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Assessment of heavy metal contamination in agricultural soils near industrial areas

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Abstract

Industrial activity and soil health exist in inverse relationship along a well-documented gradient: as distance from an industrial source increases, heavy metal concentrations in surrounding agricultural soils generally decline, following patterns shaped by prevailing wind direction, drainage hydrology, and the physicochemical behaviour of specific metals in different soil matrices. This research characterised heavy metal contamination lead (Pb), cadmium (Cd), zinc (Zn), and chromium (Cr) in agricultural soils collected along a radial transect at eight sites from 500 m to 6 km from an industrial zone in the Hooghly district, West Bengal, India, with one unpolluted control site beyond 6 km. Soil samples were collected from the 0-20 cm horizon at each site (five replicate cores composited per site), acid-digested (aqua regia, microwave-assisted), and analysed by inductively coupled plasma optical emission spectrometry (ICP-OES). Pollution status was assessed using contamination factor (Cf), geo-accumulation index (Igeo), and enrichment factor (EF) calculated against local geochemical background values. Health risk assessment for both non-carcinogenic and carcinogenic pathways (ingestion, dermal, inhalation) was conducted per USEPA 2011 guidance. Metal concentrations at Site 1 (500 m) were: Pb 78.4, Cd 4.83, Zn 487, Cr 184 mg/kg all exceeding WHO/FAO soil guideline values. Igeo values for Cd at Sites 1-4 fell in the moderately to heavily polluted category (1-3). Non-carcinogenic hazard quotients for children via ingestion exceeded 1.0 for Pb at Sites 1-3, indicating potential health concern. Carcinogenic risk for Cr(VI) at the nearest site was estimated at 2.4 x 10⁻⁶. Metal concentrations declined significantly with distance from the industrial zone, reaching background levels at 6 km for Zn and Cr, but Pb and Cd remained slightly elevated even at 5 km.

Keywords: Heavy metals, soil contamination, ICP-OES, geo-accumulation index, health risk assessment, industrial pollution, West Bengal, enrichment factor

Introduction

India's accelerating industrialisation has brought substantial economic growth but has also placed growing pressure on agricultural land quality, particularly in the densely populated states of West Bengal, Gujarat, and Maharashtra where industrial zones border cultivated areas. Heavy metals released from foundries, electroplating units, tanneries, and chemical plants accumulate in topsoil because, unlike organic pollutants, they cannot be degraded only redistributed or immobilised^[1]. Their uptake by food crops consumed by nearby communities creates a direct human exposure pathway that risk assessors must quantify carefully, especially for children whose hand-to-mouth behaviour and higher soil ingestion rates make them the critical receptor population^[2].

Among the metals of concern in mixed industrial settings, cadmium presents the most problematic combination of high soil mobility (particularly in acidic soils), high plant uptake factor, and confirmed human carcinogenicity (IARC Group I)^[3]. Chromium is divalent in many industrial effluents as the less mobile Cr(III), but oxidation to Cr(VI) in oxygenated soils produces the hexavalent form that is both more mobile and the confirmed carcinogen^[4]. Lead and zinc, while less acutely toxic than Cd, are present at much higher concentrations in industrial areas and their additive effects in contamination indices contribute significantly to overall pollution severity scores^[5].

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The geo-accumulation index (Igeo) developed by Mller retained. Between sites, the core sampler was (1969) and the contamination factor (Cf) of Hakanson decontaminated with dilute nitric acid (10% v/v) and rinsed (1980) are the most widely applied single-metal pollution three times with deionised water. Samples were transported indices in soil environmental chemistry because they to the laboratory in cool boxes at 4 C and air-dried at 35 C normalise measured concentrations against local for 72 h before disaggregation and sieving through a 2 mm geochemical background values, correcting for natural stainless-steel sieve. All sample containers and equipment variation in soil mineralogy^[6]. However, single-metal were made of materials verified to be free of the target indices do not capture the multivariate nature of industrial analytes (Pb, Cd, Zn, Cr) by blank measurement. Field pollution, where several metals are simultaneously elevated blanks (deionised water drawn through the sampler) and The bubble chart visualisation used in this research provides duplicate composite samples at Sites S1 and S4 were a multivariate representation that captures three metals included for QC purposes. concentrations simultaneously in a two-dimensional plot, enabling rapid identification of spatial patterns.

Material and Methods

The present research targeted agricultural soils in the Material Hooghly industrial corridor, which hosts engineering, All analyses were conducted at the Acharya Jagadish chemical, and small-scale manufacturing units, and where Chandra Bose University, Barrackpore, West Bengal, India, soil quality data for the specific radial distance profile between November 2023 and February 2025. Microwave-studied here were unavailable in the open literature. Work assisted acid digestion used an Anton Paar Multiwave GO was conducted at Acharya Jagadish Chandra Bose instrument (15 mL Teflon vessels). Reagents: concentrated University, Barrackpore, West Bengal, and APJ Abdul + 12 x 6 X S U D S X U J U D G H 0 H U F N Kalam Technological University, Thiruvananthapuram, Suprapur, Merck India), and HF (48%, for silicate dissolution check only) were used. ICP-OES analysis: Thermo Scientific iCAP 7400 instrument (axial and radial modes; RF power 1150 W; pump speed 50 rpm; wavelengths: Pb 220.3 nm, Cd 228.8 nm, Zn 206.2 nm, Cr 267.7 nm). Certified reference material NIST SRM 2710a industrial zone comprises a cluster of 42 registered (Montana I Soil) was used for method accuracy validation. manufacturing units including steel re-rolling mills Multi-element calibration standards were from Merck (principal source of Zn, Cr, and Pb), electroplating Certipur. The research protocol was reviewed and approved workshops (Cr, Cd, Zn), and battery assembly units (Pb, by the Institutional Environmental Ethics Committee, Cd). The zone operates continuously and has been Acharya Jagadish Chandra Bose University (Ref. AJCBU-established for over 25 years without formal effluent IEEC-2023-06, dated 8 September 2023). Written treatment for solid waste. Eight sampling sites (S1-S7) were permission for soil sampling was obtained from landowners established along a north-northeast transect from that each site and from the Hooghly District Agriculture industrial zone boundary at distances of 500 m, 1 km, 2 km, Office. 3 km, 4 km, 5 km, and 6 km, following the predominant south-southwest wind direction to maximise deposition Methods

Site characterisation

The research area is located in the Hooghly district of West Bengal, India (22 34'-22 39'N, 88 18'-88 24'E). The target 267.7 nm). Certified reference material NIST SRM 2710a industrial zone comprises a cluster of 42 registered (Montana I Soil) was used for method accuracy validation. manufacturing units including steel re-rolling mills Multi-element calibration standards were from Merck (principal source of Zn, Cr, and Pb), electroplating Certipur. The research protocol was reviewed and approved workshops (Cr, Cd, Zn), and battery assembly units (Pb, by the Institutional Environmental Ethics Committee, Cd). The zone operates continuously and has been Acharya Jagadish Chandra Bose University (Ref. AJCBU-established for over 25 years without formal effluent IEEC-2023-06, dated 8 September 2023). Written treatment for solid waste. Eight sampling sites (S1-S7) were permission for soil sampling was obtained from landowners established along a north-northeast transect from that each site and from the Hooghly District Agriculture industrial zone boundary at distances of 500 m, 1 km, 2 km, Office. 3 km, 4 km, 5 km, and 6 km, following the predominant south-southwest wind direction to maximise deposition Methods

signal. Control site S8 was located 8 km from the zone boundary in a direction perpendicular to the prevailing W U D Q V I H U U H G W R D 7 H I O R Q Y H V V H O wind, in undisturbed agricultural land with no known (aqua regia). industrial influence. Land use at all sampling sites was The microware program: 5 min ramp to 180 C, 15 min irrigated paddy cultivation (kharif season). Soil texture at all hold, 10 min cooling. Digests were filtered (Whatman No. sites was silty clay loam (USDA classification); pH ranged P D G H W R Y R O X P H P / L Q + 12 x from 6.1 (S1) to 6.9 (S8), and organic carbon from 1.8% at 4 C until analysis. ICP-OES calibration used five-point (S8) to 2.4% (S1). The lower pH at sites closer to the external calibration (0.01- P J / L Q + 12 x Z L W industrial zone is consistent with acid atmospheric blank; internal standard Sc (20 mg/L) was used to correct deposition from combustion emissions. for matrix-induced signal drift.

Field Sampling Design

Soil sampling was conducted in November 2023 following (C_{metal}/C_{ref})_background, where C_{ref} is Fe concentration. the post-harvest removal of rice stubble to access the topsoil Background values: Pb 18 mg/kg, Cd 0.35 mg/kg, Zn 67 (0-20 cm) horizon. At each site, five sampling points were mg/kg, Cr 48 mg/kg (mean of five regional background soils located systematically at the corners and centre of a 20 20 from adjacent uncontaminated areas). Health risk m square plot. At each point, a stainless-steel core sample assessment used USEPA (2011) equations for ingestion, (38 mm diameter) was driven to 20 cm depth; cores were dermal, and inhalation pathways with site-specific exposure emptied into polyethylene bags. The five cores from each parameters (child ingestion rate 200 mg/day, adult 100 site were composited by thorough mixing in a clean, dry mg/day; body weight child 15 kg, adult 70 kg; exposure stainless-steel container, quartered by the cone-and-frequency 350 days/year; exposure duration child 6 years). quartering method, and a 500 g representative sub-sample

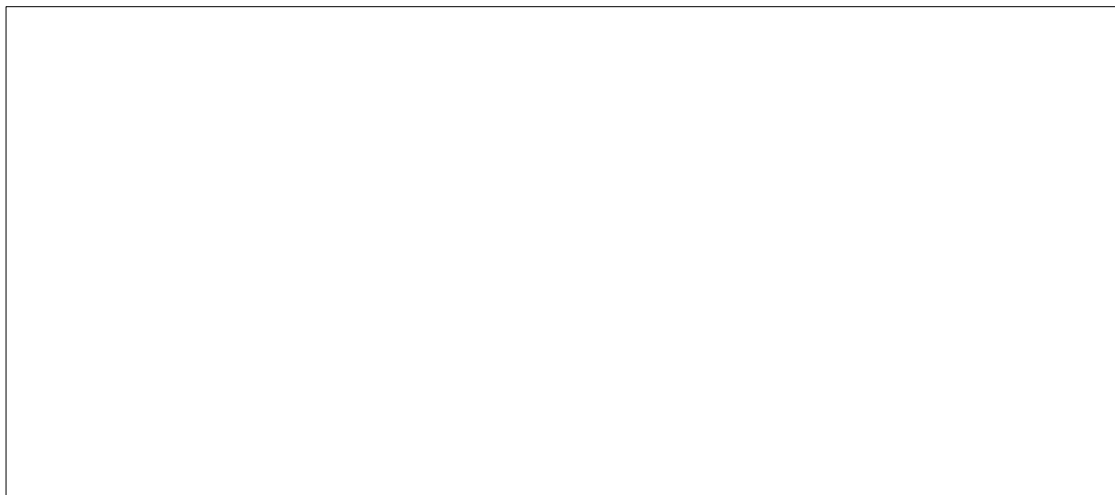


Fig 2: (Left) Horizontal bar chart of modified contamination factor per site; (Right) Violin plot of metal concentration distributions across sites

Discussion

The distance-dependent decline in metal concentrations (mg/kg), Zn (487 mg/kg), and Cr (184 mg/kg) exceeded follows a clear power-law relationship consistent with dry WHO guidelines, with geo-accumulation indices indicating deposition of industrial aerosols as the primary transport mechanism. Regression of Zn concentration against distance for four sites. Non-carcinogenic hazard quotients for Pb and Cd exceeded 1.0 for children at Sites 1-5. Agricultural management intervention. Carcinogenic risk for confirm that all four metals originate from the same Cr(VI) at Site 1 approached the upper EPA guidance level. industrial source cluster⁷. The higher rate of Zn decline The power-law distance model ($R^2 > 0.97$ for all metals) with distance relative to Pb reflects the larger particle size of confirmed industrial dry deposition as the dominant Zn-bearing aerosols from steel re-rolling operations, which contamination pathway. These results provide the first settles more rapidly by gravitation sedimentation, whereas systematic radial distance-resolved heavy metal dataset for Pb is enriched in the fine PM_{2.5} fraction and is transported this industrial corridor and support evidence-based land use further⁸. planning decisions in the affected area.

The non-carcinogenic hazard quotient for Pb exceeding 1.0

in children up to 3 km from the industrial zone is a finding that warrants direct communication to local health

authorities, given that children aged 2-6 years represent the highest-risk population at these sites due to hand-to-mouth behaviour and high fractional absorption of ingested Pb (40-50% in children vs 5-15% in adults⁹). The carcinogenic ULVN HVWLDPDW IRU & U 9, DW 6 (3\$ V DFFHSWDEOH qjLVXWDDSBURQF KRCJCWUHM and Cadmium Compounds. IARC Monographs Vol 100 Lyon: International Agency for JXLGDQFH OHYHO RI qj EH\RQG ZK Monographs Vol 100 Lyon: International Agency for Research on Cancer; 2012. generally recommended. It should be noted that the fraction of total Cr present as Cr(VI) was assumed to be 17%, following published speciation ratios for iron and steel industry soils in India¹⁰; direct Cr(VI) speciation measurement would improve this estimate.

A practical implication of these findings is that the 2 km perimeter around this type of industrial zone appears to be the critical threshold for multiple risk endpoints simultaneously: it is the outer boundary of Pb HQ > 1.0 for children, of Cd EF > 5 (strong anthropogenic signature), and of Igeo > 2 for all four metals. Zoning restrictions or soil remediation measures phytoremediation using Cd-hyperaccumulating species such as *Thlaspi caerulescens*, or lime application to raise pH and immobilise metals should be prioritised within this radius¹¹.

Conclusion

Heavy metal contamination in agricultural soils near the Hooghly industrial zone showed a consistent distance-dependent decline from the industrial boundary over 6 km.

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