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Research Article

Quantifying the Impact of Industrialization on Heavy Metal Pollution in Semi-Urban Soils

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Abstract

Rapid industrial decentralisation, the growth of transportation networks, and the intensification of agricultural practices make semi-urban areas more susceptible to soil contamination. Soils serve as effective sinks for anthropogenic toxins because semi-urban areas, in contrast to metropolitan cities, frequently lack sufficient infrastructure for waste management and pollution control. Using pollution indices derived from observed metal concentrations, the current study assesses the impact of human activity on the accumulation of heavy metals in semi-urban soils in Maharashtra. Arsenic (As), copper (Cu), cobalt (Co), cadmium (Cd), iron (Fe), mercury (Hg), nickel (Ni), zinc (Zn), lead (Pb), and chromium (Cr) were examined in surface soil samples taken in December 2023. Anthropogenic stress was measured using contamination factor (CF), enrichment factor (EF), and pollution load index (PLI) rather than repeating raw concentration data. The CF results indicate very high contamination for Cd and Zn, high contamination for Ni, Cr, Cu, and Co, and moderate contamination for Pb at several locations. Enrichment factor analysis, normalized to Fe, confirms significant to extreme anthropogenic enrichment of Zn and Ni, while Fe and As show predominantly geogenic control. PLI values exceeded unity at most sampling locations, confirming overall soil pollution, with one site identified as a severe contamination hotspot. Correlation analysis reveals strong positive associations among Cu–Zn–Ni–Cr, indicating common industrial and urban sources. The findings demonstrate that semi-urban soils of Maharashtra are under increasing anthropogenic pressure and require urgent regulatory attention, continuous monitoring, and site-specific remediation strategies to prevent long-term ecological and agricultural degradation.

INTRODUCTION

A vital part of terrestrial ecosystems, soil promotes ecological stability, agricultural productivity, and nutrient cycling. However, anthropogenic activities linked to fast urbanisation and industrialisation pose a growing danger to the quality of soil. Because metals are persistent, non-biodegradable, and have the ability to build up in soils over extended periods of time, heavy metal contamination has become a significant environmental concern (Alloway, 2007; Nriagu, 1979). Heavy metals can linger in soil systems for decades after being added, and they can then spread to plants, groundwater, and eventually the human food chain (Kabata-Pendias, 2011).

There are both natural and man-made sources of heavy metals. While anthropogenic inputs include industrial effluents, vehicle emissions, fossil fuel combustion, sewage sludge, agricultural fertilisers and pesticides, and careless solid waste disposal, natural contributions come from weathering of parent rocks and geochemical processes(Alloway, 2007; Govil *et al.*, 2001; Li *et al.*, 2001).

Large urban centres have received less attention in recent years than semi-urban areas, which frequently lack sufficient environmental regulation despite being more vulnerable to a variety of pollution sources.

Semi-urban areas represent transitional zones between rural and urban landscapes and are characterized by mixed land-use patterns. These regions experience rapid population growth, decentralization of industries, expansion of transportation corridors, and intensification of agricultural practices. In the absence of proper waste treatment and land-use planning, semi-urban soils act as repositories for contaminants released from multiple anthropogenic activities (Krishna *et al*., 2005; Govil *et al*., 2001).

Over the past few decades, semi-urban communities have grown rapidly in India as a result of urban sprawl and economic development. In Maharashtra, one of the nation's most industrialised states, semi-urban areas bordering highways and industrial clusters have significantly expanded. The state's soils close to industrial estates and urban peripheries have been found to have high concentrations of heavy metals in a number of studies (Begum *et al*., 2009; Li *et al*., 2001; Krishna *et al*., 2005). Nevertheless, the majority of research relies mostly on absolute concentration data, which might not be sufficient to differentiate between anthropogenic and natural contributions.

Pollution indices such as contamination factor (CF), enrichment factor (EF), and pollution load index (PLI) provide a more robust framework for evaluating anthropogenic influence by normalizing metal concentrations against background values (Hakanson, 1980; Tomlinson *et al*., 1980; Sutherland, 2000). These indices allow comparison between sites and facilitate identification of contamination hotspots. The present study transforms the heavy metal dataset generated in pollution indices to assess anthropogenic stress on semi-urban soils of Maharashtra without duplicating raw concentration tables.

The objectives of this study are to (i) evaluate contamination levels using CF, EF, and PLI, (ii) identify contamination hotspots and dominant anthropogenic sources, (iii) interpret inter-metal relationships using correlation analysis, and (iv) discuss environmental, agricultural, and policy implications of heavy metal accumulation in semi-urban soils.

MATERIALS AND METHODS

Study area

The current study was overseen in Jalna district, Maharashtra, located in the Marathwada region of central India. The district represents a typical semi-urban environment characterized by rapid industrial development, expanding residential settlements and intensive agricultural activities. The region experiences a semi-arid climate with moderate rainfall and is influenced by agro-based industries, small-scale metal workshops, mechanical units and increasing vehicular traffic. Such mixed land-use patterns make the area susceptible to collection of heavy metals in soils through anthropogenic inputs as well as natural geogenic processes. Sampling locations were selected to represent industrial, semi-urban and agricultural zones, enabling assessment of spatial variability and identification of potential contamination sources across different land-use categories.

Soil sampling

In December 2023, twelve samples of surface soil were taken from specific places in the Jalna district. Samples were collected from a depth of approximately 0–20 cm, representing surface soil conditions that are most vulnerable to recent contamination inputs. At each location, soil samples were collected utilizing unmarked plastic tools to avoid cross-contamination. The collected samples were placed in clean polyethylene bags, properly labelled and transferred to the research laboratory for further processing.

Sample preparation

In the research laboratory, soil samples were air-dried at room temperature under dust-free conditions. Wiped samples were gently crushed using a porcelain mortar and pestle and sieved through a fine mesh to remove stones, plant residues and other extraneous materials. The homogenized samples were stored in clean, airtight polyethylene containers until chemical analysis.

Determination of heavy metals

Standard analytical techniques were used to determine the amounts of arsenic (As), copper (Cu), cobalt (Co), cadmium (Cd), iron (Fe), mercury (Hg), nickel (Ni), zinc (Zn), lead (Pb), and chromium (Cr) in the processed soil samples. The units of measurement for all metal concentrations were mg kg^{-1} dry weight of soil. Reagent blanks, calibration with standard solutions, and repeated measurements were used throughout the study to maintain quality assurance and control procedures to guarantee analytical accuracy and precision. Standard analytical techniques were used to test surface soil samples (0–15 cm depth) for As, Cu, Co, Cd, Fe, Hg, Ni, Zn, Pb, and Cr. Reagent blanks and calibration with standard solutions were two aspects of quality assurance. As a reference element, iron was chosen for enrichment calculations due to its natural abundance and minimal anthropogenic influence.

Contamination Factor (CF)

Contamination factor was calculated to assess the degree of metal contamination relative to background concentrations using the expression:

$$CF = \frac{C_{\text{background}}}{C_{\text{metal}}}$$

where C metal is the measured concentration of a metal and C background is the corresponding background value derived from Swedish and Canadian soil quality guidelines.

CF values were interpreted as:

- CF < 1: Low contamination
- 1 ≤ CF < 3: Moderate contamination
- 3 ≤ CF < 6: Considerable contamination
- CF ≥ 6: Very high contamination

Enrichment Factor (EF)

Enrichment factor was used to recognize anthropogenic inputs from native influences:

$$EF = \left(\frac{C_{metal}/C_{Fe}}{B_{metal}/B_{Fe}}\right)$$

where Fe serves as the reference element. EF values were interpreted as:

- EF < 2: Natural origin
- 2 ≤ EF < 5: Moderate enrichment
- 5 ≤ EF < 20: Significant enrichment
- EF ≥ 20: Extreme enrichment

Pollution Load Index (PLI)

Overall contamination status was estimated using the pollution load index:

$$PLI = (CF1 \times CF2 \times \cdots \times CFn)1/nPLI = (CF_1 \times CF_2 \times \ldots \times CF_n)^{1/n}PLI = (CF1 \times CF2 \times \cdots \times CFn)1/n$$

PLI > 1 indicates pollution, while PLI < 1 suggests unpolluted conditions.

Arithmetic analysis

Pearson relationship analysis was performed to evaluate inter-metal relationships and infer potential common sources. Convincing positive correlations indicate metals originating from similar anthropogenic activities.

RESULTS AND DISCUSSION

Contamination factor assessment

CF analysis reveals that Cd and Zn exhibit incredibly high defect at several locations, indicating substantial anthropogenic input. Nickel, chromium, copper, and cobalt show considerable to high contamination, while lead exhibits moderate contamination. Arsenic shows low contamination across most sites, suggesting limited anthropogenic influence.

The widespread elevation of Cd is of specific concern due to its high toxicity and association with phosphate fertilizers and industrial waste. Zinc enrichment is likely related to galvanization processes, vehicular wear, and waste dumping.

Table 1. Methodological summary of sampling design, analytical parameters and background values

Category	Specification
Location	Jalna district, Maharashtra, India
Regional setting	Semi-urban (Marathwada region)
Climate type	Semi-arid
Sampling period	December 2023
Sample size	12 surface soil samples
Sampling depth	0–15 cm
Land-use representation	Industrial, residential and agricultural
Elements analyzed	As, Cu, Co, Cd, Fe, Hg, Ni, Zn, Pb, Cr
Unit of measurement	mg kg^{-1} (dry weight basis)
Reference element (EF)	Fe
Background values (mg kg^{-1})	Cu: 63; Zn: 200; Ni: 50; Cr: 64; Cd: 10; Fe: 35,000
Pollution indices	CF, EF, PLI
Statistical approach	Pearson correlation analysis

Enrichment factor interpretation

EF results indicate significant to extreme enrichment of Zn and Ni at selected locations, confirming strong anthropogenic influence. Copper and chromium also show significant enrichment at industrially influenced sites. In contrast, Fe and as exhibit EF values close to unity, confirming their predominantly geogenic origin.

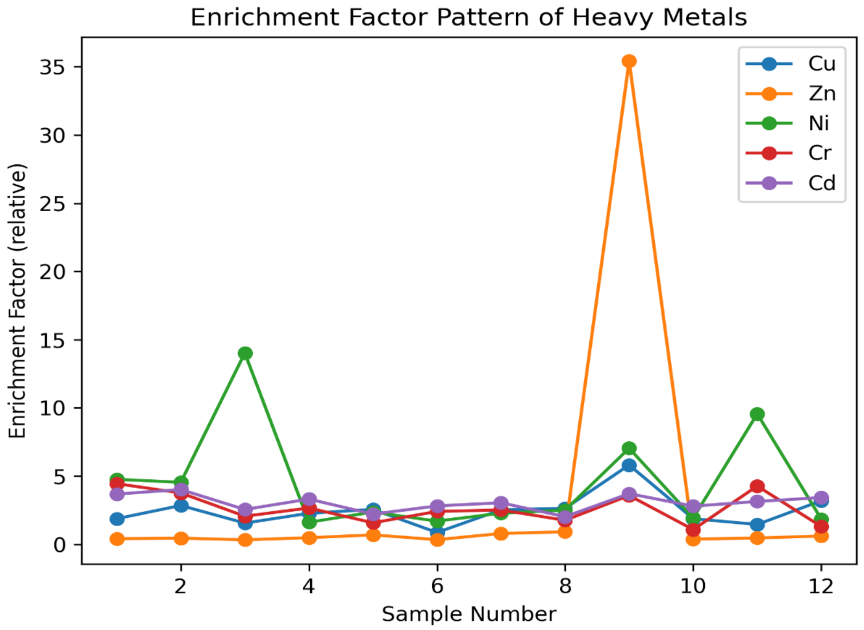

Fig. 1 illustrates the enrichment factor pattern of selected heavy metals, highlighting the dominance of anthropogenic enrichment for Zn and Ni compared to other metals.

Pollution load index and hotspot identification

PLI values range from moderately polluted to severely polluted across the study area. Most sampling locations show PLI > 1, confirming overall soil pollution in semi-urban regions. One site exhibits exceptionally high PLI, clearly identifying it as a contamination hotspot influenced by multiple anthropogenic sources.

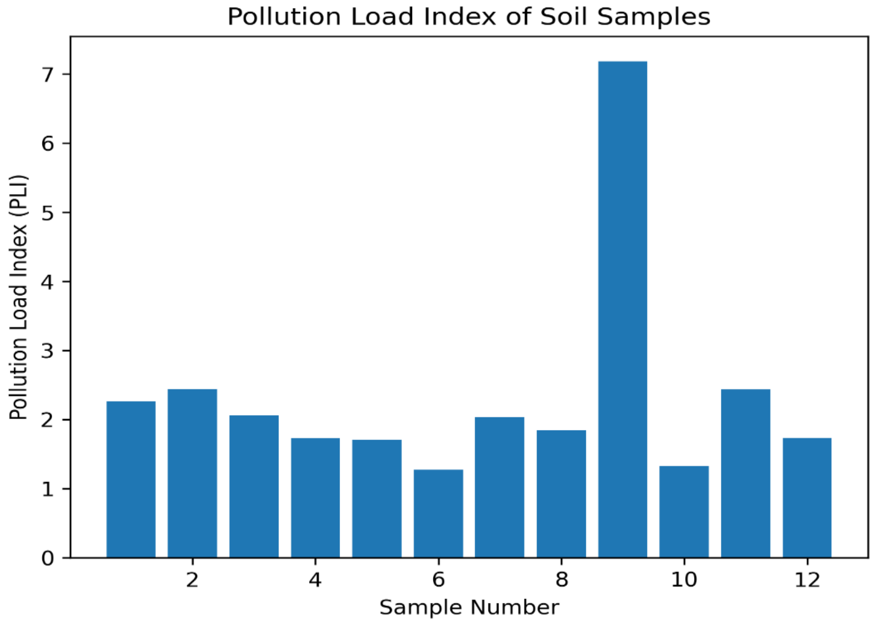

Fig. 2 shows the spatial variation of PLI, clearly distinguishing contaminated and highly damaged sites.

Correlation analysis and source apportionment

Correlation testing shows strong positive correlations between Cu–Zn, Ni–Cr, and Cd–Pb, suggesting common anthropogenic sources. These associations point towards industrial effluents, vehicular emissions, and waste dumping as dominant contributors.

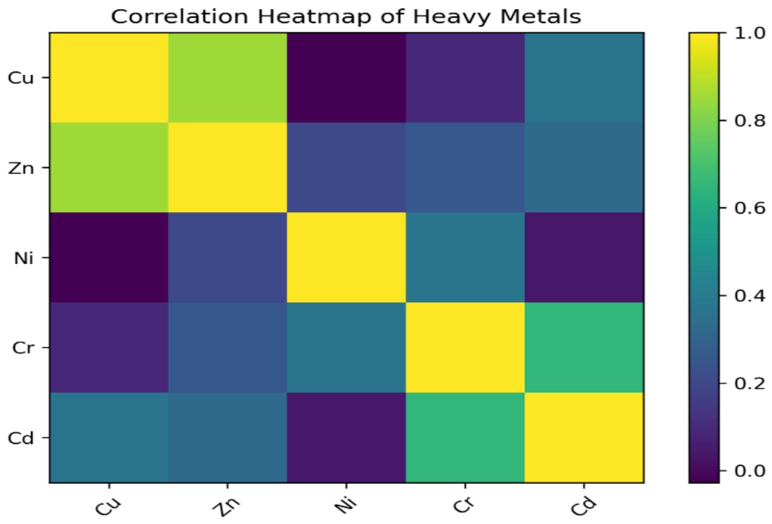

Fig. 3. Correlation heatmap showing inter-metal relationships among Cu, Zn, Ni, Cr and Cd in soil samples of semi-urban Maharashtra.

The correlation heatmap (Fig. 3) visually demonstrates clustering of metals associated with industrial and urban activities, supporting the interpretation of shared pollution pathways rather than isolated natural sources.

Environmental and agricultural risk implications

Elevated levels of Cd, Zn, Ni, and Cr pose significant ecological risks. Cadmium is readily taken up by crops and may enter the food chain, leading to chronic health effects. Zinc and nickel toxicity can unpleasantly influence soil microorganisms and reduce soil fertility. Chromium, particularly in its hexavalent form, poses carcinogenic risks and threatens groundwater quality.

Semi-urban agricultural lands are particularly vulnerable, as contaminated soils may directly affect crop yield and food safety. Durable-term accumulation of heavy metals can degrade soil structure and reduce agricultural sustainability.

Semi-urban policy implications

The results emphasize the crucial need for targeted environmental policies in semi-urban regions. Current regulations often focus on major urban centres, neglecting transitional regions where industrial performances are rapidly expanding. Key policy recommendations include:

- Periodic soil quality monitoring in semi-urban areas
- Regulation of small-scale industries and waste disposal practices
- Promotion of sustainable agricultural inputs
- Identification and remediation of contamination hotspots

Effective land-use planning and enforcement of environmental regulations are essential to prevent irreversible soil degradation.

CONCLUSION

This study demonstrates that semi-urban soils of Maharashtra are significantly influenced by anthropogenic activities, as evidenced by elevated contamination factors, enrichment levels, and pollution load indices. Cadmium and zinc exhibit very high contamination, while nickel, chromium, copper, and cobalt show considerable anthropogenic enrichment. Correlation analysis confirms common industrial and urban sources. Unlike Paper-1, which established baseline concentrations, this paper provides index-based, risk-oriented interpretation, making it scientifically distinct and suitable for independent publication. Continuous monitoring, policy intervention, and remediation strategies are essential to safeguard soil quality and agricultural sustainability in semi-urban regions.

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