Assessment of Potentially Toxic Trace Elements in Agricultural Soils of Benighat Area, Nepal

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Abstract

This study investigates the presence of potentially toxic trace elements (PTEs), including arsenic (As), cadmium (Cd), lead (Pb), and thallium (Tl), in agricultural soils of Benighat area, Dhading district, Nepal, using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Eight soil samples (MK1–MK8) were collected from an approximately 140 m × 140 m agricultural area and analyzed, revealing significant contamination, particularly in sample MK4. This sample exhibited elevated concentrations of arsenic (34.946 ppm), cadmium (0.644 ppm), lead (41.652 ppm), and thallium (up to 47.5 ppm), often-exceeding international safety thresholds set by organizations such as the World Health Organization (WHO) and the Canadian Council of Ministers of the Environment (CCME). These findings indicate serious risks to soil health, crop safety, and human health, potentially leading to conditions such as cancer, neurological disorders, and kidney damage. The study highlights the urgent need for regular soil monitoring, sustainable agricultural practices, and further research to identify contamination sources and develop effective remediation strategies to ensure the long-term productivity of Nepal's agricultural lands and safeguard public health.

Keywords: agriculture, Benighat, livelihoods, Potentially Toxic Trace Elements (PTEs), soil contamination

Introduction

With 65.60% of the workforce relying on agriculture for their livelihoods and accounting for roughly 29.23% of the country's GDP, agriculture is a vital sector of the Nepali economy (Agriculture Information and Communication Centre [AICC], n.d.). For crops to thrive and satisfy the world's food needs, healthy soils are necessary (Food and Agriculture Organization [FAO], 2015). But because of its rough terrain—which includes hills and mountains covering 8.6% of the country—only about 16.6% of Nepal's land is suitable for farming, making it a food-insecure country with many problems (Ministry of Agricultural Development [MOAD], 2013; National Planning Commission [NPC], 2012).

Ineffective soil management techniques make problems worse by causing significant soil erosion, lower crop yields, and declining soil quality. With an estimated 310 kg/ha of plant nutrients lost annually and only 67 kg/ha restored by fertilizers, research shows that 60.6% of Nepalese soils lack adequate organic matter, 23.6% are phosphorus deficient, 18.6% have low potassium levels, and 67.6% are acidic (Pimentel & Burgess, 2013; Mandal, 2007; MOADI, 2017).

Concerns over soil pollution, especially from potentially hazardous trace elements (PTEs) like arsenic, cadmium, lead, and thallium, have increased due to the growth of urbanization, industrialization, and intensive agricultural methods. Crop safety, soil health, and human welfare are all seriously threatened by these factors. A complex environment where soil contamination is becoming a problem is created by the interaction of geological elements, traffic emissions, and agricultural operations in Benighat, Dhading district, which is 90 km from Kathmandu along the Prithvi Highway (Yan et al., 2012; Keshari, 2022). Without identifying particular sources of contamination, this study uses Inductively Coupled Plasma Mass Spectrometry (ICP- MS) to measure PTE levels in Benighat's agricultural soils, evaluate their effects on the environment and human health, and suggest regions that require more investigation.

Potentially Toxic Trace Elements (PTEs) in Soils

Because of their persistence in the environment and capacity to build up in soils and plants, potentially poisonous trace elements (PTEs), such as arsenic, cadmium, lead, and thallium, are especially concerning. In addition to anthropogenic activities like mining, industrial emissions, and agricultural practices including the use of phosphate fertilizers and pesticides, these elements also come from natural sources such the weathering of parent rocks (Alloway, 2013; Nagajyoti et al., 2010). PTEs can enter the food chain through plant absorption from the soil and pose a major risk to human health, including kidney damage, neurological diseases, and cancer (Jarup, 2003; Rashid et al., 2023).

PTE pollution of soil is a well-researched problem worldwide. For instance, cadmium concentrations in rice fields in China have above safety thresholds due to the extensive use of phosphate fertilizers; in certain regions, levels have reached 1,000 ppm (Zhao et al., 2015). Lead, cadmium, and chromium levels have increased in India as a result of industrial operations and wastewater irrigation; in Varanasi, India lead concentrations have reached 146.75 mg/kg (Rai & Tripathi, 2008). The necessity for comparable research in rural areas like Benighat is highlighted by reports of moderate to high levels of cadmium, lead, and arsenic in agricultural soils in Nepal, especially in urban areas like Bhaktapur and Kathmandu, Nepal (Paudel et al., 2023).

Health and Environmental Impacts of Potentially Toxic Trace Elements

PTE exposure can have detrimental effects on both the environment and human health. Lead is known to harm the nervous system, especially in children, which can result in behavioral problems and a decline in cognitive development (NCBI, 2019). Particularly in populations exposed by tainted food or water, cadmium is linked to kidney impairment, bone abnormalities, and an elevated risk of cancer (HHEAR Program, n.d.). Skin, lung, and bladder cancers, as well as skin blemishes, are associated with arsenic, a known carcinogen (Nature, 2023). Because it is uncommon in typical soil studies and has no biological role, thallium is especially dangerous and can cause symptoms ranging from neurological damage to gastrointestinal upset.

PTEs have negative effects on plant development and soil ecosystems in addition to human health. Reduced crop yields and quality can result from high concentrations that change microbial populations, impair soil fertility, and cause phytotoxicity (Rauld et al., 2023). For example, lead can prevent photosynthesis and nutrient intake, whereas cadmium can cause chlorosis and stunted development in plants. Vegetables such as rice and spinach have been shown to collect lead, cadmium, and arsenic in Nepal; one study found geometric mean values of 15.5 μg/kg, 43.4 μg/kg, and 16.0 μg/kg, respectively (Paudel et al., 2023). This poses a concern to vulnerable populations. These effects highlight how crucial it is to keep an eye on and control PTE levels in agricultural soils in order to safeguard human health and environmental sustainability.

Materials and Methods

Study Area

The study was conducted in Benighat area, Ward No. 4 of Siddhalek Rural Municipality, Dhading District, Nepal, along the banks of the Trishuli River (Figure 1). Eight soil samples (MK1–MK8) were collected from a 140 m × 140 m agricultural area, primarily vegetable fields, with coordinates ranging from 27.813753 to 27.815024 N latitude and 84.795010 to 84.794263 E longitude. Sampling locations were selected to represent diverse environmental influences, including areas near human residences, a resort, regions far from human activities, and sites slightly near the Trishuli River, all within lands subject to continuous agricultural practices (Figure 2).

Figure 1

Map showing district and rural municipality of the sampled site.

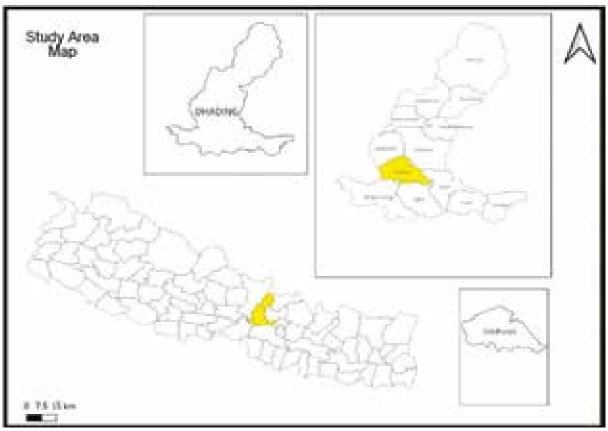


Figure 2

Map showing samples taken and their location.

Soil Sampling Techniques

Soil samples were collected using a manual soil auger at a depth of 15 cm to represent the root zone. GPS coordinates were recorded for each sample using a smartphone with a precision of 5–10 meters. To prevent cross-contamination, the auger was cleaned with water and a cotton towel after each sample, and its drilling part was covered with a zip-lock bag. Samples were stored in labeled zip-lock bags to avoid external contamination.

Sample Preparation and Analysis

Approximately 200–300 grams of each sample were collected, air-dried in an oven at 100°F for about 1 hour to remove moisture, and sieved through a 1 mm mesh to separate finer particles. These particles were further crushed using a porcelain basin and crusher, with equipment cleaned with ethanol between samples to ensure no cross-contamination. For analysis, samples were digested in a microwave system using nitric acid or a combination of hydrofluoric and nitric acids to solubilize trace elements. The digests were analyzed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS), a highly sensitive technique that ionizes samples in an argon plasma at 6,000–10,000 K, separates ions by mass-to-charge ratio, and quantifies concentrations against calibrated standards. Internal standards corrected for instrument drift and matrix effects, ensuring accurate detection of ultra-trace elements.

Results

The ICP-MS analysis of soil samples MK1–MK8 revealed significant variations in PTE concentrations, with sample MK4 identified as a contamination hotspot (Table 1, Figures 3 & 4). Specific findings include:

Table 1

Elemental concentration of PTEs from ICP-MS analysis.

Element	Sample in ppm							
	MK1	MK2	MK3	MK4	MK5	MK6	MK7	MK8
Li	28.89379	33.60719	38.49982	37.74577	33.1301	27.44276	32.35477	37.40876
Be	3.134263	2.722873	2.632905	2.037846	3.588799	2.97061	3.201377	2.828436
Ti	2170.048	1942.353	1749.67	1167.396	1901.393	1504.756	1723.953	2235.691
V	49.71799	94.16537	84.40092	95.16009	49.90855	47.99038	58.76176	87.86883
Cr	33.41411	40.86169	43.10984	42.218	33.6797	30.93045	36.98768	41.57068
Mn	463.4073	513.782	857.7204	889.8673	470.8564	450.3306	547.2734	585.1092
Co	7.199543	7.556942	9.10156	8.575578	6.916156	6.893824	7.886427	8.865532
Ni	17.46008	27.29016	29.13475	35.15117	17.14038	16.13334	20.13488	31.27809
Cu	15.92261	21.13975	21.61748	25.88984	15.63222	13.81255	16.18341	22.08255
Zn	95.48074	122.4585	167.1201	182.3216	90.93931	86.46819	100.3864	125.9851
As	10.62425	22.64867	26.58038	34.94593	11.54158	6.444784	9.969341	23.08222
Rb	134.7618	131.9145	130.4036	101.2751	152.858	115.3301	148.9143	126.5931
Sr	127.0615	66.37723	75.97747	28.09808	110.7138	118.2595	114.1612	60.34053
Mo	0.529512	1.909913	1.302006	2.374974	0.476192	0.42949	0.48407	1.684765
Cd	0.157628	0.30432	0.39164	0.643814	0.141117	0.162337	0.225496	0.304791

Ba	467.1704	412.0952	401.5869	303.8439	483.0721	449.8402	466.5492	413.2023
La	32.96622	35.56996	32.90292	28.4155	38.56526	23.14436	34.52858	29.60577
Ce	72.0296	71.89595	67.36613	53.04637	74.09732	44.38477	72.27504	58.04521
Tl	31.23832	39.26719	45.56266	47.4652	28.92074	29.61962	31.2538	41.48525
Pb	28.7637	34.2049	40.8007	41.65214	26.29157	26.69207	27.9924	37.64937
U	2.610243	3.188979	2.301417	2.167667	2.561241	2.154133	2.972868	2.817738

Arsenic (As):

Concentrations were notably high in MK4 at 34.946 ppm, MK3 at 26.80 ppm, and MK8 at 23.082 ppm (Figure 3). These levels approach or exceed safety thresholds (20–40 mg/kg, WHO/CCME).

Figure 3

Chondrite-Normalized element concentration (higher concentration and toxicity).

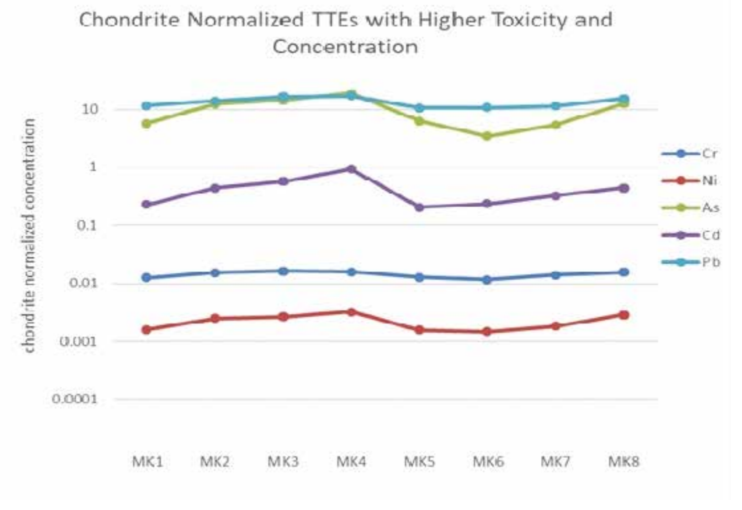
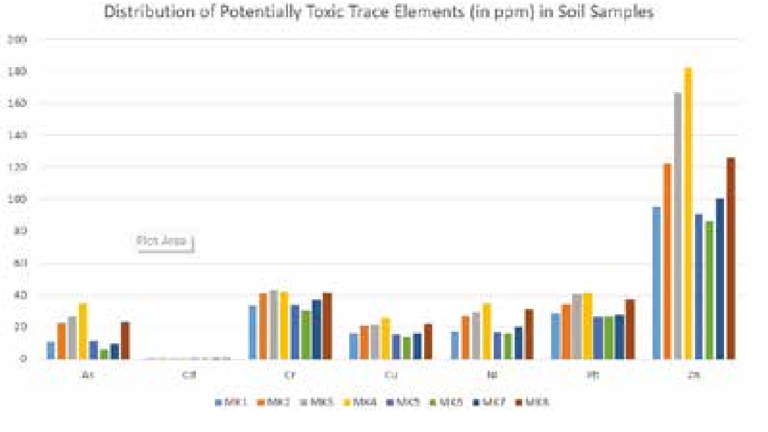


Figure 4

Bar-graph showing concentration in ppm of PTEs in different samples.



Cadmium (Cd):

Concentrations ranged from 0.14 to 0.64 ppm, with MK4 showing the highest at 0.644 ppm, slightly below the safe limit of 1–3 mg/kg.

Lead (Pb):

Levels varied from 26.3 to 41.7 ppm, with MK4 at 41.652 ppm and MK5 at 26.292 ppm, exceeding typical crustal values (15–20 ppm).

Thallium (Tl):

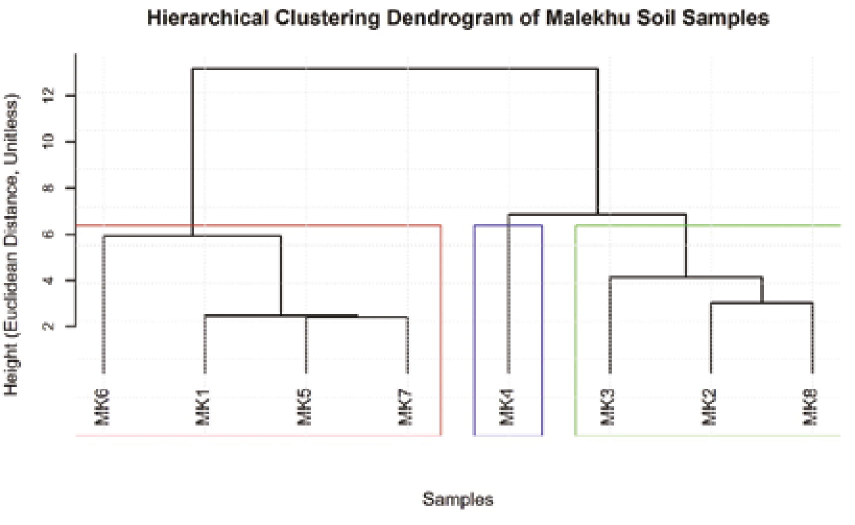
Concentrations ranged from 28.9 to 47.5 ppm, with MK4 and MK3 showing the highest levels, significantly above the safe limit of 0.5–1 mg/kg.

Cluster Analysis

Using R's base statistical package, hierarchical cluster analysis was performed to look at the spatial variability and grouping patterns of Toxic Trace Elements in the agricultural soils of Benighat area. Ward's approach using Euclidean distance as the similarity measure was used to analyze standardized amounts of 21 elements (Li to U) from eight samples (MK1 to MK8). Given the ppm units of the ICP-MS data, standardization (mean = 0, standard deviation = 1) guaranteed that elements were weighted equally despite having different scales. Linkage distances offer quantifiable information on sample dissimilarities, and the resulting dendrogram, shown in Figure 5, shows the hierarchical linkages and cluster assignments.

Figure 5

Hierarchical clustering dendrogram of Benighat soil samples.



Note: Adopted Ward's method, Euclidean distance, unit-less.

At a linkage distance of roughly 7.33 (unitless, representing normalized Euclidean distance), the dendrogram shows three separate clusters. Samples MK1, MK5, MK6, and MK7 are part of Cluster 1, which is a comparatively depleted group with lower amounts of toxic elements such As (10.62–11.54 ppm), Cd (0.14–0.23 ppm), and Pb (26.29–28.76 ppm). With higher readings for As (22.65–26.58 ppm), Cd (0.30–0.39 ppm), and Pb (34.20–40.80 ppm), Cluster 2, which includes MK2, MK3, and MK8 shows moderate enrichment and suggests intermediate contamination levels. Cluster 3 is made up entirely of MK4, which stands out as a solitary hotspot at a high linkage distance of about 14.09 and has noticeably higher As (34.95 ppm), Cd (0.64 ppm), and Pb (41.65 ppm) concentrations, which are compatible with its geographic position and possible human influence, such as fertilizer use.

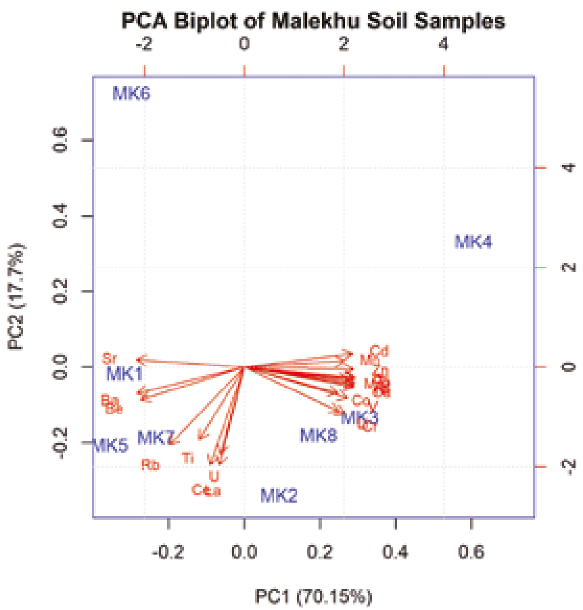
The unique geochemical profile here is highlighted by the connection distances, which show the gradual dissimilarity: Cluster 1 originates at ~7.33, merges with Cluster 2 at ~10.50, and joins MK4 at ~14.09. With Cluster 1 representing background geology (such as black slates e.g. Stöcklin, 1980) and Clusters 2 and 3 showing increasing contamination, most likely related to agricultural inputs, this pattern lends credence to the theory of mixed natural and man-made causes. The results support geographical heterogeneity and are consistent with multivariate geochemical methods (Reimann et al., 2008).

Principle Component Analysis (PCA)

Principal Component Analysis (PCA) was carried out using R's base statistical package (prcomp) in order to statistically evaluate the main sources of variance and underlying geochemical patterns in the Benighat agricultural soils. Standardization (mean = 0, standard deviation = 1) was used to reduce scale discrepancies in the ICP- MS data (measured in ppm) and was applied to the measurement of standardized amounts of 21 elements (Li to U) from eight soil samples (MK1 to MK8). The first two principal components (PC1 & PC2), which together explain 87.85% of the overall variation (PC1: 70.15%, PC2: 17.70%), are depicted in the landscape-oriented biplot shown in Figure 6.

Figure 6

PCA biplot of Benighat soil samples.

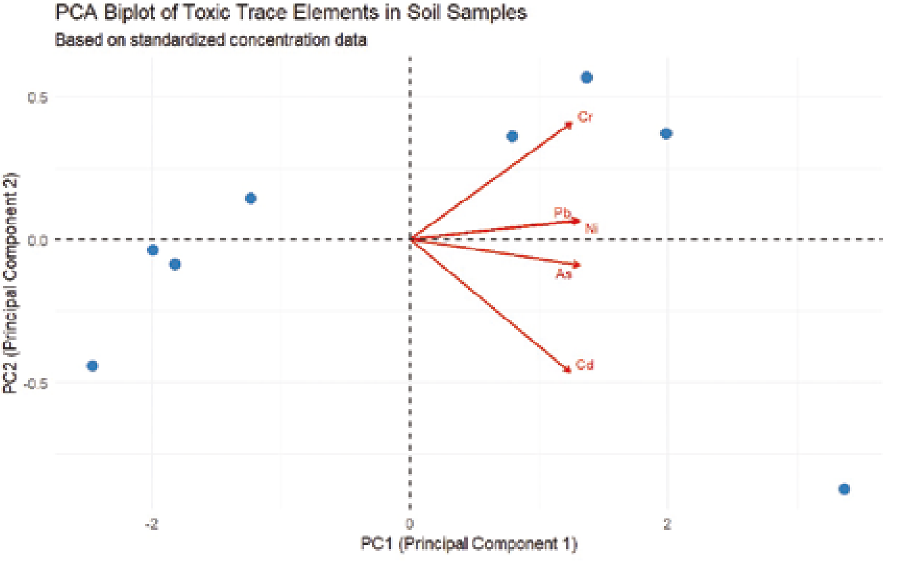


According to the biplot, PC1 is a contamination factor that accounts for 70.15% of the variance. Toxic elements such as As (0.255), Cd (0.250), Pb (0.253), Tl (0.256), Ni (0.254), Cu (0.254), and Zn (0.252) have substantial positive loadings. Sample MK4 is clearly located on the positive x-axis and has the highest PC1 score (7.03). It shows high levels of As (34.95 ppm), Cd (0.64 ppm), Pb (41.65 ppm), and Tl (47.47 ppm), indicating a localized contamination hotspot that is probably caused by human activities like phosphate fertilizers (Tripathee et al., 2016). With positive loadings for Ti, Rb, La, Ce, and U and a negative loading for Be, PC2 indicates geological/REE effect and explains 17.70% of the variance. The migmatized gneiss transported river terrace lithology is indicated by MK6's poor PC2 score.

With blue points denoting sample placements and red arrows pointing in the direction of largest variation, the landscape orientation (12x8 inches) improves the display of sample scores and element loadings. The idea of mixed natural and anthropogenic influences is supported by the spatial separation of MK4 on PC1 and MK6 on PC2, which is consistent with the geochemical literature (Reimann et al., 2008) and the hierarchical cluster analysis (Figure 5). Although the small sample size (n=8) indicates caution in extrapolating results, the cumulative variance explained (87.85%) confirms the biplot's representativeness. To improve source apportionment, future research could include more samples.

Figure 7

PCA biplot of high concentration and toxic elements.



Longer vectors of Cr, Pb, and Ni along PC1 suggest strong positive loadings, as the PCA biplot demonstrates, and they significantly contribute to the principal source of variance (Figure 7). Elevated quantities of these metals are indicative of samples with higher PC1 scores, which may indicate lithogenic or anthropogenic enrichment. The As and Cd vectors, on the other hand, indicate different geochemical behavior and maybe different input sources because they point in different directions. Lower elemental variability is seen in samples grouped close to the origin, whereas more contamination level differentiation is seen in samples farther down PC1. Overall, PCA results show that whereas As and Cd contribute significantly to the variance in overall contamination, Cr, Pb, and Ni dominate the compositional variability of toxic trace elements in the soils under study. Soil As, Cd, and Tl concentration gradients at the sampling sites are presented in Figures 8, 9 and 10.

Figure 8

Soil Arsenic concentration gradient around sample coordinates.

Note: Map layout made using QGIS

Figure 9

Soil Cadmium concentration gradient around sample coordinates.

Figure 10

Soil Thallium concentration gradient around sample coordinates.

Note: Map layout made using QGIS

Other elements detected included chromium (Cr, 33.4–43.1 ppm), nickel (Ni, 17.1– 35.2 ppm), copper (Cu, 15.6–25.9 ppm), and uranium (U, 2.1–3.2 ppm), with MK4 consistently showing elevated values.

Discussion

The elevated PTE levels in Benighat's agricultural soils, particularly in sample MK4, indicate a serious contamination issue. Concentrations of arsenic, cadmium, lead, and thallium in MK4 exceed or approach safety thresholds set by WHO and CCME. For instance, thallium levels (up to 47.5 ppm) significantly surpass the CCME's recommended limit of 1 ppm for agricultural soils, posing substantial risks to soil health and crop safety. Arsenic in MK4 (34.946 ppm, pending verification) and other samples like MK3 (26.80 ppm) and MK8 (23.082 ppm) also exceeds typical safe limits, raising concerns about potential carcinogenic effects. Lead (41.652 ppm in MK4) and cadmium (0.644 ppm in MK4) further highlight the severity of contamination, with lead posing neurotoxic risks and cadmium threatening kidney and bone health.

These findings suggest localized contamination sources, potentially from agricultural inputs like phosphate fertilizers, which are known to contain trace amounts of cadmium and arsenic (Bhandar et al., 2020). Irrigation with possibly contaminated water from the Trishuli River or traffic emissions along the Prithvi Highway may also contribute to lead and other metal pollution (Nepal Live Today, 2022). The high levels of PTEs threaten crop safety, as plants can absorb these contaminants, leading to accumulation in edible parts and entry into the food chain, potentially causing health issues such as cancer, neurological disorders, and kidney damage (Jarup, 2003; Rashid et al., 2023). The spatial variability, with MK4 as a hotspot, underscores the need for targeted monitoring and intervention.

Comparatively, the arsenic concentrations in Benighat are similar to or higher than those in contaminated areas globally. In China, rice fields have shown arsenic levels exceeding safety limits due to fertilizer use (Zhao et al., 2015). Lead concentrations in Benighat approach those in industrially impacted areas like Varanasi, India, where levels reached 146.75 mg/kg (Rai & Tripathi, 2008). In Nepal, studies in urban areas like Bhaktapur have reported moderate to high levels of cadmium, lead, and arsenic, suggesting that rural areas like Benighat face similar risks (Paudel et al., 2023). These comparisons highlight the severity of the contamination and the urgent need for action.

The high arsenic levels in MK4 are particularly alarming, as chronic exposure through contaminated food or water can lead to skin lesions, cancers, and other serious conditions (Nature, 2023). Lead contamination poses a threat to children's neurological development and can cause cardiovascular issues in adults (NCBI, 2019). Thallium's elevated levels are concerning due to its high toxicity and potential to cause gastrointestinal and neurological damage. These health risks necessitate immediate measures to prevent adverse outcomes in Benighat's agricultural community.

Recommendations

To address soil contamination in Benighat, the following measures are proposed:

- **Regular Soil Monitoring:** Implement routine soil testing programs to monitor PTE levels, focusing on hotspots like MK4.
- **Farmer Education:** Provide training on contamination risks and best practices, such as using certified fertilizers and avoiding contaminated irrigation water. Source Identification: Conduct research to identify specific contamination sources, whether agricultural, industrial, or geological.
- **Remediation Strategies:** Explore techniques like phytoremediation or soil amendments to reduce PTE bioavailability.
- **Policy Development:** Advocate for national standards for soil contaminants to protect agricultural lands and public health.

Future Research Directions

Future research should focus on:

- **Bioavailability Studies:** Investigate PTE uptake by crops to assess risks to human health.
- **Long-term Monitoring:** Establish programs to track contamination changes and evaluate remediation efforts.
- **Health Impact Assessment:** Conduct epidemiological studies to explore correlations between soil contamination and health outcomes.
- **Remediation Techniques:** Test strategies like hyper accumulator plants to reduce soil PTE levels.

Conclusion

Using ICP-MS, this study examined toxic elements in Benighat's agricultural soils, identifying a range of elemental amounts and contamination patterns. In contrast to arsenic (As) and cadmium (Cd), which are present in smaller amounts but pose serious health and environmental risks because of their high toxicity and bio-accumulative nature, chromium (Cr), lead (Pb), and nickel (Ni) showed relatively higher concentrations, indicating a combination of lithogenic and anthropogenic influences. Although localized enrichment of As and Cd suggests growing pollution concerns, the majority of identified elements stayed within international safety criteria. Overall, the findings show that human activities, agricultural inputs, and geological makeup all have an impact on the moderate levels of soil pollution. The results offer crucial baseline information for controlling and keeping an eye on soil quality in Nepal's mountainous agricultural areas.

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