are abundant in the continental crust (Walters and Lusty, 2011). Elements such as La, Ce, Pr, Nd, Sm, and Eu are commonly utilized in fertilizers. Therefore, this factor was attributed to a mixed source of fertilizer use and continental crust.

Factor 2, with high loadings of Al, Fe, Co, Cr, Mn, Fe, Ni, and Ce, explained 20.09% of the variance. Al is a crucial tracer of soil parent material (Wimolwattanapun et al., 2011). On the other hand, La, Ce, Pr, Nd, Sm, and Eu are most utilized in fertilizers (Hu et al., 2004). These elements are considered markers of pollution from natural sources because of their widespread presence in crustal parent material (Jiang et al., 2020; Wang et al., 2020).

Factor 3, which explained 12.72% of the variance, presented high loadings of P, K, S, and Mg. Phosphorus in soils originates from atmospheric deposition and agricultural activities (Ahmad et al., 2017; Zhang et al., 2020). While K and P originate from biomass burning, Mg and S can be linked to fossil fuel burning (Akbarimorad et al., 2024). This factor was identified as a mixture of agricultural activities and solid fuel burning.

Toxicity

The mean concentrations of the elements in the soil samples (n = 45) were as follows: Ni (81.88), As (77.21), Cd (0.12), Cr (169.95), Cu (36.78), and Pb (24.13) mg kg⁻¹. These concentrations exceed permissible limits reported in the literature: Co (20), Ni (50), As (5), Cd (0.02), Zn (0.6), Cr (1.6), Cu (10), and Pb (2) mg kg⁻¹ (Adagunodo et al., 2018; Vodyanitskii, 2016), indicating potential health hazards.

The tolerance limits for elements in plants are Cr (2.30), Cd (0.20), Pb (0.30), Ni (0.1), and Cu (10), mg kg⁻¹ (Alireza et al., 2015; Aquilina et al., 2009; FAO/WHO, 2011; Food standard, 2003; Pearson and Ashmore, 2019). The accumulated concentrations of these elements in the studied plants were found to be far above the reported limits.

Human exposure

The provisional tolerable daily intake (PTDI) values (mg·kg⁻¹ d⁻¹) reported for As, Cu, Pb, and Cd are 0.00214, 0.5, 0.00357, and 0.00083, respectively (Sawut et al., 2018). In the Ambagarh Chowki area, the PTDI values (for the bark and leaf samples) were 0.00321–0.08544 for As, 0.03888–1.12167 for Cu, 0.02097–0.37632 for Pb, and 0.00014–0.00488 for Cd. The PTDI values for As and Pb exceeded the recommended values of 0.00214 and 0.00357 mg·kg⁻¹ d⁻¹. For Cu and Cd, only a few samples exceeded the limit values (**Table S11**).

The THQ and CR values for toxic elements (As, Cd, and Pb) in the bark and leaf samples ranged from 3.48×10⁻⁸ to 2.16×10⁻² and from 8.18×10⁻¹¹ to 8.24×10⁻⁷, respectively (**Tables S12–14**). The HI values for As, Cs, Pb, and Cu in the bark and leaf samples ranged from 5.65452×10⁻⁴ to 4.3804111×10⁻² and from 9.14×10⁻⁴ to 5.48×10⁻², respectively (**Table S15**). The THQ and CR values did not exceed the limit values of 1 and 1×10⁻⁴, respectively, suggesting that there are no expected noncancer or cancer health risks for people residing in this area (USEPA, 2005).

Future research directions and applications

The findings of this study open several promising avenues for future research and practical applications in both environmental science and traditional medicine. Four main areas deserve particular attention.

In terms of phytoremediation and environmental applications, the exceptional accumulation of critical elements by certain species, particularly *B. racemosa*, *T. arjuna*, and *C. arborea*, suggests their potential use in phytoremediation strategies. Future research should focus on the optimization of cultivation conditions to maximize metal uptake efficiency while investigating rhizosphere processes and their role in element selectivity. Sustainable harvesting practices for contaminated biomass need to be developed, along with the evaluation of potential value chains for recovered metals. Additionally, a comprehensive assessment of the performance of these species in different contaminated environments would provide valuable insights for large-scale applications.

With respect to quality control and safety protocols, the varying accumulation patterns observed across plant families highlight the need for systematic quality control approaches. The development of region-specific safety guidelines based on local soil conditions should be prioritized, alongside the establishment of standardized sampling protocols for routine monitoring. Rapid screening methods for toxic element detection need to be created, and blockchain-based traceability systems for medicinal plant products could ensure quality control throughout the supply chain. Risk assessment frameworks that consider both beneficial and toxic elements would provide a more comprehensive approach to safety evaluation.

The complex relationship between soil composition and plant mineral content has important implications for therapeutic applications in traditional medicine. Future work should address the investigation of the bioavailability of accumulated elements in traditional preparations and study the impact of processing

methods on element concentrations. The development of cultivation guidelines to optimize beneficial element contents is essential, as is the assessment of seasonal variations in element accumulation. The exploration of potential synergistic effects between accumulated elements and bioactive compounds could reveal new therapeutic possibilities.

The findings also suggest several areas requiring policy attention. Specific guidelines for medicinal plant cultivation in contaminated areas need to be developed, along with the establishment of maximum permissible limits for toxic elements in medicinal plant products. The creation of certification systems for "clean" medicinal plant production would help ensure consumer safety, while the implementation of monitoring programs in known contaminated areas could prevent unsafe practices. The development of remediation protocols for contaminated cultivation sites is also crucial.

This research provides a foundation for these future directions, but successful implementation will require long-term monitoring programs to understand temporal variations and collaborative efforts between research institutions, regulatory bodies, and traditional medicine practitioners. The integration of traditional knowledge with modern analytical approaches is essential, as is the development of cost-effective monitoring solutions. Education and training programs for stakeholders will be crucial for effective implementation.

The successful pursuit of these research directions could significantly increase both the safety and efficacy of traditional medicine practices while contributing to environmental remediation efforts. Moreover, the development of standardized protocols and guidelines could help establish a more sustainable and scientifically grounded approach to medicinal plant utilization. This comprehensive approach would benefit both public health and environmental quality while preserving and enhancing the value of traditional medicinal practices.

Conclusions

This study of 23 medicinal plants commonly used in traditional Indian medicine revealed significant patterns of heavy metal accumulation across different species and plant parts. The total heavy metal concentrations varied substantially, ranging from 10.4–58.9 mg kg⁻¹ in bark (maximum in BR), 20.0–144.1 in leaves (maximum in CA), and 11.2–113.7 mg kg⁻¹ in seeds (maximum in TA). Notable accumulation was observed in several species: TI bark accumulated Cr and Pb (42.5 and 37.6 mg kg⁻¹), CA leaves accumulated Ni and As (23.1 and 8.5 mg kg⁻¹), CF leaves accumulated Cu (112.2 mg kg⁻¹), and HR leaves accumulated Cd (0.49 mg kg⁻¹). Soil analysis revealed significant contamination with As (77.2 mg kg⁻¹) and other heavy metals, reflecting both geogenic and anthropogenic sources, as confirmed by factor analysis, which identified three main elemental sources: continental crust (41.15% of variance), soil parent material (20.09%), and agricultural activities (12.72%). Despite these elevated soil concentrations, health risk assessments indicated that the THQ and CR values remained below critical thresholds (THQ < 1, CR < 1×10⁻⁴), suggesting minimal immediate health risks from therapeutic use. However, the accumulation of toxic elements above permissible limits in some species (particularly As and Pb, with PTDI values reaching 0.08544 and 0.37632 mg kg⁻¹d⁻¹, respectively) emphasizes the need for systematic monitoring and quality control in medicinal plant production. Plant taxonomy significantly influences element accumulation, with distinct profiles observed among families such as Malvaceae, Lecythidaceae, and Combretaceae. These findings provide crucial information for the safe use of medicinal plants while highlighting their potential for phytoremediation, although further research on selective element accumulation mechanisms is warranted for developing comprehensive quality control guidelines.

Declarations

Data Availability

The data are available in the text and supporting document. Further information could be getting from corresponding author on request.

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All authors conceived the idea. D.V. sampling and data curation. P.K.S. supervision. K.S.P. conceptualization and writing original draft. P.K.P. Resource development and funding. S.V. validation and graphics. S.Y. source apportion. P.M-R. Editing. D.B. methodology and data generation.

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Competing interests

The authors declare no conflict of interest.

Supplementary Information

HMR-Sup.

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Figures

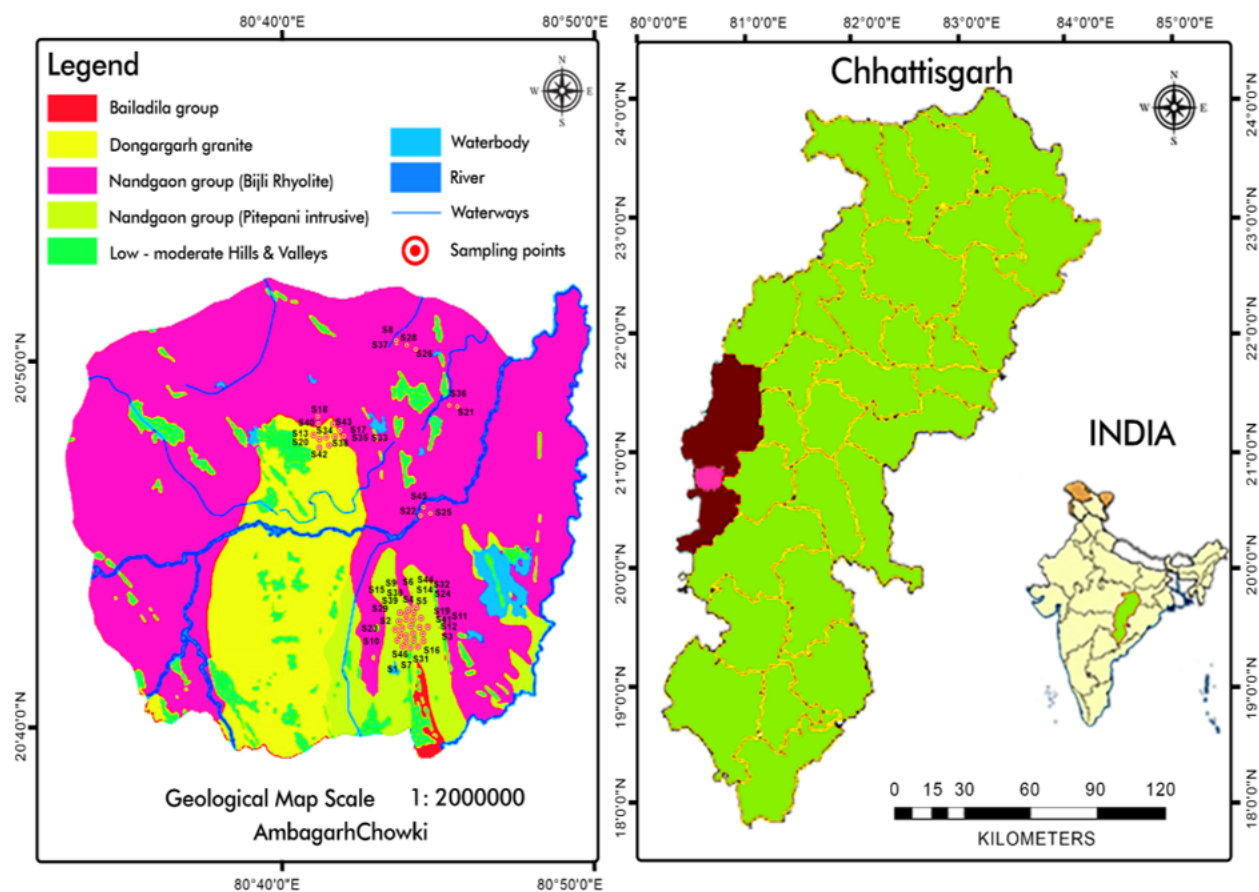


Figure 1

Representation of soil sampling locations in Ambagarh Chowki district, Chhattisgarh, India.

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