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Assessment of Heavy Metal Contamination and Human Health Risk in Greater Mumbai, India

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Abstract

Urbanization and industrialization have significantly increased heavy metal contamination in soils, raising concerns over ecological balance and human health. The present study investigates heavy metal concentrations and associated health risks in urban soils of Greater Mumbai, India. Soil samples from nineteen different locations were analyzed for pH, Nickel (Ni), Lead (Pb), Zinc (Zn), Cadmium (Cd), Chromium (Cr), Copper (Cu), Arsenic (As), and Mercury (Hg). Results reveal spatial variation in concentrations, with elevated levels of Pb (64-85 mg/kg), Zn (128-165 mg/kg), and Cu (47-67 mg/kg), indicating anthropogenic influence from traffic emissions, industrial discharge, and urban waste. Health risk assessment, evaluated through Hazard Index (HI) for children and adults shows higher vulnerability in children (HI-values up to 1.25), suggesting potential non-carcinogenic risks. Carcinogenic risk (CR) values for As and Cr, though within acceptable limits (10^{-6}-10^{-4}), highlight localized hotspots of concern. The Potential Ecological Risk Index ranged from 185 to 310, with higher risks observed in northeastern and industrial zones. Correlation with rainfall data suggests leaching and mobility of certain metals, which may further influence exposure pathways. This study underscores the urgent need for continuous monitoring of urban soils and the implementation of risk mitigation strategies to safeguard public health. The findings provide baseline data for policymakers, environmental managers, and urban planners, supporting sustainable land use planning and pollution control measures in rapidly growing metropolitan environments like Mumbai.

Keywords: Ecological Risk, Greater Mumbai, Health Risk Assessment, Heavy Metals, Soil Contamination, Urban Soils.

Introduction

Developing nations' land use changes and industrialization are identified as significant factors contributing to land use change and degradation in soil quality. Soils are recognized as dynamic environmental systems that provide support for vital ecological processes (1). These ecological processes include plant growth, water filtration, nutrient cycling, and carbon storage. However, in urban areas, soils are increasingly subject to contaminants from anthropogenic activities. Of all contaminants, heavy metals are identified as critical because they are non-biodegradable and are subject to bioaccumulation (2). Heavy metals are found in industrial effluents, vehicle emissions, atmospheric precipitation, waste disposal, and agrochemical applications. The movement and retention of heavy metals in soils are subject to factors such as pH, organic matter content, and rainfall. Unlike organic pollutants, heavy metals are not biodegradable and are subject to bioaccumulation, thus causing long-term ecological and health hazards. Exposure to heavy metals by humans occurs through ingesting contaminated soil and dust, dermal contact, and

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ingesting crops grown in contaminated soils. Children are identified as vulnerable groups because they ingest more heavy metals in relation to body weight. Adults and elderly people are also vulnerable because they are subject to long-term exposure to heavy metals, thus causing neurological, carcinogenic, and systemic disorders (3). Besides causing health hazards, heavy metal contamination also affects crop productivity, especially in peri-urban areas where crop productivity is closely related to urban pollutants. Contaminating crops grown in heavy metal-contaminated soils also results in heavy metal uptake in crops, thus establishing a direct relationship between crop safety and heavy metal contamination in peri-urban areas such as Mumbai.

Heavy Metal Pollution in Urban Soils

Heavy metal pollution of soils is recognized as a global environmental problem. The most studied metals include nickel (Ni), lead (Pb), zinc (Zn), cadmium (Cd), chromium (Cr), copper (Cu), arsenic (As), and mercury (Hg). The metals enter the soil through different anthropogenic activities (4). The industrial activities that cause pollution of soil with metals such as nickel, chromium, and copper include smelting operations, electroplating, and tanning. The metals lead, zinc, and cadmium enter the soil through vehicle exhaust and tire wear. The other anthropogenic activities that cause metal pollution of soil include building and demolition works, incineration of wastes, and improper disposal of wastes (5). The agricultural activities that cause metal pollution of soil include the use of fertilizers and pesticides and the use of wastewater for irrigation of crops in peri-urban areas. From the point of view of their toxicity, the metals have been found to cause different types of adverse effects. Lead is found to cause neurological disorders and developmental problems. Cadmium is found to cause renal toxicity and bone damage and to be carcinogenic. Hexavalent chromium is found to cause cancer. Arsenic is found to cause skin lesions, cardiovascular diseases, and cancer. Even metals such as copper and zinc, which have been found to act as micronutrients for plants and animals, have been found to cause toxicity and to affect soil chemistry and metabolism. The role of urban soils in serving as sinks and secondary sources for heavy metals has been established, thus facilitating their persistence in nature (6). Once they are part of the food chain, through uptake by plants, they pose serious health and food security risks to humans. Crops that grow in contaminated soils will have low productivity and will be toxic to consumers. This demonstrates the complexity involved in heavy metal pollution, thus calling for integrated approaches to assess various aspects, from environmental to agricultural to health, to determine contamination hotspots and mitigation measures to be employed.

Literature Review

The impacts of rapid urbanization and industrialization have been established as significant factors influencing soil quality in urban areas. Urban soils have been identified as major sinks for pollutants, particularly heavy metals, because of their persistence and toxicity in nature (7). Unlike organic pollutants, heavy metals do not degrade with time and thus remain in soils for long periods, posing serious health and environmental risks to humans and nature, respectively. Research conducted worldwide has established that urban soils are contaminated with various heavy metals, such as Ni, Pb, Zn, Cd, Cr, Cu, As, and Hg, which are attributed to anthropogenic activities.

Health Risks with Heavy Metals

The persistence of heavy metals in soils has been established as a major contributor to health risks for humans, particularly through exposure to contaminated soils, ingestion, and inhalation of contaminated soils and particles, respectively. Neurotoxic heavy metals, such as Pb and Hg, were established to affect human health, with Pb exposure causing cognitive impairment and developmental delay, while Hg exposure was established to cause serious neurological disorders in exposed individuals. Carcinogenic and multi-organ toxic heavy metals, such as Cd, Cr, and As, were established to cause renal, respiratory, and cancer problems in exposed individuals. Children have been identified as the most susceptible group as they have the highest rate of ingestion and the least body weight. Various research works have been carried out in different regions of the world. The results show that the hazard index is high for children compared to adults. The effects of long-term exposure to adults and elderly populations show the bioaccumulation of metals in their body tissues. The health risks can be analyzed through the USEPA model (8).

The model assesses the risks through three main routes of exposure: ingestion, dermal contact, and inhalation. The dose is measured as Average Daily Dose (ADD). The ADD is given as Equation [1]:

$$\mathrm{ADD_{ing}} = \frac{\mathrm{C_s \times IngR \times EF \times ED}}{\mathrm{BW \times AT}} \qquad [1]$$

Where Cs is contaminant concentration, IngR is ingestion rate, EF is exposure frequency, ED is exposure duration, BW is body weight, and AT is averaging time. The non-carcinogenic risk is given as Equation [2]:

$$\mathrm{HQ} = \frac{\mathrm{ADD}}{\mathrm{RfD}} \qquad [2]$$

Where RfD is the reference dose. The summation of the hazard quotient is given as Equation [3], if HI is greater than 1, it shows that there is a potential health concern. The carcinogenic risks can be analyzed using Equation [4].

$$\mathrm{HI} = \sum \mathrm{HQ_i} \qquad [3]$$

$$\mathrm{CR} = \mathrm{ADD} \times \mathrm{SF} \qquad [4]$$

Where SF is the slope factor. The acceptable levels of SF vary between 10^{-6} and 10^{-4}.

Ecological Risk Assessment

The ecological risks of heavy metals can be analyzed through the Potential Ecological Risk Index (PERI). The PERI assesses both the concentration of metals and the factors of toxic response (9). The factors of risk can be calculated from Equation [5] and the total ecological risk is represented as using Equation [6].

$$\mathrm{E_r^i} = \mathrm{T_r^i} \times \frac{\mathrm{C_i}}{\mathrm{C_n}} \qquad [5]$$

$$\mathrm{PERI} = \sum \mathrm{E_r^i} \qquad [6]$$

An increase in PERI results in more ecological threats to the organisms in the soil and the ecosystem.

Agricultural Implication of Heavy Metal Contamination

Urban and peri-urban agriculture is more susceptible to heavy metal contamination. Plants grown in contaminated soil take in heavy metals through their roots and carry them to other parts of the plant, including edible parts (10). In cities such as Shanghai, Dhaka, and Delhi, research findings indicated that the concentration of Pb and Cd in vegetables was found to be beyond permissible levels. This affects crop productivity and introduces toxic elements into the food chain. Heavy metals also affect the quality of soil, causing decreased microbial diversity, enzymatic activity, and nutrient cycles. This affects the fertility and sustainability of the land for agricultural purposes.

Methodology

Description of the Study Area

The study was conducted in the region of Greater Mumbai, India, a densely populated metropolitan region located along the western coast of the country (approximate GPS coordinates range 18.9ºN-19.3ºN and 72.8ºE-73.1ºE). The city is bounded by the Arabian Sea to the west and the Western Ghats to the east, creating a unique geographical setting influenced by both marine and terrestrial systems. Topographically, Mumbai exhibits elevations ranging from near sea level along the coastline to about 450 meters in its eastern hilly regions. The terrain is a mix of coastal plains, reclaimed lands, and hilly tracts. Slope gradients vary across the city, flatter regions dominate the western and central zones, while steeper slopes are found in the eastern suburbs where the terrain rises toward the Western Ghats. These variations in elevation and slope influence soil erosion, drainage patterns, and the distribution of pollutants. Mumbai experiences a tropical climate characterized by high humidity and heavy monsoonal rainfall, averaging between 2,000-2,500 mm annually. The monsoon plays a crucial role in shaping soil processes, leaching contaminants, and redistributing pollutants across the landscape. The study area is illustrated in Figure 1, which shows the geographical location of Greater Mumbai region. Figure 2 depicts the elevation and slope characteristics of the study area, highlighting the diverse terrain that governs soil dynamics.

The methodology of this study involved systematic soil sampling, laboratory analysis, and risk assessment to evaluate heavy metal contamination in the urban soils of Greater Mumbai, India. Soil samples were collected from nineteen representative locations across the city to capture spatial variations associated with urban activities, traffic emissions, and industrial influence.

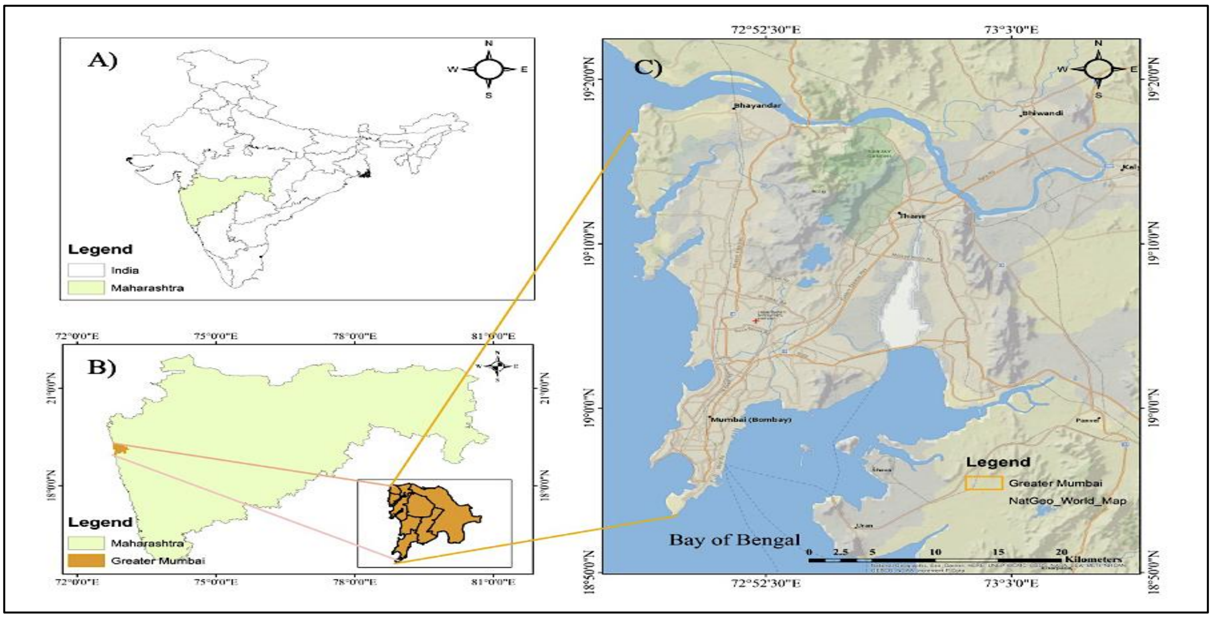

Figure 1: Geographical Location Map of the Study Area - A) India State Boundary, B) Maharashtra, C) Greater Mumbai

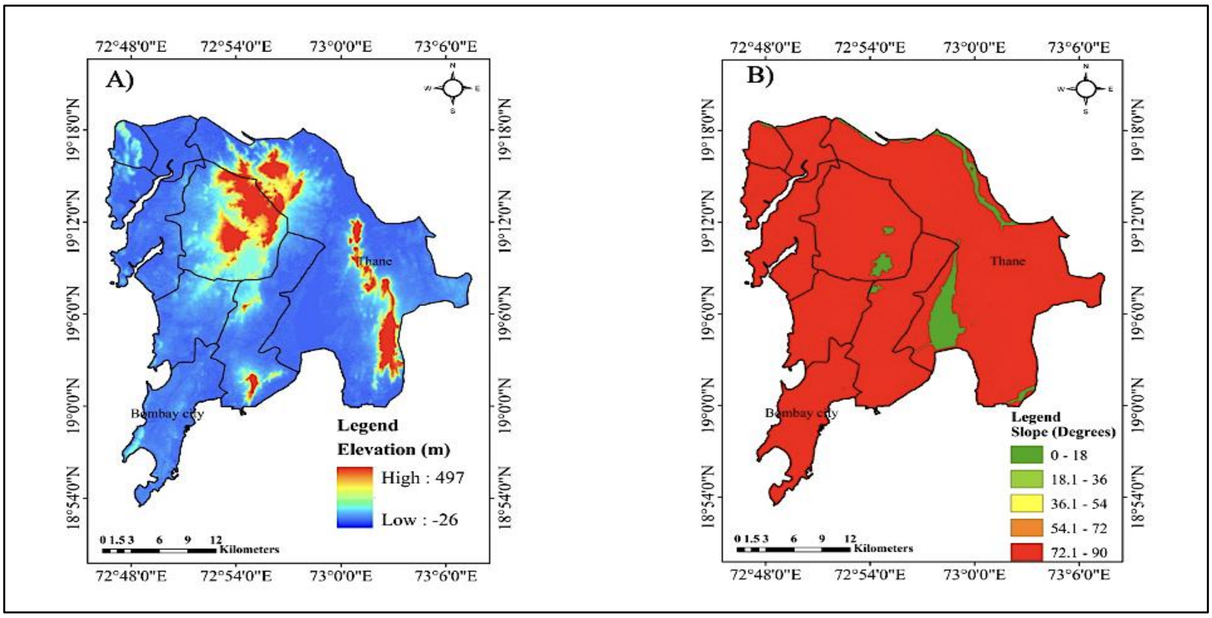

Figure 2: Spatial Variation - A) Elevation, B) Slope Over the Greater Mumbai, India

A total of nineteen sampling sites were selected across the Greater Mumbai region to represent different land-use categories, including residential, traffic-dominated, commercial, and industrial areas. The selection aimed to capture the spatial variability of heavy metal contamination influenced by urban activities and pollution gradients.

Sampling locations were chosen based on field reconnaissance, accessibility, and proximity to potential anthropogenic sources such as road networks, industrial zones, and densely populated areas (11). The adopted sampling density is also consistent with previous urban soil contamination studies that employ representative point-based sampling to characterize spatial variability across metropolitan environments. This approach ensures adequate coverage of the study area while maintaining practical feasibility for detailed laboratory analysis. To ensure the accuracy and reliability of the analytical results, standard quality assurance and quality control procedures were followed during laboratory analysis. The instruments were calibrated using standard solutions prior to measurement, and replicate analyses were conducted for selected samples, with the relative standard deviation maintained within ±5%, indicating acceptable analytical precision. Standard laboratory protocols were followed to minimize contamination and maintain data reliability. The collected samples were air-dried, homogenized, and sieved before analysis. Soil physicochemical properties, particularly pH, were measured to understand their influence on the mobility and availability of heavy metals (12).

The concentrations of major heavy metals including Ni, Pb, Zn, Cd, Cr, Cu, As, and Hg were determined using standard analytical procedures. Human health risks were evaluated by estimating the Hazard Index (HI) for both children and adults to assess non-carcinogenic risks, while (CR) values were calculated for toxic elements such as arsenic and chromium. In addition, the ecological impact of metal contamination was assessed using the PERI (13). Rainfall data were also examined to understand their role in influencing the mobility and distribution of heavy metals in urban soils. This integrated approach enabled the assessment of contamination levels, ecological risk, and potential human health impacts in the study area.

Results and Discussion

Data Sources and Sample Collection

The methodology followed a structured sequence beginning with site selection and sampling, followed by laboratory analysis, statistical evaluation, spatial mapping, and risk assessment. The methodology for assessing heavy metal contamination in soil requires a combination of laboratory analysis, geospatial techniques, and quantitative risk assessment models (14). In this study, the research framework integrates soil sampling, classification, laboratory based heavy metal quantification, health risk modeling, and ArcGIS driven spatial distribution mapping. The selected approach ensures that the concentrations of metals such as Ni, Pb, Zn, Cd, Cr, Cu, As, and Hg are systematically analyzed in relation to soil pH, rainfall, and slope characteristics of the study area. Furthermore, the evaluation of the HI, CR, and PERI strengthens the study by linking soil chemistry with human health and agricultural productivity (15). The detailed data sets which are used in the current study related sources are summarized in Table 1.

Table 1: Data Sources with Specific Information Obtained from Each Source

Parameter	Description	Source of information
DEM	USGS	30 m resolution
LULC	Landsat-8 OLI	Classified using supervised methods
Soil data	Field sampling and laboratory testing	pH, Ni, Pb, Zn, Cd, Cr, Cu, As, Hg
pH	Soil acidity/alkalinity	Laboratory analysis (pH meter, standard slurry)
Ni, Pb, Zn, Cd, Cr, Cu, As, Hg	Heavy metal concentrations (mg/kg)	AAS/ICP-MS after acid digestion
Rainfall	Average rainfall (mm) per site	Meteorological data
HI (child, adult)	Hazard Index	Calculated using USEPA (8) exposure equations
CR	CR	Modelled using slope factors
PERI	PERI	The method based on toxic-response factors is used.

Note: pH - potential of hydrogen; Ni - Nickel; Pb - Lead; Zn - Zinc; Cd - Cadmium; Cr - Chromium; Cu - Copper; As - Arsenic; Hg - Mercury; concentrations are expressed in mg/kg.

Soil samples were collected from the 0-20 cm depth, which represents the topsoil layer most directly influenced by anthropogenic activities such as traffic emissions, industrial deposition, and urban waste accumulation. This surface layer is particularly relevant for environmental and health assessments because it is the zone where contaminants tend to accumulate and where human exposure through soil ingestion, dermal contact, and inhalation of re-suspended dust particles commonly occurs. In addition, the 0-20 cm layer corresponds to the active root zone of most agricultural and urban vegetation, making it critical for evaluating the potential uptake of heavy metals by plants and their subsequent entry into the food chain (16). Therefore, sampling within this depth provides a reliable representation of contamination dynamics and potential ecological and human health risks in urban environments.

Analytical Methods for Heavy Metal Detection

Reliable quantification of heavy metals in soil requires systematic sampling and robust analytical techniques. Soil samples are typically collected from the topsoil layer (0-20 cm) of nineteen different sampling sites are shown in Figure 3, which is most vulnerable to pollution due to direct deposition and human activities. Samples are air-dried, sieved to <2 mm, and digested using strong acids such as aqua regia (a mixture of HCl and HNO_3 in 3:1 ratio) or through microwave assisted digestion, which ensures complete dissolution of metals. For analysis, several instrumental methods are widely employed (17). Atomic Absorption Spectroscopy (AAS) remains the most common technique for detecting Pb, Zn, Cd, Cu, and Ni due to its reliability and moderate cost. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) offers higher sensitivity and allows the simultaneous detection of trace elements such as "As and Hg". X-Ray Fluorescence provides a rapid and non-destructive method for elemental analysis, although its detection limits may be higher than AAS and ICP-MS. The choice of method often depends on the required sensitivity, available resources, and the metals under investigation (18).

Soil Classification and Laboratory Analysis

The soils from the study area were classified according to texture and field observations. Samples were air-dried, sieved, and subjected to chemical digestion following USEPA method 3051A. The concentrations of Zn, Cu, Pb, Cd, Ni, Cr, As, and Hg were measured using AAS. Soil classification revealed predominantly sandy loam to loamy textures, with pH values ranging between moderately acidic and slightly alkaline across the sampling sites. These variations in pH are critical as they directly influence the mobility and bioavailability of heavy metals, thereby affecting agricultural productivity (19). Nineteen sampling points were identified across the study area and the details of those locations are summarized in Table 2, ensuring coverage of locations representing residential, roadside, industrial, and agricultural influences. The data includes soil pH, heavy metal concentrations, rainfall distribution, and human health indices (HI for children and adults, CR, PERI).

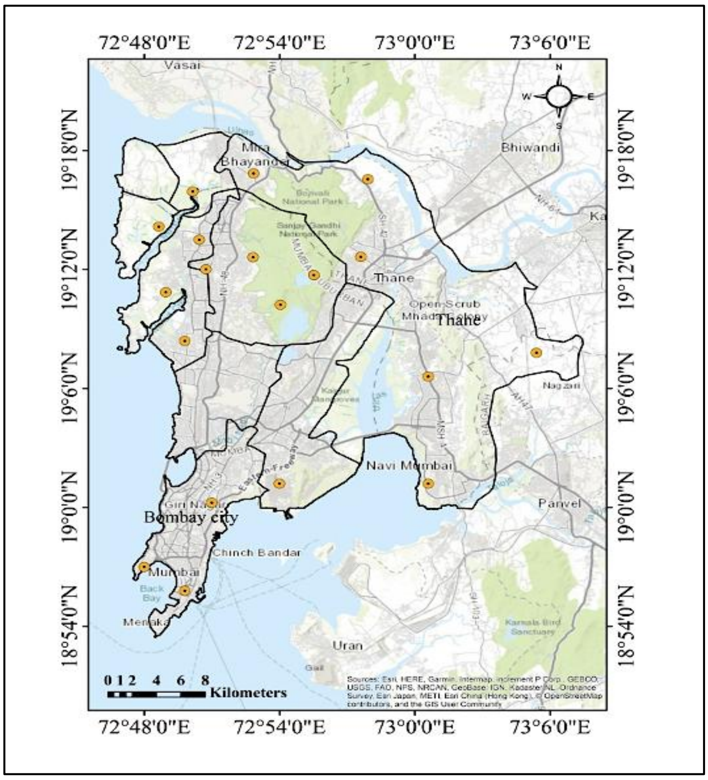

Figure 3: Sampling Location Across the Study Region

Table 2: Sampling Locations with Geographic Coordinates

Latitude	Longitude	Name of the location
19.2103	72.8804	Andheri East
19.1808	72.8159	Juhu / Vile Parle West
19.1952	72.9254	Ghatkopar West
19.225	72.8407	Jogeshwari West
19.2759	72.9653	Powai
19.2807	72.8808	Goregaon East
19.2106	72.9601	Vikhroli
19.1703	72.9007	Kurla
19.2359	72.8108	Versova / Andheri West
19.2002	72.8456	Santacruz East
19.2655	72.8358	Malad
19.11	73.01	Navi Mumbai (Belapur)
19.13	73.09	Panvel
19.02	73.01	Nerul
19.02	72.9	Chembur
19.14	72.83	Bandra
19.004	72.85	Dharavi / Sion
18.95	72.8	Colaba / Cuffe Parade
18.93	72.83	Mazgaon / Byculla

Data Processing and Implementation

The data obtained from laboratory analysis were processed and spatial analysis was performed using ArcGIS software. The Kriging interpolation technique was applied to generate spatial distribution maps of heavy metal concentrations, as it accounts for spatial autocorrelation among sampling points and provides statistically reliable predictions of spatial variability across the study area. A 30 m DEM is obtained from USGS to extract slope and drainage characteristics, and Land Use/Land Cover (LULC) classification was developed from Landsat-8 imagery, highlighting the spatial relationship between land use categories and heavy metal accumulation (20). Health risk indices and the PERI were calculated based on the equations provided in literature. The spatial distribution of all different heavy metals and other risk indices is shown in Figure 4. Further the DEM was used to represent the general topographic characteristics of the study area. Soil sampling locations were collected through field site visits at specific points, and their spatial coordinates were integrated within the GIS environment. Since the DEM was used primarily to support terrain interpretation rather than detailed micro-scale analysis, the difference in scale between the DEM resolution and point-based sampling does not significantly affect the analysis (21). All spatial layers were carefully aligned to maintain consistent spatial referencing during GIS processing.

Soil pH and Rainfall

Soil pH ranged between 6.7 and 7.2, reflecting slightly acidic to neutral conditions, as shown in Figure 4A. Such a range promotes the mobility of Cd and Zn, while relatively immobilizing Cr and Pb. Rainfall, more than 2500 mm annually enhances leaching, surface runoff, and vertical migration of mobile metals, increasing their ecological significance.

Heavy Metal Concentrations: Nickel (Ni)

Ni concentrations (37-54 mg/kg) were above typical background levels, as shown in Figure 4B. While Ni is an essential micronutrient in trace amounts, excess accumulation is linked to phytotoxicity and reduced crop yields. GIS mapping revealed hotspots of Ni in low-lying areas, suggesting downslope migration with surface water.

Lead (Pb)

Pb levels (64-85 mg/kg) exceeded several international soil guideline values, as shown in Figure 4C. Pb is largely immobile in neutral soils but can bind strongly to organic matter. LULC overlays showed higher Pb concentrations near built-up and road-proximate areas, indicating traffic and anthropogenic deposition as primary contributors (22).

Zinc (Zn)

As shown in Figure 4D, Zn concentrations ranged from 128-165 mg/kg, values approaching toxicity thresholds for sensitive crops. While, Zn supports plant enzymatic activity, its excess can suppress uptake of other micronutrients. DEM-linked analysis suggested Zn accumulation in depositional sites, reinforcing the role of topography in spatial variation.

Cadmium (Cd)

Cd (1.0-1.8 mg/kg) consistently exceeded natural backgrounds, highlighting strong anthropogenic input, possibly fertilizers and industrial residues, as shown in Figure 4E. Cd poses high ecological risk due to its mobility under prevailing pH conditions. Its presence in agricultural soils is particularly concerning dietary exposure pathways.

Chromium (Cr)

Cr concentrations (79-102 mg/kg) were moderate but remain critical due to its carcinogenic hexavalent form, as shown in Figure 4F. Areas with industrial proximity showed relatively elevated Cr, and rainfall patterns likely mobilize it into drainage channels. Although there is less mobile in neutral pH, Cr still presents long-term persistence issues (23).

Copper (Cu)

As shown in Figure 4G, Cu levels (47-67 mg/kg) were slightly above natural backgrounds. Cu, though essential, can inhibit root elongation and soil microbial activity at high concentrations. The highest values coincide with intensive agricultural land, suggesting links to fungicide and pesticide usage.

Arsenic (As)

The concentrations of As (5.4-7.5 mg/kg) were comparatively lower but significant given its toxicity, as shown in Figure 4H. Carcinogenic risk estimates, though within acceptable thresholds, warrant continuous monitoring. GIS overlays indicated higher as in irrigated agricultural zones, possibly due to contaminated groundwater inputs.

Mercury (Hg)

As shown in Figure 4I, Hg (0.17-0.28 mg/kg) was detected at low levels yet requires attention because of bioaccumulation potential. Its distribution did not strongly correlate with land use but showed slight elevation in water-proximal areas, consistent with hydrological redistribution.

Health Risk Assessment

The HI values for children (0.9-1.25) occasionally exceeded the safe threshold, identifying them as the most vulnerable group. Adults and elderly groups showed lower HI, but marginal exceedances were still noted. From Figures 5 (A and B), it can be observed that “As and Cr” range between 10^{-4} to 10^{-6}, which shows within permissible but cautionary ranges.

Ecological Risk

PERI indicated moderate to considerable ecological risk, driven primarily by Cd, Ni, and Zn. Sites with intensive agriculture and low slope gradients showed the highest risk, consistent with pollutant accumulation in depositional areas (24). PERI combines heavy metal concentrations and toxic response factors to assess ecological hazards. In Greater Mumbai soils, PERI values range from 185 to 310, indicating moderate to considerable risk. Mapping PERI highlights contamination hotspots, aiding sustainable land management, agricultural safety, and human health protection. The spatial distribution of PERI and Carcinogenic risks are shown in Figures 6 (A and B).

Integration of DEM and LULC

The Digital Elevation Model (DEM) analysis revealed that low-lying regions and gentle slopes act as sinks for contaminants, while steeper terrains showed less accumulation due to runoff. In Figures 7 (A and B), LULC classes were highlights agricultural land adjoining built-up and industrial zones as contamination hotspots, while forested areas showed comparatively lower values (25). The combined DEM and LULC approach proved effective in identifying spatial pathways of contamination and anthropogenic influence.

Agricultural Implications

Zn and Cu levels, though micronutrients, approached toxicity thresholds, threatening crop health. Pb and Cd pose risks of food chain entry through edible crops. Sustainable agricultural practices, including organic amendments, crop rotation, and possible phytoremediation, are necessary to mitigate these risks and maintain long-term soil productivity.

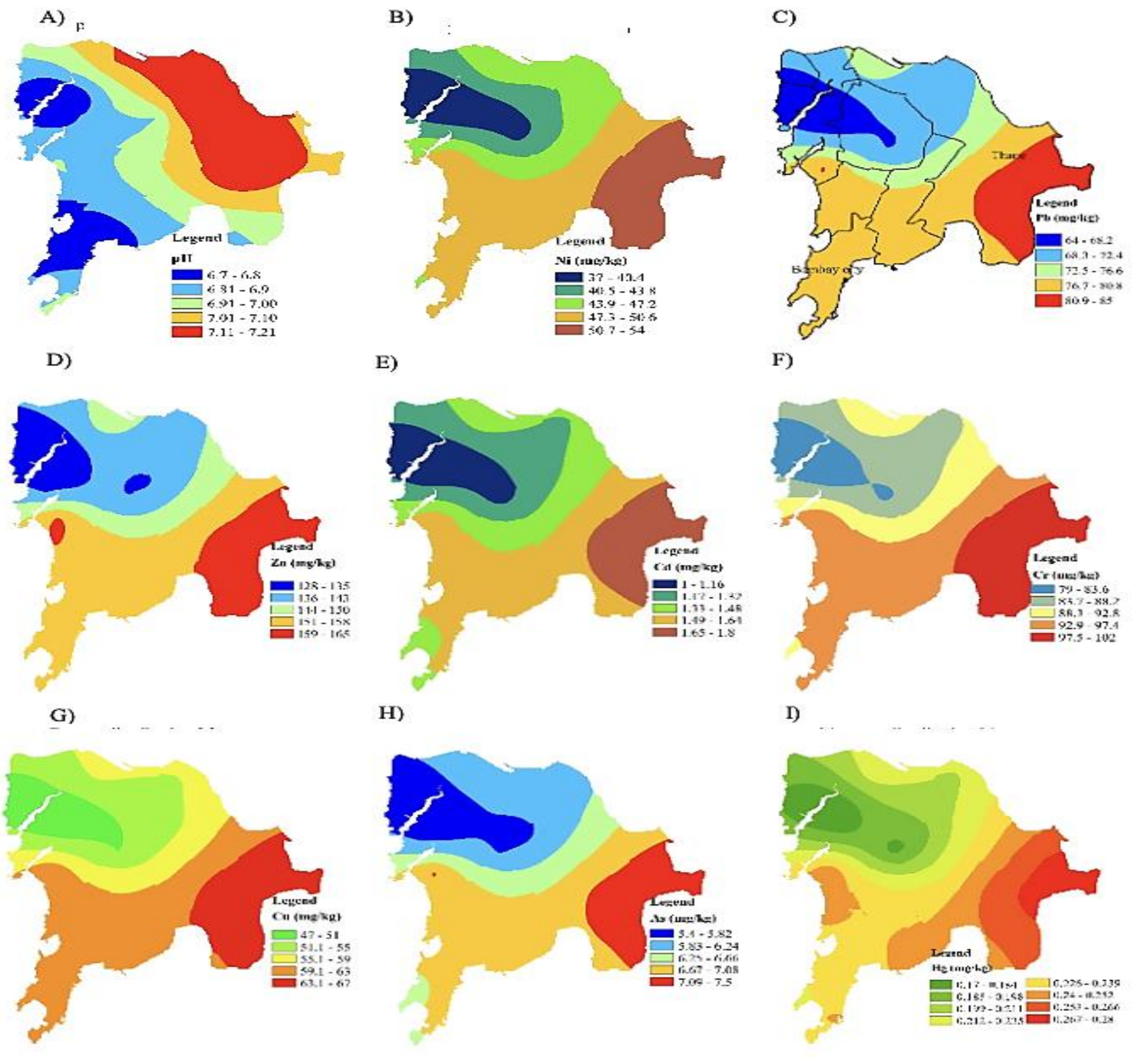

Figure 4: Spatial Distribution of Across the Greater Mumbai Region - A) Ph and Heavy Metal Concentration, B) Nickel, C) Lead, D) Zinc, E) Cadmium, F) Chromium, G) Copper, H) Arsenic, I) Mercury

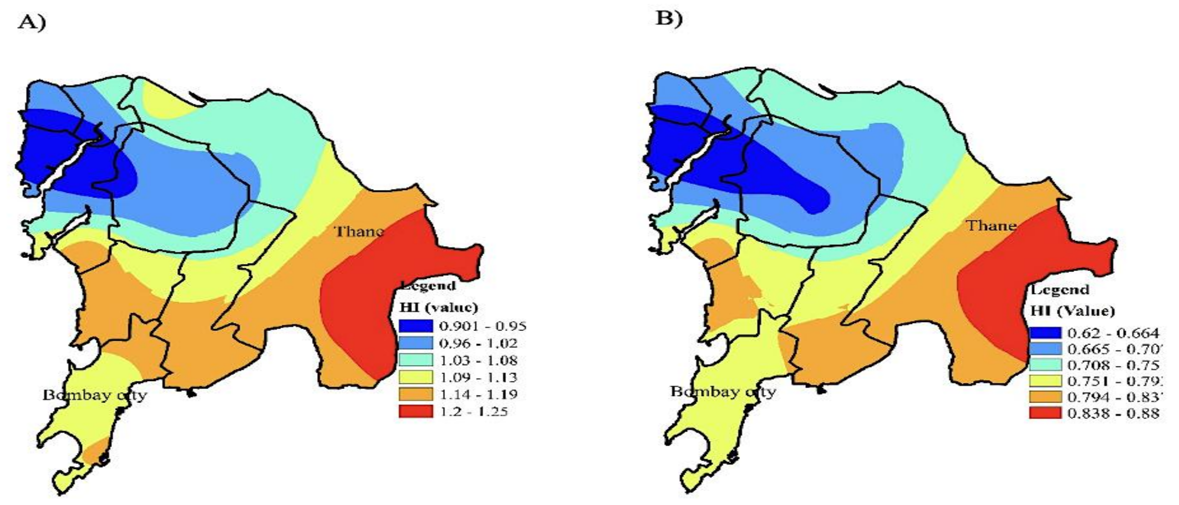

Figure 5: Spatial Distribution Maps Showing the Health Hazard Indices of - A) Child, B) Adults

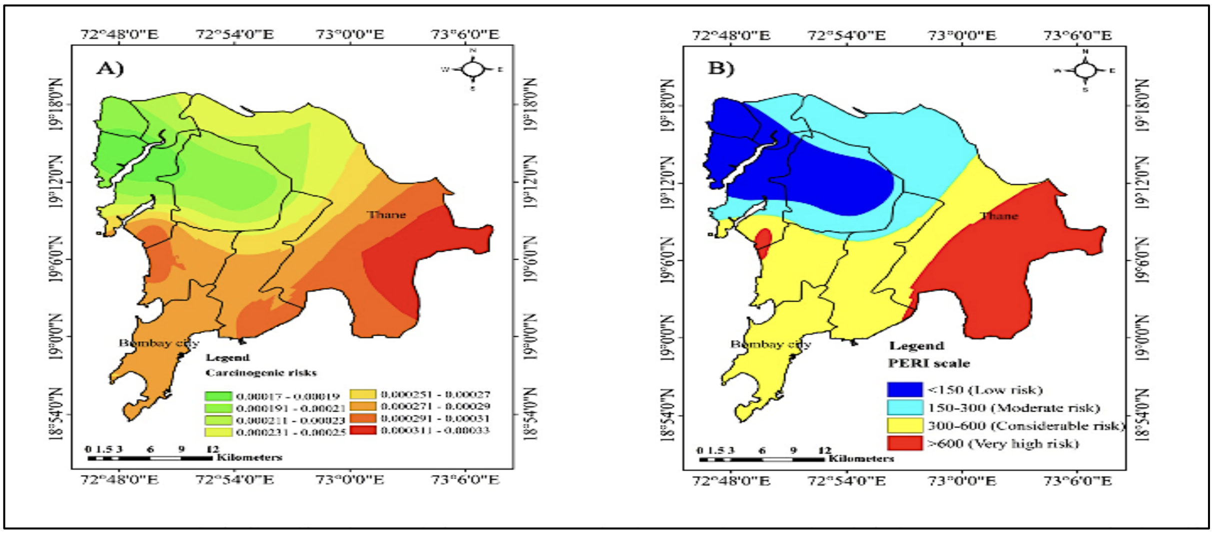

Figure 6: Spatial Distribution of the A) PERI And Carcinogenic Risk in Greater Mumbai Soils, Illustrating B) Ecological Risk Zones and Localized Hotspots of Contamination

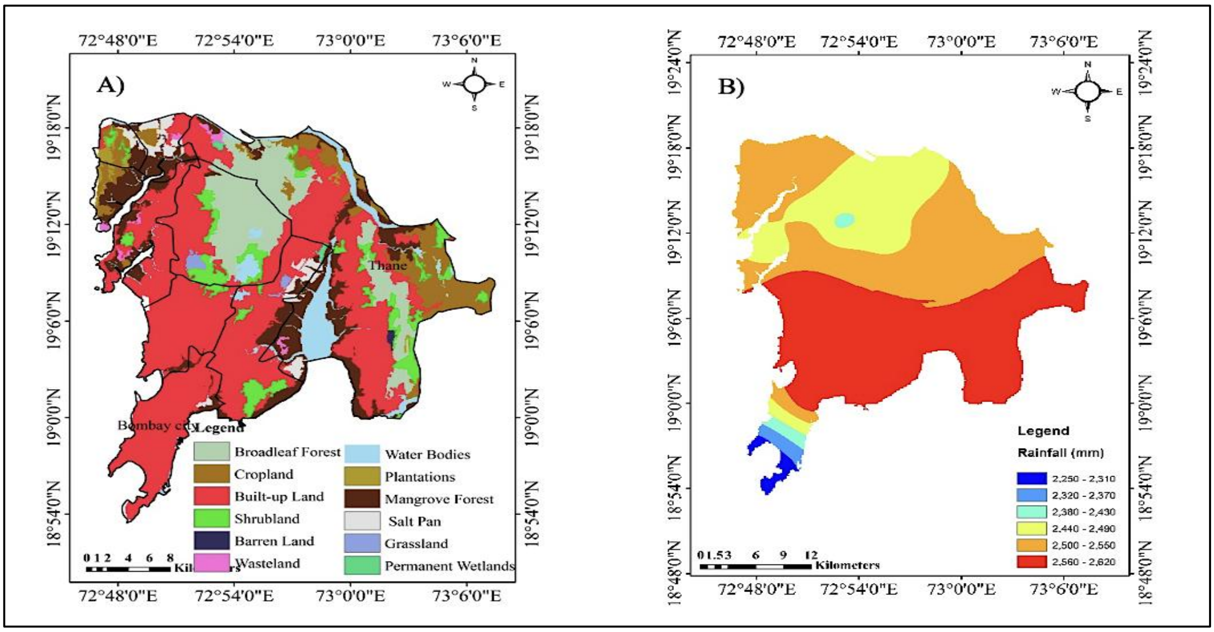

Figure 7: A) LULC Classification, B) Spatial Distribution of Annual Average Rainfall Map of the Greater Mumbai

Validation of the results and comparison with standards

The concentrations of heavy metals measured in the study area were compared against national CPCB/Indian standards (26) and international standards of WHO (27) permissible limits for agricultural soils. This comparison highlights where observed values exceed safe thresholds and the potential implications for soil and crop health. Table 3 shows the detailed comparison between the values obtained with the standard and permissible limits.

Table 3: Heavy Metal Concentrations vs Permissible Standards in Agricultural Soils

Metal	Range in Study (mg/kg)	CPCB / Indian Standard (mg/kg)	WHO Permissible Limit (mg/kg)	Remarks
Ni	37 - 54	30–50	50	Several sites exceed Indian limits; risk of phytotoxicity in sensitive crops.
Pb	64 - 85	50	100	Almost all sites exceed Indian limits, though below WHO/FAO upper limit; concern for edible crops (root vegetables, leafy greens).

Zn	128 - 165	300	300	Well within limits, but higher concentrations may cause micronutrient imbalance.
Cd	1.0 - 1.8	3	3	Within permissible levels, continuous accumulation can be critical due to bioavailability.
Cr	79 - 102	50	100	Many samples exceed Indian standards and are near the FAO threshold; long-term buildup may impair soil microbial activity.
Cu	47 - 67	135	100	Below CPCB and FAO thresholds; current levels acceptable.
As	5.4 - 7.5	20	20	Within limits, but of concern due to high toxicity even at low concentrations.
Hg	0.17 - 0.28	0.5	1	Within permissible limits; however, accumulation in paddy soils could be problematic.

Note: Ni - Nickel; Pb - Lead; Zn - Zinc; Cd - Cadmium; Cr - Chromium; Cu - Copper; As - Arsenic; Hg - Mercury

In addition to visual interpretation of the spatial distribution maps, statistical correlation analysis was conducted to support the identification of heavy metal hotspots and their potential influencing factors (28). The analysis revealed significant associations between certain metals and environmental characteristics such as topographic position, road proximity, and depositional zones. For example, elevated nickel concentrations were observed in relatively low-lying areas, while higher lead levels showed spatial correspondence with major road networks, suggesting traffic-related emissions (29). Similarly, zinc enrichment was observed in depositional zones where urban runoff and sediment accumulation occur. These statistical relationships provide additional evidence supporting the spatial patterns observed in the GIS-based distribution maps.

Agricultural Relevance

The observed contamination patterns have direct implications for soil fertility, crop productivity, and food safety. Ni contamination in soils can adversely affect agricultural productivity when present in excessive concentrations. High levels of Ni may lead to chlorosis in leafy vegetables and disrupt nitrogen metabolism, particularly in leguminous crops, thereby reducing overall crop yields. Pb, although relatively less mobile in soils, tends to accumulate in root crops such as carrots and radishes as well as in leafy vegetables, creating potential risks of entry into the food chain (30). Zn is an essential micronutrient for plant growth; however, elevated concentrations can induce Cu deficiency in cereal crops, thereby disturbing the nutrient uptake balance and affecting plant development. Cd is highly mobile in soil environments and poses significant risks even at relatively low concentrations. It can easily transfer into staple crops such as rice and wheat grains, raising serious public health concerns due to its toxic nature. Cr, particularly in its hexavalent form, is highly toxic and can negatively influence plant growth by impairing seed germination and inhibiting enzymatic activities in crops such as rice and maize (31). Cu is also an essential element required for plant physiological processes, and the current levels observed are generally considered safe; however, continuous monitoring is necessary to prevent potential accumulation resulting from excessive use of fertilizers and pesticides. As is known to bio-accumulate in crops, especially in rice cultivated under flooded conditions, which enhances its mobility and uptake by plants. Long-term exposure through rice consumption can therefore pose serious health risks. Hg, although currently within permissible limits, may undergo methylation in anaerobic conditions commonly found in paddy soils (32). This transformation facilitates its entry into the food chain, potentially leading to neurotoxic effects in humans through prolonged exposure.

Conclusion

The present study systematically investigated the spatial distribution of heavy metals in agricultural soils, integrating laboratory analysis with geospatial mapping, health risk assessment, and ecological evaluation. A total of nineteen sampling sites were analyzed for metals including Ni, Pb, Zn, Cd, Cr, Cu, As, and Hg. Soil pH values (6.7-7.2) reflected slightly acidic to neutral conditions, enhancing the solubility and mobility of certain metals such as Cd and Zn. The DEM analysis highlighted that topographic depressions act as sinks for contaminant accumulation, while slope-driven runoff redistributes pollutants downslope. The LULC classification from Landsat-8 imagery further demonstrated that agricultural zones near built-up areas face heightened contamination due to industrial emissions, vehicular activity, and agricultural inputs. Metal concentrations across the study area were generally higher than natural background values, with Pb and Cd exceeding several international agricultural guideline limits. Zn and Cu, while essential micronutrients, were near phytotoxic thresholds in some sites, raising concerns about long-term soil fertility and crop productivity.

Health risk assessment indicated that children were the most vulnerable group, with HI-values approaching or exceeding unity in certain areas, particularly for Pb, Cd, and Zn. Adults and the elderly exhibited comparatively lower HI values, though occasional exceedances were observed. Carcinogenic risk values for As and Cr were within but close to permissible ranges, warranting continued monitoring. Ecological risk assessment through the PERI emphasized that Cd posed the most severe ecological hazard, followed by Ni and Zn, categorizing some areas under moderate to considerable ecological risk. From an agricultural standpoint, the results reveal a dual challenge, while some heavy metals may initially enhance plant growth (e.g., Zn, Cu), their prolonged accumulation risks toxicity, yield reduction, and contamination of food chains. This underscores the importance of adopting soil remediation strategies, judicious fertilizer use, and monitoring programs to ensure sustainable crop production. Overall, the integration of laboratory findings, GIS-based spatial mapping, and risk modeling provides a comprehensive framework to evaluate both human health and ecological consequences of soil contamination in agricultural landscapes.

Limitations of the study

Although the USEPA health risk assessment framework is widely used for evaluating environmental exposure, certain limitations exist when applying it to the Indian context. The model parameters are largely based on standard exposure assumptions developed for Western populations, which may not fully represent variations in lifestyle, soil contact behaviour, dietary habits, and environmental conditions prevalent in Indian urban environments. For instance, differences in outdoor activity patterns, consumption of locally grown food, and higher population density in urban settlements may influence actual exposure levels. Therefore, while the USEPA framework provides a standardized and scientifically validated approach for risk estimation, the results should be interpreted as indicative estimates, and future studies may benefit from incorporating region-specific exposure parameters for improved accuracy.

Future Scope

The findings of this study provide a strong foundation for further investigation into heavy metal contamination and its environmental implications. Future research should focus on establishing long-term monitoring programs that involve continuous observation of soil and crop systems to identify temporal variations in heavy metal concentrations and their seasonal dynamics. Such monitoring would help in understanding trends in contamination and in developing timely mitigation strategies. In addition, detailed crop uptake studies are necessary to examine the bioaccumulation of heavy metals in major staple food crops. This approach would help establish a direct relationship between soil contamination and potential dietary exposure risks to human populations. Advanced remote sensing approaches can also play an important role in future studies. The integration of hyper-spectral imaging and unmanned aerial vehicle-based monitoring systems may enable the early detection of soil stress and heavy metal accumulation across large agricultural landscapes.

Furthermore, phytoremediation trials should be explored as a sustainable remediation strategy. Research focusing on hyper-accumulator plant species, along with the use of organic amendments such as biochar and compost, could help reduce heavy metal concentrations in contaminated soils and improve overall soil health. These approaches may contribute to developing environmentally friendly and cost-effective solutions for managing heavy metal pollution in urban and peri-urban agricultural areas. In summary, while this study establishes the baseline understanding of heavy metal contamination in agricultural soils, its continuity lies in advancing towards mitigation and sustainable management strategies. The approach of coupling laboratory evidence with spatial analytics has demonstrated strong potential, and future efforts should aim to integrate these insights with socio-economic and policy frameworks to safeguard agriculture, ecosystems, and community health.

Abbreviations

AAS: Atomic Absorption Spectroscopy, ADD: Average Daily Dose, CR: Carcinogenic Risk, DEM: Digital Elevation Model, HI: Hazard Index, ICP-MS: Inductively Coupled Plasma Mass Spectrometry, LULC: Land Use and Land Cover, PERI: Potential Ecological Risk Index, UAV: Unmanned Aerial Vehicle, USEPA: United States Environmental Protection Agency, XRF: X-Ray Fluorescence.

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Author Contributions

Venkatasubbaiah MC: conceptualization, field data collection, Bala Padmaja S: conceptualization, field data collection, Padma Priya KT: laboratory analysis, data validation, Padmaja M: laboratory analysis, data validation, Ravi Sankar VCh: statistical analysis, result interpretation, Madhusudhan Reddy M: supervision, study design, manuscript finalization, Salla Arun Tejadhar Reddy: data curation, mapping, visualization, Sai Kumar R: data curation, mapping, visualization. All authors reviewed and approved the final manuscript.

Conflict of Interest

The authors declare no conflict of interest.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declaration of Generative AI And AI Assisted Technologies in the Writing Process

Artificial Intelligence (AI) tools, including GPT-based language models, were used only for language editing and paraphrasing. All scientific ideas, methodology design, data analysis, and interpretations were developed by the authors based on existing literature. The authors retain full responsibility for the content.

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Not applicable.

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