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Speciation and Mobility Assessment of Heavy Metals in the Edaphic Environment Surrounding a Non-Ferrous Metal Smelting Area

Dr. Smt.Kalpana M Painagoni

Associate professor, Department of physics, Government First Grade college Paschapur-591122

Abstract- Non-ferrous metal smelting activities are among the most significant anthropogenic sources of heavy metal contamination in soils. The edaphic environment surrounding smelting industries often accumulates elevated concentrations of toxic metals such as cadmium (Cd), lead (Pb), zinc (Zn), arsenic (As), copper (Cu), mercury (Hg), and nickel (Ni). These contaminants undergo complex geochemical transformations that determine their speciation, mobility, bioavailability, and ecological risk. This research paper examines the mechanisms controlling heavy metal speciation and mobility in soils adjacent to non-ferrous metal smelting areas, with emphasis on geochemical fractionation, transport pathways, influencing environmental factors, ecological implications, and remediation strategies. Sequential extraction procedures, geochemical modeling, and risk assessment approaches are critically discussed. The study highlights that metal mobility is strongly controlled by soil pH, organic matter, clay minerals, redox conditions, and mineralogical composition. Exchangeable and carbonate-bound fractions exhibit higher mobility and bioavailability, especially for Cd and Zn, whereas Pb and As are generally associated with reducible and residual fractions. The paper concludes that integrated assessment approaches combining chemical speciation, spatial analysis, and ecological risk indices are essential for sustainable management of smelter-contaminated soils.

Keywords: Anthropogenic contamination; Arsenic (As); Bioavailability; Cadmium (Cd); Copper (Cu); Ecological risk assessment; Edaphic environment; Environmental pollution; Geochemical fractionation; Geochemical modeling; Heavy metal contamination; Heavy metal speciation; Lead (Pb); Mercury (Hg); Metal mobility; Nickel (Ni); Non-ferrous metal smelting; Sequential extraction; Smelter-contaminated soils; Soil geochemistry; Soil pollution; Soil remediation; Toxic metals; Zinc (Zn)..

I. INTRODUCTION

Industrialization and urbanization have significantly increased environmental contamination by heavy metals. Among industrial activities, non-ferrous metal smelting represents a major source of soil pollution due to atmospheric emissions, slag disposal, wastewater discharge, and fugitive dust deposition. Smelting operations release substantial quantities of potentially toxic elements into surrounding ecosystems, where soils act as long-term sinks for contaminants.

Heavy metals are persistent pollutants that do not degrade biologically and may remain in soils for centuries. Their environmental behavior depends not only on total concentration but also on chemical speciation and mobility. Speciation refers to the distribution of metals among different physicochemical forms, while mobility describes their ability to migrate through soil and groundwater systems.

The edaphic environment around non-ferrous smelting sites is particularly vulnerable because heavy metals can accumulate in agricultural soils, enter food chains, contaminate groundwater, and pose severe ecological and human health risks. Understanding the mechanisms controlling heavy metal speciation and mobility is therefore essential for risk assessment and remediation planning.

Studies around zinc, copper, and lead smelters have demonstrated severe contamination of soils with Cd, Pb, Zn, Cu, and As, often extending several kilometers from emission sources. Sequential extraction studies indicate that cadmium frequently occurs in exchangeable forms, making it highly mobile and bioavailable.

II. HEAVY METALS ASSOCIATED WITH NON-FERROUS SMELTING

2.1 Major Contaminants

Table 1. Non-ferrous smelting industries commonly release:

| Metal | Primary Source | Toxicological Significance |
|--------------|----------------------------------|----------------------------------|
| Cadmium (Cd) | Zinc and lead smelting | Kidney toxicity, carcinogenicity |
| Lead (Pb) | Lead smelting, battery recycling | Neurotoxicity |
| Zinc (Zn) | Zinc refining | Phytotoxicity |
| Arsenic (As) | Copper and lead ores | Carcinogenicity |
| Copper (Cu) | Copper smelting | Soil microbial toxicity |
| Mercury (Hg) | Ore processing | Neurotoxicity |
| Nickel (Ni) | Alloy production | Respiratory toxicity |

2.2 Sources of Soil Contamination

Heavy metals enter soils around smelters through several pathways, including atmospheric deposition of particulates, smelter slag disposal, wastewater irrigation, leachate migration, fugitive dust transport, and surface runoff with erosion. Among these, smelter-derived airborne particles are considered one of the major sources of contamination. Studies conducted near zinc smelters have shown that fugitive dust plays a significant role in increasing the mobility and bioavailability of cadmium (Cd), zinc (Zn), and lead (Pb) in nearby agricultural soils.

III. CONCEPT OF HEAVY METAL SPECIATION

Heavy metal speciation determines environmental behavior, mobility, toxicity, and bioavailability.

3.1 Operationally Defined Fractions

Table 2. The BCR and Tessier sequential extraction procedures commonly classify metals into the following fractions:

| Fraction | Characteristics | Mobility |
|-----------------------|----------------------------|-----------|
| Exchangeable | Weakly adsorbed ions | Very high |
| Carbonate-bound | Associated with carbonates | High |
| Fe-Mn oxide-bound | Reducible fraction | Moderate |
| Organic/sulfide-bound | Oxidizable fraction | Low |

| Fraction | Characteristics | Mobility |
|----------|-----------------|----------|
| Residual | Mineral lattice | Very low |

3.2 Sequential Extraction Techniques

The BCR sequential extraction method is extensively used for evaluating metal partitioning in smelter-contaminated soils. Recent studies involving lead and zinc smelting sites employed BCR extraction to assess chemical lability and mobility factors. ([Springer Link](#))

IV. MECHANISMS OF HEAVY METAL MOBILITY

4.1 Soil pH

Soil pH is the most influential factor controlling heavy metal mobility.

*Acidic conditions increase metal solubility.

*Neutral to alkaline conditions favor precipitation and adsorption.

For example: $pH = -\log[H^+]$

Acidic conditions significantly enhance Cd, Zn, and Mn release from contaminated soils. ([ScienceDirect](#))

4.2 Organic Matter

Soil organic matter influences the mobility of heavy metals through processes such as complexation, chelation, adsorption, and redox reactions. Humic substances present in soil can immobilize metals like lead (Pb) and copper (Cu) by binding them strongly to soil particles, while under certain environmental conditions they may also increase the formation of dissolved organic-metal complexes, thereby enhancing metal mobility and transport.

4.3 Clay Minerals

Clay minerals play an important role in reducing heavy metal migration by providing adsorption sites that retain contaminants within the soil matrix. Common clay minerals such as kaolinite, montmorillonite, and illite possess high surface reactivity and adsorption capacity, which help limit the mobility of toxic metals. As a result, clay-rich soils generally exhibit lower heavy metal movement and greater contaminant retention. Studies conducted around non-ferrous smelting zones have identified soil clay content as a major factor controlling the migration and distribution of toxic elements

4.4 Redox Conditions

Oxidation-reduction (redox) potential plays a critical role in controlling the transformation and stability of metal-bearing minerals in soils. Under reducing conditions, iron and manganese oxides tend to dissolve, releasing previously adsorbed metals into the soil pore

water, whereas oxidizing environments can destabilize sulfide minerals and promote the mobilization of contaminants. These redox-driven processes significantly influence the release, mobility, and bioavailability of heavy metals such as lead (Pb), zinc (Zn), and arsenic (As) in contaminated soils.

4.5 Mineralogical Associations

Heavy metals in contaminated soils commonly occur within minerals such as galena (PbS), sphalerite (ZnS), hematite, and franklinite, which act as important reservoirs of toxic elements. The weathering, dissolution, and transformation of these minerals over time strongly control the long-term mobility, persistence, and environmental behavior of contaminants in soil systems.

V. SPATIAL DISTRIBUTION AND VERTICAL MIGRATION

5.1 Spatial Distribution

The spatial and vertical distribution of heavy metals in soils surrounding smelters is strongly influenced by both environmental and hydrological factors. Metal concentrations generally decrease with increasing distance from smelting facilities, with distribution patterns controlled by wind direction, topography, land use, and the intensity of atmospheric deposition. Studies conducted in China and Brazil have reported particularly severe contamination in downwind areas near smelters due to airborne particulate transport. In addition to horizontal dispersion, heavy metals also migrate vertically through processes such as infiltration, leaching, colloidal transport, and preferential flow within the soil profile. Among commonly observed contaminants, cadmium (Cd) typically exhibits the highest migration potential because of its greater mobility and solubility, followed by zinc (Zn), lead (Pb), and arsenic (As), with the general migration order reported as $Cd > Zn > Pb > As$.

VI. BIOAVAILABILITY AND ECOLOGICAL RISK

6.1 The bioavailability of heavy metals in contaminated soils is governed by factors such as metal speciation, soil chemistry, plant uptake capacity, and rhizosphere interactions, all of which influence the extent to which metals can be absorbed by organisms. In general, exchangeable and carbonate-bound metal fractions are considered more bioavailable because they are more easily released into soil solution. To evaluate the potential environmental impact of such contamination, the ecological risk index (ERI) is widely used, where the ecological risk factor is determined by the toxic response

factor and the ratio of measured metal concentration to its background concentration. $E_{ri} = \frac{C_i}{C_n} \times T_{r_i}$ Among heavy metals, cadmium (Cd) often poses the greatest ecological risk due to its high toxicity, mobility, and bioavailability in soil environments. Furthermore, understanding the mechanisms controlling heavy metal bioavailability and ecological risk is essential for developing effective soil remediation strategies and mitigating long-term environmental and human health impacts in smelter-contaminated regions.

VII. HUMAN HEALTH IMPLICATIONS

Heavy metals present in contaminated soils can enter the human body through several exposure pathways, including ingestion of contaminated food, inhalation of contaminated dust particles, dermal contact with polluted soil, and consumption of contaminated groundwater. Prolonged exposure to toxic metals such as lead (Pb) and cadmium (Cd) can result in serious health effects, including neurological disorders, kidney damage, developmental abnormalities, carcinogenic effects, and cardiovascular diseases. Among exposed populations, children are considered particularly vulnerable because of their higher sensitivity to the toxic effects of Pb and Cd and their greater likelihood of exposure through hand-to-mouth activities and dust inhalation.

VIII. ANALYTICAL TECHNIQUES FOR SPECIATION ASSESSMENT

The investigation of heavy metal contamination in soils commonly relies on advanced instrumental and geochemical techniques for accurate characterization and risk assessment. Widely used analytical methods include inductively coupled plasma mass spectrometry (ICP-MS) for trace metal quantification, atomic absorption spectroscopy (AAS) for metal concentration analysis, X-ray fluorescence (XRF) for elemental mapping, scanning electron microscopy with energy-dispersive spectroscopy (SEM-EDS) for mineral characterization, and X-ray diffraction (XRD) for mineralogical identification. Recent studies have integrated XRF, SEM-EDS, and sequential extraction techniques to better understand trace metal partitioning and distribution in contaminated soils. In addition, geochemical modeling tools such as PHREEQC, Visual MINTEQ, and WHAM are extensively applied to predict metal speciation, solubility, sorption processes, and transport behavior in soil and groundwater systems. More recently, Monte Carlo simulation approaches have

also been employed to assess and predict groundwater contamination risks in areas surrounding smelter sites.

IX. REMEDIATION STRATEGIES

Physical remediation methods are commonly employed to manage heavily contaminated soils near smelter sites and include techniques such as excavation, soil replacement, and capping. Excavation involves the removal of contaminated soil for safe disposal or treatment, while soil replacement substitutes polluted material with clean soil. Capping isolates contaminated zones using protective layers that minimize human exposure, dust generation, and water infiltration, thereby reducing contaminant migration.

Chemical stabilization is widely used to decrease the mobility and bioavailability of heavy metals in soils through the addition of stabilizing amendments such as lime, phosphate, biochar, and clay minerals. These materials promote adsorption, precipitation, and complexation reactions that transform metals into more stable and less bioavailable forms, thereby reducing their environmental and health risks.

Phytoremediation utilizes plants capable of absorbing and accumulating heavy metals from contaminated soils. Hyperaccumulator species such as *Brassica juncea* are effective for removing lead (Pb) and cadmium (Cd), while *Sedum alfredii* is commonly used for zinc (Zn) and cadmium uptake. Vetiver grass has also demonstrated the ability to tolerate and remediate multiple heavy metals, making it suitable for contaminated industrial areas.

Bioremediation involves the use of microorganisms to reduce heavy metal contamination through processes such as biosorption, bioaccumulation, and biotransformation. Microbial activity can immobilize metals, alter their chemical forms, and enhance contaminant degradation or stabilization, offering an environmentally sustainable approach for the remediation of polluted soils.

X. TOP OF FORM

CURRENT CHALLENGES AND FUTURE DIRECTIONS

Major challenges in the management of heavy metal-contaminated soils arise from the inherent heterogeneity of polluted sites, where contaminant distribution varies widely in concentration and form across small spatial scales. This variability complicates accurate assessment and remediation planning, often requiring repeated sampling efforts. Another major challenge is the need for long-term monitoring to assess the effectiveness and stability of remediation strategies, as heavy metals

persist in soils and may remobilize into food and water chains over time. The presence of mixed-metal contamination further complicates remediation because different metals interact within soil systems and exhibit varying mobility, toxicity, and treatment responses, reducing the effectiveness of single-method approaches. Climate change also influences heavy metal mobility by altering soil moisture, temperature, and redox conditions, thereby affecting contaminant redistribution. In addition, the lack of reliable site-specific risk assessment models limits accurate prediction of environmental and health risks. Future research is expected to focus on advanced methods such as nano-scale speciation analysis, synchrotron-based characterization, machine learning prediction models, hydrogeochemical simulations, and sustainable remediation technologies to improve the management of contaminated soils.

XI. CONCLUSION

Heavy metal contamination in soils surrounding non-ferrous metal smelting areas represents a significant environmental challenge. The environmental risk associated with these contaminants depends not only on total concentrations but also on chemical speciation and mobility. Sequential extraction studies consistently demonstrate that cadmium exhibits the highest mobility and bioavailability, whereas lead is generally retained within stable mineral phases. Environmental factors such as soil pH, organic matter, clay content, redox conditions, and mineralogical composition critically influence heavy metal behavior. Advanced analytical methods and geochemical modeling approaches are increasingly improving understanding of contaminant transport mechanisms and ecological risks. Integrated assessment frameworks combining chemical speciation, spatial analysis, ecological risk evaluation, and remediation planning are essential for effective management of smelter-contaminated edaphic environments..

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