



RESEARCH ARTICLE

Impact of heavy metal pollution on some physical and chemical properties in major soil orders of India

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Abstract

Heavy metal pollution poses a major threat to soil health, crop productivity and environmental safety in industrial and wastewater-affected regions of India. This study assessed the influence of industrial discharge and wastewater irrigation on soil physicochemical properties and heavy metal dynamics across three major soil orders-Alfisols (Sukinda Valley, Odisha), Inceptisols (Sonipat, Haryana) and Vertisols (Dewas Industrial Area, Madhya Pradesh). Composite soil samples were collected from polluted and adjoining non-polluted sites at two depths (0–15 and 15–30 cm). Soils were analysed for texture, pH, electrical conductivity (EC), organic carbon (OC), cation exchange capacity (CEC), total nickel (Ni), cadmium (Cd), lead (Pb) and chromium (Cr) as well as bioavailable Ni, Cd, Pb and Cr using diethylenetriaminepentaacetic acid (DTPA) and ethylenediaminetetraacetic acid (EDTA) extractants. Results showed that soil physicochemical properties varied significantly among soil orders, with Alfisols being acidic, Inceptisols near neutral and Vertisols alkaline with high clay content and CEC. Pollution generally increased EC and OC but reduced CEC, particularly in Alfisols and Vertisols. Total metal concentrations increased markedly in polluted soils, especially Cr in Alfisols (256–296 mg kg⁻¹) and Ni in Inceptisols (765–876 mg kg⁻¹). Bioavailable fractions followed a similar trend, with polluted Inceptisols exhibiting exceptionally high DTPA-extractable Ni (9.18 mg kg⁻¹) and Cd concentrations, while polluted Alfisols showed elevated Cr mobility. The findings highlight that industrial and wastewater pollution substantially enhance heavy metal load and mobility, altering key soil properties and increasing ecological risk. Soil order strongly governs metal retention and bioavailability, emphasising the need for order-specific monitoring, remediation and sustainable land-use strategies to safeguard environmental and food system health.

Keywords: bioavailability; heavy metals; India; industrial effluents; soil order; soil pollution; wastewater irrigation

Introduction

Heavy metal contamination is a global concern due to its harmful effects on ecosystems, human health and agriculture (1). In India, accumulation of heavy metals in soil due to the long-term use of wastewater has been widely reported. For example, a high accumulation of zinc (Zn), copper (Cu), nickel (Ni) and lead (Pb), to the extent of 141 %, 219 %, 75 % and 28.1 % respectively was recorded in arable soil due to long-term wastewater irrigation (2). Metals enter soils, water and air from natural sources such as weathering of rocks, geological processes and soil erosion (3), as well as anthropogenic activities like industrial discharge, mining, agrochemical use and urbanisation (4). Parent rock composition and soil formation influence natural metal levels, while human activities often raise concentrations beyond these background levels. Understanding these sources and pathways is essential for effective soil management, pollution control and sustainable environmental practices. The discharge of sewage, sludge, municipal waste and industrial effluents is a major source of heavy metals such as Cu, cadmium (Cd), Zn, Pb, Ni and iron (Fe) in the environment (5). Continuous disposal elevates metal concentrations in topsoil and alters soil properties, reducing fertility. Crops grown in contaminated areas or irrigated with untreated

wastewater accumulate toxic metals (6–9), leading to bioaccumulation and health risks. Persistent metals also disrupt soil microbial diversity, hinder enzymatic activity and degrade soil quality, facilitating their transfer through trophic levels and causing long-term environmental and public health hazards (10).

The mobility of heavy metals in soils depends on their binding mechanisms, chemical forms and association with soil phases, which are influenced by environmental physicochemical and biological properties (11). Strong sorption to negatively charged soil particles often limits their transport. Due to this complexity, the binding mechanisms for heavy metals in soils are diverse and highly variable, depending on factors such as soil composition, pH, redox potential, cation exchange capacity (CEC) and the presence of competing ions or ligands. Soils are broadly classified into different orders based on their genesis, morphology and physicochemical properties under the United States Department of Agriculture (USDA) soil taxonomy system. Major soil orders such as Alfisols (Sukinda Valley, Odisha), Inceptisols (Sonipat, Haryana) and Vertisols (Dewas Industrial Area, Madhya Pradesh) differ significantly in characteristics such as clay mineralogy, organic matter content and CEC, which in turn influence heavy metal retention, mobility and bioavailability. Metals may exist as adsorbed

ions, organic complexes, precipitates or mineral-bound species, with binding strength determining bioavailability, leachability and ecological risk. Heavy metals in soil organic matter are absorbed by plants and enter the human food chain, causing bioaccumulation and biomagnification risks (12). Dietary exposure to metals like Cd, Pb and Cu can lead to neurological damage, haemolysis, metabolic disorders and diseases such as Wilson's disease, itai-itai disease, renal and hepatic damage and reproductive failure (2, 13, 14). Their persistence makes heavy metal contamination a major environmental and public health challenge, requiring monitoring and mitigation to ensure food safety and ecosystem sustainability.

Materials and Methods

Soil sampling

Soil samples were collected from selected metal-polluted sites and adjoining non-polluted areas across different soil orders of India. Polluted sites were chosen based on proximity to industrial zones, mining areas and wastewater-irrigated agricultural lands, while non-polluted sites served as controls.

1. Soil 1: Sukinda Valley, Jajpur, Odisha (Alfisols)-Cr polluted (chromite mining).
2. Soil 2: Sonipat, Haryana (Inceptisols)-Ni polluted (Atlas cycle factory effluent irrigated).
3. Soil 3: Dewas Industrial Area, Madhya Pradesh (Vertisols)-Cr, Ni polluted (industrial effluent irrigated).

From each location, composite samples were collected from the topsoil (0–15 cm depth) and subsoil (15–30 cm depth) and were air-dried, ground and passed through a 2 mm sieve for further analysis. The total number of soil samples = 3 soils/orders $\times$ 2 pollution levels (polluted and non-polluted) $\times$ 2 depths $\times$ 3 replications = 36.

General characteristics of the soils

Soil pH was measured in a 1 : 2.5 (soil : water) ratio using a combined electrode. The electrical conductivity (EC) of the supernatant liquid was determined at 25 °C using a conductivity bridge and expressed in dS m^{-1} (15). The hydrometer technique was used to determine the mechanical composition of the experimental soil i.e. the proportion of sand, silt and clay size particles (16). The USDA proposed textural triangle was used to determine the soil texture (17). The soil's CEC was determined using Jackson's (15) ammonium acetate method. The soil sample was sieved through a 0.2 mm sieve for the measurement of oxidisable organic carbon (OC). The OC content of the soil was determined using the Walkley and Black (18) wet oxidation technique with $\text{K}_2\text{Cr}_2\text{O}_7$.

Total metal content in soil

For the determination of total metal content, soil samples (2 g) were digested with 25 mL aqua regia ($\text{HCl} : \text{HNO}_3$ 3 : 1) on a hot plate (80–100 °C) until the volume of the contents was reduced to 3–5 mL (19). The samples were then allowed to cool for 30 min, diluted and filtered through the Whatman No. 42 filter paper. The filtrates were analysed for Ni, Pb, Cr and Cd contents using atomic absorption spectrophotometry (AAS).

Diethylenetriaminepentaacetic acid extractable heavy metal

The bioavailable fraction of heavy metals (e.g., Cd, Pb, Ni and Cr) in soil was determined using the diethylenetriaminepentaacetic acid (DTPA) extraction method as described by Lindsay and Norvell (20).

Briefly, 10g of air-dried and 2mm sieve was placed in a 100mL conical flask. A 20 mL of DTPA extraction solution, containing 0.005M DTPA, 0.01M CaCl_2 and 0.1M triethanolamine (TEA), was added to the soil. The pH of the solution was adjusted to 7.3 ± 0.05 . The suspension was shaken on a mechanical shaker at 180rpm for 2 hr at room temperature. After shaking, the mixture was filtered through Whatman No.42 filter paper. The concentration of extractable heavy metals in the filtrate was determined using AAS (Analytik-Jena NovAA350), with calibration curves generated from Cd, Pb, Ni and Cr standards (Merck KGaA, Germany). The detection limits for Cd, Cr and Ni ranged from 0.25 to 2.5 ppm, whereas those for Pb ranged from 2.5 to 40 ppm.

Ethylenediaminetetraacetic acid extractable heavy metal content

A 10 g sample of air-dried soil was placed in a 250 mL wide-mouth plastic bottle along with 60 mL of 0.05 M ethylenediaminetetraacetic acid (EDTA) solution adjusted to pH 7.0, maintaining a soil-to-extractant ratio of 1 : 6. The mixture was shaken for 1 hr on a reciprocating shaker (19). After shaking, the suspension was filtered and the resulting filtrate was analysed for metal concentrations. For quality control, the AAS was calibrated using standard metal solutions from Merck KGaA, Darmstadt, Germany. To verify instrument stability, standard solutions were analysed after every batch of 30 samples. The results were accepted only when the measured standard concentrations were within 95–105 % of the certified values.

Statistical analysis

The laboratory-determined soil parameter data were recorded and analysed using OPSTAT software. Mean values for different soils under polluted and non-polluted conditions were compared using a three-way analysis of variance (ANOVA). The ANOVA model included soil order (A), pollution level (B) and soil depth (C) as main factors, along with their interactions ($A \times B$, $A \times C$, $B \times C$ and $A \times B \times C$), to evaluate their individual and combined effects on soil physicochemical properties and heavy metal concentrations.

Results

Soil physicochemical properties

The study revealed significant variations in soil properties across soil orders (Table 1). Alfisols (Sukinda Valley, Odisha) were classified as loamy sand, Inceptisols (Sonipat, Haryana) as sandy loam and Vertisols (Dewas Industrial Area) as clay, with 50.3 % clay content. Soil pH varied significantly with soil order, while pollution level and soil depth showed no statistical effect. Alfisols were acidic (≈ 5.8), with a slight increase under pollution conditions (≈ 6.12), Inceptisols remained near-neutral to slightly alkaline (7.57–7.85) and Vertisols were alkaline (7.99–8.52). Electrical conductivity also differed significantly by soil order (critical difference (CD) = 0.048, $p = 0.05$), but not by pollution or depth. Polluted Alfisols and Inceptisols exhibited higher EC than non-polluted samples, whereas Vertisols showed a mixed trend, an increase at the 0–15 cm (0.57 dS m^{-1}) and a decrease at 15–30 cm (0.18 dS m^{-1}).

The data on OC and CEC under different soil orders and pollution levels are presented in Table 2. In Alfisols (Sukinda Valley, Odisha), OC ranged from 1.20 to 1.59 g/100 g and was slightly higher in polluted soils (1.59 and 1.24 g/100 g at 0–15 and 15–30 cm) than in non-polluted soils (1.53 and 1.20 g/100 g). However, CEC was

lower in polluted soils (10.6 and 6.2 cmol(p⁺)/kg) compared to non-polluted (12.3 and 8.1 cmol(p⁺)/kg). In Inceptisols (Sonipat, Haryana), OC was relatively low (0.65–0.89 g/100 g), with polluted soils showing higher values (0.89 and 0.77 g/100 g) than non-polluted soils (0.70 and 0.65 g/100 g). The CEC showed little variation between polluted (16.3 and 11.0 cmol(p⁺)/kg) and non-polluted soils (16.7 and 11.2 cmol(p⁺)/kg). Vertisols (Dewas Industrial Area) had OC values ranging from 1.08 to 1.17 g/100 g, which were slightly lower in polluted soils (1.15 and 1.08 g/100 g) than in non-polluted soils (1.17 and 1.09 g/100 g). The CEC was markedly higher in Vertisols, with non-polluted soils recording 50.9 and 47.0 cmol(p⁺)/kg, while polluted soils slightly lower values (48.6 and 43.9 cmol(p⁺)/kg).

Effect of polluted and non-polluted soils on total metal content

The total metal contents (Ni, Cd, Pb and Cr) of soils collected from polluted and non-polluted areas under different soil orders of India

is presented in Table 3. In Alfisols (Sukinda Valley, Odisha), Ni content was comparable between non-polluted (22.4–43.4 mg kg⁻¹) and polluted soils (22.9–49.5 mg kg⁻¹). The Cd remained low (0.60–0.69 mg kg⁻¹) with negligible variation. The Pb increased under polluted conditions (10.5–14.0 mg kg⁻¹) compared to non-polluted soils (6.7–7.5 mg kg⁻¹). The Cr showed a sharp rise in polluted soils (256–296 mg kg⁻¹) against 43.5–45.7 mg kg⁻¹ in non-polluted soils. In Inceptisols (Sonipat, Haryana), polluted soils exhibited extremely high Ni (765–876 mg kg⁻¹) and Cd (8.71–9.54 mg kg⁻¹) compared to non-polluted soils (Ni: 54–55 mg kg⁻¹; Cd: 1.23–1.39 mg kg⁻¹). The Pb increased slightly (106–111 mg kg⁻¹ vs. 78.5–106 mg kg⁻¹), while Cr showed a marginal increase (31.3–42.4 mg kg⁻¹ vs. 28.1–31.7 mg kg⁻¹). In Vertisols (Dewas Industrial Area), polluted soils recorded higher Ni (74.8–95.1 mg kg⁻¹) and Cr (91.1–94.2 mg kg⁻¹) contents than non-polluted soils (Ni: 46.4–51.0 mg kg⁻¹; Cr: 32.9–40.1 mg kg⁻¹). The Cd remained similar (1.27–1.29 mg kg⁻¹), while Pb showed a slight increase (17.3–17.5 mg kg⁻¹ vs. 13.3–13.6 mg kg⁻¹).

Table 1. Texture, pH and electrical conductivity of polluted and non-polluted soils at different depths under major soil orders of India

Soil orders		pH		EC (dS m ⁻¹)		Clay (%)	Texture
		0–15 cm	15–30 cm	0–15 cm	15–30 cm		
Alfisol (Sukinda Valley, Odisha)	NP	5.86	5.82	1.49	1.47	6.46	Loamy sand
	P	5.64	6.12	1.58	1.57		
Inceptisol (Sonipat, Haryana)	NP	7.66	7.85	0.76	0.88	14.1	Sandy loam
	P	7.57	7.62	0.98	0.93		
Vertisol (Dewas Industrial Area)	NP	8.03	8.52	0.32	0.47	50.3	Clay
	P	7.99	8.02	0.57	0.18		
CD (<i>p</i> = 0.05)		A-0.215, B-NS, C-0.175		A-0.048, B-NS, C-NS			

A: soil order; B: pollution level; C: depth; EC: electrical conductivity; CD: critical difference; P: polluted soils; NP: non-polluted soils.

Table 2. Organic carbon and cation exchange capacity of soil collected from polluted and non-polluted soils at different depths under major soil orders of India

Soil orders		OC (g/100 g)		CEC (cmol (p ⁺)/kg)	
		0–15 cm	15–30 cm	0–15 cm	15–30 cm
Alfisol (Sukinda Valley, Odisha)	NP	1.53	1.20	12.3	8.1
	P	1.59	1.24	10.6	6.2
Inceptisol (Sonipat, Haryana)	NP	0.70	0.65	16.7	11.2
	P	0.89	0.77	16.3	11.0
Vertisol (Dewas Industrial Area)	NP	1.17	1.09	50.9	47.0
	P	1.15	1.08	48.6	43.9
CD ($p = 0.05$)		A-0.039 B-0.032 C-0.032		A-1.68 B-1.37 C-1.37	

A: soil order; B: pollution level; C: depth; OC: organic carbon; CEC: cation exchange capacity; CD: critical difference; P: polluted soils; NP: non-polluted soils.

Table 3. Total metal content of soil collected from polluted and non-polluted soils at different depths under major soil orders of India

Soil orders		Ni (mg kg ⁻¹)		Cd (mg kg ⁻¹)		Pb (mg kg ⁻¹)		Cr (mg kg ⁻¹)	
		0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Alfisol (Sukinda Valley, Odisha)	NP	43.4	22.4	0.66	0.60	7.5	6.7	45.7	43.5
	P	49.5	22.9	0.69	0.62	10.5	14.0	296	256
Inceptisol (Sonipat, Haryana)	NP	55	54	1.39	1.23	106	78.5	31.7	28.1
	P	876	765	9.54	8.71	111	106	42.4	31.3
Vertisol (Dewas Industrial Area)	NP	51.0	46.4	1.18	1.11	13.6	13.3	40.1	32.9
	P	95.1	74.8	1.27	1.07	17.3	17.5	94.2	91.1
CD ($p = 0.05$)		A-7.75 B-6.32 C-6.32		A-0.15 B-0.12 C-0.12		A-3.82 B-3.12 C-3.12		A-34.2 B-27.9 C-NS	

A: soil order; B: pollution level; C: depth; Ni: nickel; Cd: cadmium; Pb: lead; Cr: chromium; P: polluted soils; NP: non-polluted soils.

Safe limit of total Ni, Cd, Pb and Cr in soils are 75, 3, 100 and 50 mg kg⁻¹, respectively (13).

Effect of polluted and non-polluted soils on diethylenetriaminepentaacetic acid-extractable metal content

The DTPA-extractable concentrations of Ni, Cd, Pb and Cr in polluted and non-polluted soils under major soil orders of India are presented in Table 4. In Alfisols (Sukinda Valley, Odisha), extractable Ni ranged from 0.42–0.62 mg kg⁻¹ with negligible differences between polluted and non-polluted soils. The Cd remained very low (0.02–0.03 mg kg⁻¹), while Pb showed a slight increase under polluted conditions (0.11–0.15 mg kg⁻¹). The Cr exhibited a pronounced increase in polluted soils (2.17–2.35 mg kg⁻¹) compared to non-polluted soils (0.43–0.74 mg kg⁻¹). In Inceptisols (Sonipat, Haryana), polluted soils recorded significantly higher Ni (5.78–9.18 mg kg⁻¹) and Cd (0.75–0.95 mg kg⁻¹) than non-polluted soils (Ni: 0.93–1.80 mg kg⁻¹; Cd: 0.12–0.24 mg kg⁻¹). Pb was also elevated (3.63–6.44 mg kg⁻¹ vs. 2.51–5.45 mg kg⁻¹), while Cr showed minor variation (0.73–0.89 mg kg⁻¹ in polluted vs. 0.48–0.94 mg kg⁻¹ in non-polluted soils). In Vertisols (Dewas Industrial Area), Ni was higher in polluted soils (0.58–0.92 mg kg⁻¹) compared to non-polluted soils (0.19–0.34 mg kg⁻¹). The Cd remained low (0.03–0.09 mg kg⁻¹), Pb increased under polluted conditions (2.93–3.07 mg kg⁻¹ vs. 1.47–2.28 mg kg⁻¹) and Cr showed a marked rise (1.59–2.77 mg kg⁻¹ vs. 0.19–0.34 mg kg⁻¹).

Effect of polluted and non-polluted soils on ethylenediaminetetraacetic acid-extractable metal content

The EDTA-extractable concentrations of Ni, Cd, Pb and Cr in polluted and non-polluted soils under different soil orders of India are presented in Table 5. In Alfisols (Sukinda Valley, Odisha), extractable Ni ranged from 6.1 to 9.8 mg kg⁻¹, with slightly higher values observed in polluted soils. Cd remained very low (0.28–0.46 mg kg⁻¹) with only minor differences. The Pb showed a marginal increase under polluted conditions (2.40–2.65 mg kg⁻¹ vs. 1.86–2.27 mg kg⁻¹), while Cr exhibited a sharp rise (27.1–41.6 mg kg⁻¹ vs. 9.6–11.2 mg kg⁻¹). In Inceptisols (Sonipat, Haryana), polluted soils recorded significantly higher Ni (5.27–9.18 mg kg⁻¹) and Cd (0.75–0.95 mg kg⁻¹) than non-polluted soils (Ni: 0.93–1.80 mg kg⁻¹; Cd: 0.12–0.24 mg kg⁻¹). Pb was also elevated (3.63–6.44 mg kg⁻¹ vs. 2.51–5.45 mg kg⁻¹), while Cr showed minor variation (0.73–0.89 mg kg⁻¹ in polluted vs. 0.48–0.94 mg kg⁻¹ in non-polluted soils). In Vertisols (Dewas Industrial Area), Ni was higher in polluted soils (0.58–0.92 mg kg⁻¹) compared to non-polluted soils (0.19–0.34 mg kg⁻¹). The Cd remained low (0.03–0.09 mg kg⁻¹), Pb increased under polluted conditions (2.93–3.07 mg kg⁻¹ vs. 1.47–2.28 mg kg⁻¹) and Cr showed a marked rise (1.59–2.77 mg kg⁻¹ vs. 0.19–0.34 mg kg⁻¹).

Table 4. Diethylenetriaminepentaacetic acid extractable heavy metal content in polluted and non-polluted soils at different depths under major soil orders of India

Soil orders		Ni (mg kg ⁻¹)		Cd (mg kg ⁻¹)		Pb (mg kg ⁻¹)		Cr (mg kg ⁻¹)	
		0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Alfisol (Sukinda Valley, Odisha)	NP	0.59	0.42	0.03	0.02	0.14	0.11	0.74	0.43
	P	0.62	0.49	0.03	0.02	0.15	0.14	2.35	2.17
Inceptisol (Sonipat, Haryana)	NP	1.80	0.93	0.24	0.12	5.45	2.51	0.72	0.48
	P	9.18	5.78	0.95	0.75	6.44	3.63	0.89	0.73
Vertisol (Dewas Industrial Area)	NP	0.34	0.19	0.06	0.03	2.28	1.47	0.34	0.19
	P	0.92	0.58	0.42	0.28	3.39	2.69	2.77	1.59
		A-0.34		A-0.51		A-0.29		A-0.05	
		B-0.28		B-0.42		B-0.24		B-0.04	
CD ($p = 0.05$)		C-0.28		C-0.42		C-0.24		C-0.04	

A: soil order; B: pollution level; C: depth; Ni: nickel; Cd: cadmium; Pb: lead; Cr: chromium; P: polluted soils; NP: non-polluted soils.

Table 5. Ethylenediaminetetraacetic acid extractable heavy metal content (mg kg⁻¹) in polluted and non-polluted soils at different depths under major soil orders of India

Soil orders		Ni		Cd		Pb		Cr	
		0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Alfisol (Sukinda Valley, Odisha)	NP	8.4	6.1	0.28	0.16	2.27	1.86	11.2	9.6
	P	9.8	8.0	0.46	0.33	2.65	2.40	41.6	27.1
Inceptisol (Sonipat, Haryana)	NP	80.6	60.5	1.61	0.88	66.6	42.5	10.5	7.4
	P	151	114	5.27	3.69	74.5	79.1	15.9	12.5
Vertisol (Dewas Industrial Area)	NP	6.3	5.7	0.90	0.62	4.31	3.08	7.13	5.62
	P	11.2	9.0	1.18	0.97	6.85	4.85	23.8	18.1
		A-1.41		A-0.12		A-1.90		A-0.83	
		B-1.15		B-0.10		B-1.55		B-0.67	
CD ($p = 0.05$)		C-1.15		C-0.10		C-1.55		C-0.67	

A: soil order; B: pollution level; C: depth; Ni: nickel; Cd: cadmium; Pb: lead; Cr: chromium; P: polluted soils; NP: non-polluted soils.

polluted soils recorded markedly higher Ni (114–151 mg kg⁻¹) and Cd (3.69–5.27 mg kg⁻¹) compared to non-polluted soils (Ni: 60.5–80.6 mg kg⁻¹; Cd: 0.88–1.61 mg kg⁻¹). The Pb was substantially elevated (74.5–79.1 mg kg⁻¹ vs. 42.5–66.6 mg kg⁻¹) and Cr also increased (12.5–15.9 mg kg⁻¹ vs. 7.4–10.5 mg kg⁻¹). In Vertisols (Dewas Industrial Area), Ni was moderately higher in polluted soils (9.0–11.2 mg kg⁻¹) than non-polluted soils (5.7–6.3 mg kg⁻¹). Cd remained low (0.62–1.18 mg kg⁻¹), Pb increased under polluted conditions (4.85–6.85 mg kg⁻¹ vs. 3.08–4.31 mg kg⁻¹) and Cr showed a strong rise (18.1–23.8 mg kg⁻¹ vs. 5.62–7.13 mg kg⁻¹).

Discussion

Effect of polluted and non-polluted soils on soil pH and electrical conductivity texture

Distinct variations in soil physicochemical properties across Alfisols, Inceptisols and Vertisols (Table 1) highlight the strong influence of pedogenic characteristics on pH, texture and EC. Alfisols exhibited a loamy sand texture, Inceptisols a sandy loam texture and Vertisols a clayey texture, with the latter's high clay content (50.3 %) reflecting smectitic mineralogy and shrink-swell behaviour (21). Soil pH differed significantly among soil orders (factor A), while pollution level (B) and soil depth (C) showed no significant effects. Acidic Alfisols (pH ~5.8) in Sukinda Valley correspond to high leaching and low base saturation in humid tropical regions (22), with a slight pH increase at depth under pollution due to alkaline particulates. Inceptisols maintained a near-neutral to slightly alkaline pH, indicating carbonate buffering, whereas Vertisols were consistently alkaline (7.99–8.52), which is linked to base-rich parent material and 2 : 1 clay minerals (23). Electrical conductivity also varied significantly among soil orders, with marginal increases under pollution in Alfisols and Inceptisols, likely due to the deposition of soluble ions. Vertisols showed higher EC at the surface under

polluted conditions, with a decrease at greater depths due to salt adsorption and restricted percolation in clay horizons (24). Overall, soil order dominated pH and EC variation, confirming that pedogenic controls outweigh short-term anthropogenic effects, with Alfisols, Inceptisols and Vertisols exhibiting distinct resilience patterns under pollution stress.

Effect of polluted and non-polluted soils under major soil orders of India on organic carbon and cation exchange capacity

The OC and CEC varied significantly among soil orders, reflecting differences in mineralogical and organic matter characteristics as well as the effects of metal pollution (Table 2). Alfisols, dominated by low activity kaolinitic clays, showed moderate OC but low CEC, consistent with limited humus stabilisation. Polluted Alfisols exhibited slightly higher OC, likely due to the deposition of carbon-rich particulates or inhibited decomposition under metal stress, while CEC declined, possibly because of heavy metal occupation of exchange sites. Inceptisols, being dominantly illitic, maintained low OC and moderate CEC, with a minor increase in OC under pollution and stable CEC, indicating resilience from balanced clay composition (25). Vertisols recorded the highest CEC due to smectitic clays, with marginal decline under pollution, suggesting partial saturation of exchange sites by metals. Depth-wise decreases in OC and CEC reflect typical pedogenic gradients. Overall, soil order, pollution and depth significantly influenced OC and CEC, confirming that metal contamination alters exchange reactions differently across mineralogical contexts (26).

Effect of polluted and non-polluted soils under major soil orders of India on total metal content

Total metal content varied across soil orders, reflecting both pedogenic controls and anthropogenic inputs (Table 3). Alfisols of Sukinda Valley showed moderate increases in Ni, Cd and Pb, which were within the safe limit; however, total Cr under polluted conditions exceeded the safe limit, indicating Cr enrichment from chromite mining (27). Their low activity kaolinitic clays and limited functional groups restrict metal retention, facilitating vertical redistribution (21). Inceptisols of Sonipat exceeded the safe limit of total Ni, Pb and Cd under polluted conditions, indicating strong industrial pressure from electroplating and wastewater sources (28). Despite their mixed mineralogy, their intermediate retention capacity allows elevated metal accumulation (29, 30). Vertisols of Dewas, rich in smectitic clays, exceeded the safe limit of Ni and Cr under polluted conditions, whereas only moderate increase in total Cd and Pb were observed under pollution due to the strong adsorption affinity of this organic matter, leading to limited mobility in the soil (31, 32). Depth-wise variation was minimal, supporting the low subsurface mobility of metals once they become bound to clay-humus complexes (33). Overall, pollution level was the dominated factor influencing metal accumulation, overriding pedogenic controls under high contamination loads, while contrasting behaviours among soil orders underscores the role of mineralogy and exchange properties in metal retention (26).

Effect of polluted and non-polluted soils under major soil orders of India on diethylenetriaminepentaacetic acid- and ethylenediaminetetraacetic acid-extractable heavy metals

The DTPA- and EDTA-extractable metal fractions varied across soil orders, reflecting the combined influence of soil properties, pollution load and soil depth on metal lability (Table 4). In Alfisols of

Sukinda Valley, low extractable Ni, Cd and Pb concentrations indicate strong fixation by Fe-Mn oxides and clay minerals, while a sharp increase in Cr under polluted conditions suggests higher mobility in coarse-textured systems, consistent with earlier findings (34). Inceptisols of Sonipat showed pronounced increases in extractable Ni, Cd and Pb under polluted conditions, highlighting weak metal binding due to moderate organic matter and variable-charge mineralogy (35). The Cr remained less extractable, consistent with its tendency to form stable complexes in neutral soils (32). Vertisols exhibited moderate but consistent increases in Ni, Pb and Cr, indicating that prolonged industrial deposition can saturate smectitic clays despite their high CEC (35). The EDTA consistently extracted higher amounts of metals than DTPA, reaffirming its stronger ligand strength and ability to release both exchangeable and organically bound metals (20). Overall, pollution intensity was the dominant factor influencing metal lability, while soil order modulated metal extractability. Alfisols showed limited metal release except Cr, Inceptisols were highly sensitive and Vertisols displayed intermediate mobilisation. These patterns underscore the need for soil-order-specific strategies in managing heavy-metal-contaminated regions.

Conclusion

The study demonstrates that soil order exerts a dominant influence on physicochemical properties and metal dynamics, even under anthropogenic stress. Alfisols, Inceptisols and Vertisols exhibited distinct responses to pollution, governed by their mineralogy, organic matter content and pedogenic development. Soil pH and electrical conductivity (EC) were primarily controlled by inherent characteristics, with pollution causing only marginal shifts. Organic carbon (OC) and cation exchange capacity (CEC) varied significantly across soil orders and declined under metal contamination, indicating disruption of exchange sites by heavy metals. Total metal accumulation was strongly driven by pollution intensity, overriding natural buffering mechanisms, with Inceptisols showing the highest sensitivity and Vertisols the greatest resilience. Extractable metal fractions (diethylenetriaminepentaacetic acid (DTPA) and ethylenediaminetetraacetic acid (EDTA)) confirmed that bioavailable pools increase substantially under pollution, particularly in Inceptisols, while Vertisols retained metals more effectively due to the presence of smectitic clays. The EDTA consistently extracted higher amounts of metals than DTPA, highlighting its utility in assessing mobilisable metal fractions. Overall, the findings underscore that soil mineralogy and development stage critically regulate chemical behaviour, metal retention and lability, necessitating soil-order-specific strategies for managing heavy metal contamination in industrial regions. Soil-order-specific monitoring should be prioritised, particularly for sensitive Inceptisols. Appropriate remediation strategies, such as the application of organic amendments including farm yard manure (FYM), vermicompost and biochar, can be adopted to reduce metal contamination in soils.

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Authors' contributions

CB contributed to the conceptualisation, data curation, formal analysis, investigation, methodology, visualisation, preparation of the original draft and review and editing of the manuscript. NA was involved in data curation, investigation, methodology, supervision and review and editing of the manuscript. KMM participated in the review and editing of the manuscript. DG carried out data curation and review and editing of the manuscript. BS contributed to the methodology and review and editing of the manuscript. SM was involved in review and editing of the manuscript. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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