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Investigating Heavy Metal Accumulation in Agricultural Soils and its Correlation with Crop Yield Reduction

Lakshmi Iyer Tamilan

School of Biotechnology, SIMTS University, Chennai, India

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ABSTRACT

Heavy metal contamination of agricultural soils poses a critical global food security and public health challenge. This study investigates the accumulation of heavy metals—specifically lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), and mercury (Hg)—in farm soils across three agroecological regions and examines their correlation with crop yield reductions in staple cereals (rice, wheat, maize). Soil samples (n=120) and corresponding crop tissues were analyzed using inductively coupled plasma mass spectrometry (ICP-MS) to quantify metal concentrations. Soil physico-chemical properties (pH, organic matter, cation-exchange capacity) were measured to assess metal mobility. Crop yield data (over two growing seasons) were compared against contamination levels. Statistical analyses included Pearson correlation, principal component analysis (PCA), and multiple regression to elucidate relationships between heavy metal indices and yield outcomes. Results show that 38% of soil samples exceeded WHO/FAO permissible limits for Cd and Pb. Tissue accumulation mirrored soil trends, notably higher Cd in roots and shoots. A significant negative correlation ($r = -0.67$, $p < 0.01$) between total soil Cd concentration and grain yield was observed, with regression models predicting a 12% yield loss per mg/kg Cd increase. PCA highlighted that metal accumulation contributed 45% variance in yield reduction. Findings emphasize that soil heavy metal buildup exerts a quantifiable impact on crop productivity, mediated by soil chemistry and plant uptake dynamics. The study underscores the urgent need for soil remediation, crop rotation strategies, and heavy metal monitoring frameworks in contaminated regions. It provides a robust analytical framework to inform policymaking and sustainable agricultural practices.

INTRODUCTION

Heavy metal pollution of agricultural soils, driven by industrial emissions, wastewater irrigation, agrochemical use, and mining activities, has emerged as a major environmental concern worldwide. Metals like lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), and mercury (Hg) persist in the environment, accumulate in soils, and bioaccumulate in crop plants. These metals can inhibit plant growth, reduce crop yields, and compromise food safety due to human exposure through dietary routes.

Cadmium is particularly problematic; it exhibits high mobility in acidic soils and is readily taken up by crops, where it can reduce germination rates, impair photosynthesis, and disrupt nutrient uptake. Lead, while

less mobile, can accumulate in root tissues and reduce biomass production. Chromium and nickel toxicity similarly impair root development and chlorophyll synthesis. Mercury, though less frequently encountered, presents acute toxicity even at low concentrations.

South Asian agricultural regions, such as those in riverine floodplains, face elevated metal contamination due to upstream industrial discharges and frequent use of phosphate-based fertilizers containing impurity elements. Earlier studies have documented metal hotspots and their impact on cereal yield, yet gaps remain regarding soil-plant transfer mechanisms, yield response functions, and region-specific thresholds.

*Corresponding Author: Lakshmi Iyer Tamilan

Address: School of Biotechnology, SIMTS University, Chennai, India

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This study investigates heavy metal accumulation in agricultural soils across three climatically distinct zones: alluvial plains, plateau-irrigated farmland, and coastal delta systems. With paired soil and plant sampling and time-series yield data, our goals are: (1) quantify soil and plant heavy metal concentrations, (2) assess soil factors influencing metal bioavailability, and (3) model metal–yield relationships to determine critical soil contamination thresholds. By integrating analytical chemistry, soil science, and agronomic modeling, we seek to provide actionable insights for land managers, agronomists, and policymakers to safeguard productivity and public health.

LITERATURE REVIEW

Heavy metal contamination in agroecosystems has been extensively researched. Kabata-Pendias (2011) established foundational guidelines on metal uptake mechanisms, emphasizing the influence of soil pH, organic matter, and cation exchange capacity (CEC) on heavy metal bioavailability. Liu et al. (2019) conducted a meta-analysis across Asia, finding that Cd and Pb ranked highest in terms of yield reduction per contamination unit in rice, maize, and wheat. Soil pH emerged as a key moderator of metal mobility, with acidic soils showing up to 60% higher Cd uptake.

Research by Gupta and Singh (2020) in the Indo-Gangetic Plains used ICP-MS to map soil metal hotspots, revealing moderate Cd (0.4–2.1 mg/kg) and Pb (50–160 mg/kg) levels. Regression modeling linked Cd above 1.5 mg/kg with a 15% drop in rice yield. A review by Sharma et al. (2021) indicated that crop-specific metal uptake factors (transfer factors) vary widely—Cd transfer can exceed unity for leafy vegetables, while cereals typically show 0.2–0.5 soil-to-grain ratios.

Experiments by Wang et al. (2022) demonstrated that biochar amendments reduced Cd and Pb uptake by 30–40%, while lime application raised soil pH and curtailed metal mobility. However, cross-study comparisons are impeded by differences in soil texture, agronomic practices, and metal speciation methods.

More recent field studies (e.g., RodríguezEstepar et al., 2023) applied PCA to isolate heavy metal influence from abiotic stress factors like salinity and drought. They quantified yield loss due to metal accumulation as separate from water-stress effects. Nevertheless, regionally-specific yield response functions remain limited, and multi-season paired soil, tissue, and yield datasets are rare.

This study extends the literature by systematically quantifying Cd, Pb, Cr, Ni, and Hg accumulation in soils along yield response curves, accounting for soil chemistry and crop phenology. By combining analytical rigor with field yield data, we aim to fill a crucial knowledge gap in threshold identification and remediation prioritization.

RESEARCH METHODOLOGY

This study follows a mixed-methods quantitative approach across three agroecological zones (alluvial plains, plateaus, coastal deltas)

Sample Design

In each region, 40 paired sampling plots (total 120) were selected, representing gradients of land use intensity. In each growing season, composite soil samples (0–20 cm) and corresponding crop grain and shoot samples were collected. Crop yields were recorded across two consecutive seasons under standard agronomic practices.

Soil and Plant Analysis

Soil physical-chemical parameters (texture, pH, organic matter, CEC) were determined per standard protocols. Heavy metals (Cd, Pb, Cr, Ni, Hg) in soil and plant tissues were quantified using ICPMS following acid digestion (USEPA 3050B). Quality control employed certified reference materials, achieving recovery rates of 95–105% and detection limits below 0.005 mg/kg for Cd and Hg.

Data Processing

Soil Metal Accumulation Index (MAI) was calculated for each site. Transfer Factor (TF = metal_concentration_crop / metal_concentration_soil) was computed for leaves and grains. Crop Yield Reduction Index was defined as the yield deviation from regional average control plots.

Statistical Analysis

Pearson correlations assessed relationships between soil metal levels, TF, and yield reduction. Multiple linear regression modeled yield as a function of soil metals and soil properties. PCA reduced dimensionality to isolate contamination-driven yield decline. Significance threshold was set at $p < 0.05$, with Bonferroni corrections for multiple testing.

Validation

Model accuracy was tested through 10-fold cross-validation and regional holdout sets (one region excluded per iteration). Diagnostic analysis verified assumptions of normality, homoscedasticity, and multicollinearity (VIF < 5).

KEY FINDINGS

Heavy Metal Soil Levels:

- 38% of sites exceeded FAO limits for Cd (>0.8 mg/kg); 25% for Pb (>50 mg/kg).
- Average soil ranges: Cd 0.2–3.4 mg/kg; Pb 15–180 mg/kg; Cr 25–110 mg/kg; Ni 10–85 mg/kg; Hg 0.02–0.15 mg/kg.

Plant Uptake and Transfer Factors:

- Cd TF varied 0.35–0.7 (grain) and 0.6–1.1 (shoots). High Cd TF corresponded to low sandy soils (pH < 6).

- Pb TF in grain remained <0.1; in roots 0.2–0.4, indicating limited grain translocation.

Yield Correlations and Regression Outcomes

- Soil Cd had strongest negative correlation with yield ($r = -0.67$, $p < 0.001$); Pb followed ($r = -0.48$).
- Regression predicts a 12% yield loss per 1 mg/kg Cd increase, and 5% per 10 mg/kg Pb.
- Soil pH counteracted Cd impacts; higher organic matter mitigated yield losses by ~20%.

PCA Insights

- Principal Component 1 (accounting for 45% variance) loaded heavily on Cd and Pb and aligned with yield loss.
- Components 2 and 3 captured Ni, Cr, Hg loadings and soil texture.

Model Validation

- Cross-validation achieved $R^2 = 0.72 \pm 0.04$, RMSE = 0.15 ton/ha.
- Regional hold-out model retained $R^2 = 0.68$, indicating generalizability.

These findings confirm that Cd and Pb soil contamination pose significant threats to cereal productivity, moderated by soil chemistry. The dataset supports targeted remediation thresholds (e.g., Cd < 1.0 mg/kg to avoid >10% yield loss).

WORK FLOW

Site Selection & Sampling Strategy

Employ GIS to map agroecological zones and overlay industrial/agricultural intensity. Randomly stratify 40 plots per region, ensuring representation of high, medium, and low contamination risk.

Field Sampling & Crop Yield Assessment

Collect composite soil samples (5 cores per plot) before planting and after harvest; harvest crops at physiological

maturity, measuring grain weight and yield per hectare under uniform practice.

Laboratory Analysis

Analyze soil for texture (hydrometer), pH (potentiometric), organic matter (Walkley–Black), and CEC (ammonium acetate). Digest soil and plant tissues ($\text{HNO}_3\text{-HClO}_4$) and quantify heavy metals via ICPMS.

Data Integration & Indexing

Merge lab results with yield data. Calculate Soil Metal Accumulation Index, Transfer Factor for each crop part, and Yield Reduction Index. Geocode results for spatial mapping.

Statistical Modeling & PCA

Compute Pearson correlation matrix. Build multiple regression models predicting yield reduction from metal levels and soil modifiers. Run PCA to identify underlying factor structure and dominant contamination variables.

Validation & Reporting

Validate models via cross-validation and regional hold-out. Generate contour maps of heavy metal hotspots and yield-risk zones. Identify contamination thresholds for agronomic decision-making. Compile results and disseminate to stakeholders and policymakers.

CONCLUSION

The study conclusively demonstrates that soil Cd and Pb accumulation significantly impairs cereal crop yields. There is a strong dose-response relationship: as soil Cd rises, yield decreases proportionally. Soil factors like pH and organic matter provide partial mitigation. These results point to the necessity of contamination-based agronomic advisories and prioritization of remediation interventions.

FUTURE WORK

- **Longitudinal Monitoring:** Extend study across 5–10 years to track contamination trends and yield trajectories.
- **Remediation Trials:** Implement and monitor interventions such as biochar, lime, and phytoremediation species.
- **Crop Diversification Studies:** Investigate alternative crops or cultivars with lower metal uptake.
- **Food Safety Analysis:** Analyze heavy metal residues in edible grain to assess consumer health risks and regulatory compliance.
- **Risk Modelling:** Develop toolkits and maps for farmers and land managers to predict yield losses under varying contamination levels.



Fig 1

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