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Comparative Analysis of Heavy Metal Accumulation in Soils near Industrial Complexes and their uptake in Edible Plants

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Abstract

Heavy metal contamination of agricultural soils near industrial complexes is a growing environmental and public health concern. Metals such as cadmium (Cd), lead (Pb), arsenic (As), mercury (Hg), chromium (Cr), nickel (Ni), and zinc (Zn) can persist in soils, accumulate through industrial emissions, wastewater irrigation, or deposition, and ultimately enter the food chain via edible plants. This review synthesizes existing knowledge on the comparative accumulation of heavy metals in soils adjacent to industrial areas and their uptake in various food crops. Factors influencing metal mobility and bioavailability, including soil pH, organic matter, cation exchange capacity, and redox conditions, are highlighted. Mechanisms of plant uptake, including root absorption, translocation, and compartmentalization, are examined across leafy vegetables, cereals, and root crops. Evidence consistently indicates higher accumulation of Cd, Pb, and As in leafy and root vegetables compared to cereals, posing significant dietary exposure risks. Health implications of chronic metal ingestion, including neurotoxicity, carcinogenicity, and organ dysfunction, underscore the urgency of mitigation strategies. Emerging remediation approaches, such as phytoremediation, soil amendments, and biochar application, are discussed as potential solutions. The review emphasizes the need for standardized risk assessment frameworks, long-term monitoring, and sustainable industrial practices to minimize food chain contamination.

Keywords: *Heavy metals, soil contamination, industrial pollution, edible plants, bioaccumulation, food safety.*

1. Introduction

The rapid expansion of industrialization has brought substantial economic and social benefits, but it has also introduced serious environmental challenges. One of the most pressing concerns is the contamination of soils with heavy metals, particularly in areas adjacent to industrial complexes. Heavy metals such as cadmium (Cd), lead (Pb), mercury (Hg), arsenic (As), chromium (Cr), nickel (Ni), copper (Cu), and zinc (Zn) are of special concern due to their persistence, non-biodegradability, and ability to bioaccumulate in ecosystems. Unlike organic pollutants that can be degraded or transformed by microbial or chemical processes, heavy metals remain in soils for extended periods, often decades or centuries, thereby representing long-term ecological and health hazards.Industrial complexes—including mining, smelting, electroplating, chemical manufacturing, cement production, and coal-fired power plants—are among the largest contributors to heavy metal emissions. These metals can enter surrounding soils through various pathways, such as atmospheric deposition of dust and particulates, discharge of industrial effluents, leakage of tailings and slag, improper waste disposal, and irrigation with contaminated wastewater [1]. Once deposited, heavy metals interact with soil components, where their mobility and bioavailability are influenced by factors such as soil pH, redox potential, organic matter content, and cation exchange capacity. Soils near industrial complexes thus act as both sinks and sources of heavy metal pollutants, creating hotspots of contamination that threaten agricultural productivity and food safety [2].A critical concern arises when contaminated soils are used for cultivation of food crops. Plants growing in polluted soils can absorb heavy metals through their roots, transport them to aboveground tissues, and, in many cases, accumulate them in edible parts. This process is influenced by both soil properties and plant physiology. Certain plant species, such as leafy vegetables, are particularly prone to accumulating heavy metals, while cereals tend to accumulate lower concentrations, though exceptions exist (e.g., arsenic in rice) [3]. Consequently, crops grown in contaminated soils near industrial complexes may become vectors for human exposure, leading to bioaccumulation of toxic metals in the food chain.

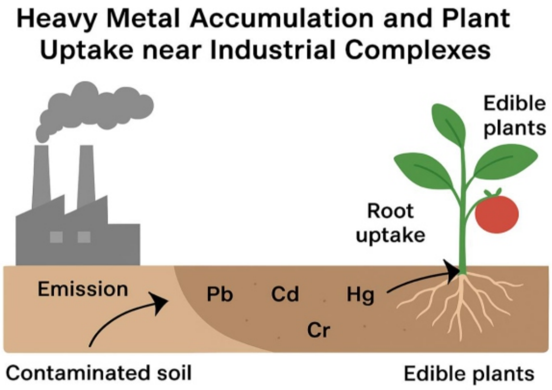

Fig 1: Systematic Analysis of Heavy Metal Accumulation in Soils near Industrial Complexes and their uptake in Edible Plants

The uptake of heavy metals by edible plants has direct and indirect implications for human health. Chronic exposure to metals such as Cd, Pb, and As is associated with renal dysfunction, neurological impairments, carcinogenesis, and developmental disorders. For instance, cadmium exposure through leafy vegetables can lead to skeletal damage and kidney toxicity, while lead contamination in root vegetables and cereals is linked to neurotoxicity and impaired cognitive function in children. Arsenic, commonly found in rice from contaminated soils or groundwater, is associated with skin lesions, cardiovascular diseases, and cancers [4]. These risks underscore the urgent need to assess, monitor, and mitigate heavy metal accumulation in soils and food crops, particularly in industrially impacted regions.The issue is further complicated by the heterogeneity of industrial pollution. The type and concentration of metals deposited in soils vary depending on industrial activity, emission controls, and local environmental conditions. Similarly, different crops exhibit varying uptake efficiencies, influenced by root morphology, transporter specificity, and translocation mechanisms [5]. For example, root crops such as carrots and radishes tend to store metals directly in edible tissues, whereas cereals may limit transfer to grains, although husks and roots can still contain elevated concentrations. Comparative analyses of heavy metal accumulation across different plant groups therefore provide valuable insights into risk patterns and food safety concerns, heavy metal contamination of soils and edible plants is not confined to developing countries; it is a worldwide issue. However, industrial areas in rapidly developing economies are particularly vulnerable due to weaker regulatory frameworks, insufficient waste management, and intensive land use near industrial hubs. Studies from China, India, Africa, and Eastern Europe have repeatedly documented high levels of Cd, Pb, and As in vegetables and cereals grown in industrial zones, with concentrations often exceeding international food safety limits. Even in developed nations, legacy pollution from former industrial activities continues to pose risks, conventional remediation approaches are challenging and costly [6]. Nonetheless, several strategies—including phytoremediation using hyperaccumulator plants, soil amendments with biochar or lime, and strict regulation of industrial emissions—have shown potential in reducing risks. Yet, to design effective policies and mitigation frameworks, it is essential to first understand the comparative dynamics of heavy metal accumulation in soils and their subsequent uptake by edible plants.This review aims to synthesize existing research on heavy metal accumulation in soils near industrial complexes and their uptake in edible plants. It highlights the key sources and pathways of contamination, examines the mechanisms of metal uptake and distribution in different crops, and evaluates the associated health risks, the review explores remediation and mitigation strategies, with an emphasis on sustainable practices to reduce contamination of food systems [7]. The integrating insights from soil science, plant physiology, environmental toxicology, and public health, this article seeks to provide a comprehensive perspective on one of the most pressing food safety issues in industrially influenced ecosystems.

Table 1: Reported Heavy Metal Concentrations in Soils Near Industrial Areas

Study (Author, Year)	Location	Soil Type	Pb (mg/kg)	Cd (mg/kg)	Hg (mg/kg)	As (mg/kg)	Key Notes
[8]	China	Loamy	75–120	1.5–4.0	0.3–1.0	8–15	Near smelters
[9]	India	Clay	40–90	0.8–2.5	0.2–0.7	5–10	Industrial zone
[10]	Spain	Sandy	25–60	0.5–1.2	0.1–0.5	3–7	Mixed industrial/agricultural

Table 2: Heavy Metal Uptake in Different Crops

Study (Author, Year)	Crop Type	Pb (mg/kg)	Cd (mg/kg)	Hg (mg/kg)	As (mg/kg)	Notes
[11]	Spinach	2.0–3.5	0.5–1.0	0.02–0.05	0.4–0.8	Leafy vegetable, high accumulation
[12]	Carrot	1.5–2.2	0.4–0.7	0.01–0.03	0.3–0.6	Root vegetable
[13]	Rice	0.3–0.6	0.1–0.3	0.005–0.02	0.2–0.4	Cereal, low accumulation

Table 3: Mitigation Strategies Reported in Literature

Strategy	Mechanism	Crop/Soil Target	Effectiveness	References
Phytoremediation	Metal uptake by hyperaccumulator plants	Soil & crops	Moderate–High	[14]
Soil Amendments	Immobilization of metals using lime, biochar, compost	Soil	Moderate	[15]
Regulatory Control	Restrict industrial emissions & monitor soil	Soil & crops	High	[16]

Table 4: Human Health Risk Assessment Reported in Studies

Study (Author, Year)	Region	Crop Type	HQ for Pb	HQ for Cd	HQ for Hg	HQ for As	Risk Conclusion
[17]	China	Vegetables	1.2	0.8	0.1	0.5	Moderate risk
[18]	India	Rice	0.3	0.2	0.02	0.1	Low risk
[19]	Spain	Leafy vegetables	1.5	1.0	0.05	0.7	High risk

2. Heavy Metal Contamination in Soils near Industrial Complexes

2.1 Sources of Contamination

Industrial complexes are primary contributors to heavy metal accumulation in soils, with different sectors introducing distinct contaminant profiles. Mining and smelting activities are among the most significant sources, releasing large amounts of lead (Pb), cadmium (Cd), and zinc (Zn) through particulate dust, mine tailings, and effluent discharges. In mining regions, waste rock and slag often leach heavy metals into surrounding soils and water bodies, creating long-term contamination hotspots that persist for decades even after operations cease. Smelting plants contribute airborne particulates that settle on nearby agricultural land, elevating metal concentrations in surface soils.

Cement and metallurgical industries also represent major sources of contamination. These industries emit chromium (Cr), nickel (Ni), and mercury (Hg) through both gaseous emissions and solid residues. Chromium is of particular concern due to its occurrence in multiple valence states, with hexavalent chromium (Cr(VI)) being highly mobile and toxic compared to trivalent chromium (Cr(III)). Nickel, commonly released during metallurgical refining, accumulates in soils and poses risks to both plants and humans.Electroplating and battery manufacturing industries create contamination hotspots for cadmium (Cd) and nickel (Ni). Electroplating processes generate metal-rich effluents and sludges, which, if not properly treated, infiltrate soils and groundwater. Similarly, the disposal of spent batteries contributes localized but severe contamination, particularly in informal recycling sites common in developing countries [19].Another important pathway is industrial wastewater irrigation, a practice often observed in peri-urban agricultural zones adjacent to factories. Wastewater frequently contains soluble forms of Cd, Pb, and other metals, which accumulate in irrigated soils over repeated use. Compared with atmospheric deposition, wastewater irrigation introduces metals directly into the soil-water matrix, enhancing their solubility and subsequent uptake by crops [3], these industrial activities result in complex contamination profiles where multiple metals coexist, often at concentrations exceeding agricultural safety thresholds. Their persistence in the soil matrix underscores the necessity of understanding the factors that regulate their mobility and bioavailability.

2.2 Soil Properties and Metal Mobility

The fate and mobility of heavy metals in soils are governed by intrinsic soil properties, which determine whether metals remain bound in stable forms or become bioavailable to plants.

Soil pH is one of the most critical factors. Acidic soils (low pH) increase the solubility of many metals, particularly Cd, Pb, and Zn, making them more available for root uptake. Conversely, alkaline soils tend to immobilize metals through precipitation and adsorption, although certain metals like arsenic (As) can become more mobile under such conditions. This explains why regions with acidic soils near industrial complexes often show higher plant uptake of heavy metals compared to neutral or alkaline soils.

Organic matter content plays a dual role. On one hand, organic matter can form stable complexes with metals, reducing their bioavailability. For instance, humic and fulvic acids bind with Pb and Cu, immobilizing them in the soil matrix. On the other hand, decomposition of organic matter can release soluble complexes, increasing mobility under specific conditions. Therefore, soils with high organic matter may act as temporary sinks, delaying but not eliminating risks.

Cation exchange capacity (CEC), which reflects the soil's ability to retain and exchange positively charged ions, directly influences heavy metal retention. Soils with high CEC, such as clay-rich soils, generally hold metals more strongly than sandy soils with low CEC. However, the type of clay minerals present (e.g., montmorillonite vs. kaolinite) also affects binding strength. High-CEC soils may therefore buffer against metal mobility but can still release metals under acidic or saline conditions.

Redox potential (Eh) further regulates heavy metal behavior, especially in waterlogged soils near industrial discharge zones. Under reducing conditions (low Eh), certain metals such as iron (Fe) and manganese (Mn) oxides dissolve, releasing adsorbed heavy metals like arsenic into the soil solution. In contrast, oxidizing conditions can promote the precipitation of metals as oxides or hydroxides, reducing mobility. Chromium provides a clear example: Cr(VI), stable under oxidizing conditions, is highly soluble and toxic, whereas Cr(III) is less mobile and less hazardous [4].

The interplay of these soil properties creates highly variable contamination patterns around industrial complexes. For example, two sites with similar emission sources may show markedly different levels of plant contamination depending on soil chemistry. This complexity underscores the importance of site-specific assessments rather than generalized assumptions about heavy metal risks.

3. Uptake of Heavy Metals by Edible Plants

Heavy metal contamination of soils surrounding industrial complexes poses a significant risk to food security because edible plants cultivated in these soils often absorb and accumulate toxic metals. The uptake, translocation, and storage of heavy metals within plants are influenced by a combination of soil chemistry, plant genotype, and environmental conditions. Understanding these mechanisms and crop-specific accumulation patterns is crucial for assessing food safety risks and prioritizing monitoring strategies.

3.1 Root Absorption and Translocation

The primary entry point of heavy metals into plants is the root system. Metal ions in the soil solution are absorbed through the root epidermis, often via membrane transporters originally evolved for essential nutrients such as calcium (Ca), magnesium (Mg), and iron (Fe). For example, Cd uptake often occurs through divalent cation transporters intended for Zn and Fe, while Pb may compete with Ca transporters.Once absorbed, heavy metals can be sequestered in the root apoplast or symplast, or transported further into the xylem for distribution to aboveground tissues. Xylem loading is facilitated by chelation with organic acids or peptides such as phytochelatins, which allow metals to move upward with the transpiration stream. The efficiency of this process varies by plant genotype: some species restrict metal translocation to protect edible tissues, whereas others, particularly hyperaccumulators, actively translocate metals to leaves and stems.

Rhizosphere conditions strongly influence absorption. Acidic pH enhances solubility and uptake of Cd, Pb, and Zn, while waterlogged conditions increase arsenic mobility, particularly in paddy fields. Root exudates such as citric and malic acids also modify metal availability by chelating ions in the rhizosphere, thereby facilitating uptake [5].

3.2 Crop-Specific Accumulation Patterns

The degree of heavy metal uptake and distribution varies widely across crop groups, reflecting differences in morphology, physiology, and growth conditions.

Leafy Vegetables (e.g., spinach, lettuce, cabbage): Leafy greens are recognized as the most efficient accumulators of heavy metals, especially Cd, Pb, and As. Their large surface area not only favors root-to-shoot transport but also enables direct deposition of atmospheric particulates emitted by nearby industrial sources. Studies have shown that spinach grown near smelting complexes often exceeds permissible Cd limits by several fold. The rapid growth rate and high transpiration of leafy vegetables further promote metal accumulation in edible tissues.

Root Crops (e.g., carrots, radishes, potatoes): Root vegetables absorb heavy metals from the soil solution and store them directly in edible organs. This makes them particularly vulnerable to soil contamination, as there is little translocation barrier between uptake and consumption. Carrots and radishes are prone to Pb and Cd accumulation, while potatoes can accumulate As and Ni in tubers. However, root crops typically show lower concentrations of metals than leafy vegetables when expressed per unit dry weight, though their risk is high due to direct soil contact.

Cereals (e.g., rice, wheat, maize): Cereals generally exhibit lower accumulation of Pb and Cd in edible grains compared to leafy or root crops, largely because of restricted translocation across the grain-filling barrier. However, rice represents a major exception: under flooded paddy conditions, reductive dissolution of Fe and Mn oxides in the soil releases arsenic, which is readily absorbed by rice roots through silicon transporters. Consequently, rice grains often contain significant As levels, posing a serious dietary exposure risk in contaminated regions. Wheat and maize show relatively lower uptake of most metals but can accumulate Cd under acidic or saline conditions [6].

3.3 Comparative Analysis

Across multiple studies and geographical regions, a consistent pattern emerges in the relative accumulation of heavy metals among edible plants:

Leafy vegetables > Root crops > Cereals [7].

This ranking reflects both plant physiology and growing environments. Leafy vegetables, with their high transpiration rates and exposed foliage, are highly efficient metal accumulators. Root crops, in direct contact with contaminated soils, accumulate metals primarily in storage tissues, while cereals restrict translocation of many metals to grains but may accumulate substantial levels of arsenic.This comparative understanding is essential for risk assessment and regulatory monitoring. In areas surrounding industrial complexes, leafy greens should be prioritized for testing and restrictions due to their propensity to accumulate toxic metals at unsafe levels. Rice cultivation in industrially impacted floodplains requires special attention due to arsenic risks, while cereals like maize and wheat may pose relatively lower but still significant risks under certain soil conditions.

4. Health Implications of Dietary Heavy Metal Exposure

The accumulation of heavy metals in edible plants grown near industrial complexes has profound consequences for human health. Unlike many organic contaminants, heavy metals are non-biodegradable and persist in biological systems, often bioaccumulating and biomagnifying along the food chain. Chronic dietary exposure to contaminated crops contributes significantly to the global burden of disease, particularly in industrially impacted regions where regulatory oversight and remediation efforts are limited. The following subsections summarize the health risks associated with the most concerning heavy metals found in food crops.

4.1 Cadmium (Cd)

Cadmium is one of the most toxic metals frequently detected in leafy vegetables and root crops. Its high mobility in acidic soils makes it readily available for plant uptake. Chronic Cd exposure is strongly associated with renal dysfunction, including tubular damage and impaired glomerular filtration. Prolonged exposure also leads to skeletal damage, characterized by osteoporosis and osteomalacia, as cadmium interferes with calcium metabolism. Epidemiological evidence has classified cadmium as a human carcinogen, linked to cancers of the lung, prostate, and kidney.

A well-known case is the "Itai-Itai disease" in Japan, where populations consuming Cd-contaminated rice developed severe bone and kidney disorders.

4.2 Lead (Pb)

Lead exposure through contaminated vegetables and cereals remains a major public health concern. Once ingested, Pb is absorbed in the gastrointestinal tract and accumulates in the bones, where it can be mobilized into the bloodstream over time. Pb is particularly dangerous to children, causing neurotoxicityandreduced cognitive function, as it disrupts neurotransmitter signaling and brain development. Even low-level exposure has been linked to attention deficits, learning disabilities, and decreased IQ. In adults, Pb exposure is associated with hypertension, anemia, and kidney dysfunction. Given its long half-life in the human body, dietary Pb intake from crops grown near industrial areas is a cumulative and persistent health hazard.

4.3 Arsenic (As)

Arsenic contamination, particularly in rice grown under flooded conditions, represents one of the most significant dietary risks worldwide. Inorganic arsenic is highly toxic and classified as a Group 1 human carcinogen. Chronic ingestion is associated with skin, bladder, and lung cancers, as well as non-cancer outcomes such as cardiovascular diseases, diabetes, and developmental toxicity. Long-term exposure also causes skin lesions, pigmentation changes, and keratosis, which are early warning signs of arsenicosis. The widespread reliance on rice as a dietary staple in Asia magnifies the global burden of arsenic exposure. Populations consuming rice cultivated near industrial zones or irrigated with contaminated water are particularly at risk.

4.4 Mercury (Hg)

Although mercury contamination is less common in terrestrial crops than in aquatic food webs, industrial emissions and wastewater can still lead to Hg accumulation in soils and plants. Once absorbed, Hg can be converted into methylmercury, a highly toxic organic form that biomagnifies in the food chain. Mercury exposure causes neurological impairment, including tremors, memory loss, and cognitive deficits. Prenatal and early-life exposures are especially concerning, as methylmercury crosses the placental barrier, leading to developmental toxicity, impaired motor function, and reduced attention span in children. While fish remains the primary dietary source of Hg, crops cultivated near industrial complexes may also contribute to human exposure.

4.5 Nickel (Ni) and Chromium (Cr)

Nickel is an essential trace element in small amounts but becomes toxic at elevated concentrations. Dietary Ni exposure from contaminated vegetables and cereals can lead to dermatitis, respiratory issues, and allergic reactions. Occupational studies have also linked high Ni exposure to an increased risk of lung and nasal cancers.

Chromium exhibits dual behavior depending on its valence state. Trivalent chromium (Cr(III)**)** is relatively benign and even considered beneficial in glucose metabolism. However, hexavalent chromium (Cr(VI)), commonly released from industrial processes such as leather tanning and metal plating, is highly toxic. It causes respiratory toxicity, DNA damage, and carcinogenesis upon ingestion or inhalation. Soils near metallurgical industries often contain elevated Cr(VI) levels, leading to potential accumulation in leafy vegetables and posing serious dietary risks [8].

4.6 Global Health Burden

Chronic dietary exposure to heavy metals contributes substantially to global disease burden. The World Health Organization (WHO) has identified Cd, Pb, As, and Hg as top priority contaminants of concern due to their widespread occurrence and severe health outcomes. In industrial regions, the risk is amplified because contaminated crops are often consumed locally, exposing populations continuously to unsafe levels. The cumulative effects of multi-metal exposure further complicate health outcomes, as combined toxicities can exacerbate oxidative stress, impair detoxification systems, and accelerate chronic disease progression.

5. Mitigation and Remediation Strategies

Given the persistence of heavy metals in soils and their potential transfer into the food chain, effective mitigation strategies are crucial to safeguard food security and public health in regions near industrial complexes. Unlike organic pollutants, heavy metals cannot be degraded into harmless products; therefore, remediation approaches focus on containment, immobilization, or removal from soils [20]. These strategies can be broadly classified into biological, chemical, and policy-driven interventions, each with distinct advantages and limitations.

5.1 Phytoremediation

Phytoremediation harnesses the natural ability of plants to absorb, accumulate, and stabilize heavy metals in contaminated soils. It is considered a cost-effective, eco-friendly, and aesthetically acceptable strategy compared with conventional engineering approaches such as excavation or soil washing.

Phytoextraction involves the cultivation of hyperaccumulator plants capable of absorbing large quantities of metals into their aboveground tissues, which are then harvested and safely disposed of. Examples include *Brassica juncea* (Indian mustard), which is effective in accumulating lead (Pb) and cadmium (Cd), and *Helianthus annuus* (sunflower), which has demonstrated uptake of uranium, arsenic (As), and chromium (Cr). Repeated cropping cycles can gradually reduce metal concentrations in soils.

Phytostabilization relies on plants to immobilize heavy metals in the rhizosphere, thereby reducing leaching and bioavailability to crops. Grasses and legumes with extensive root systems, such as vetiver (*Chrysopogonzizanioides*), are often used to stabilize contaminated soils and prevent erosion in industrial zones, phytoremediation is promising, its effectiveness depends on metal type, soil chemistry, and plant physiology. Moreover, the slow pace of remediation and the need for safe disposal of contaminated biomass remain significant challenges. Nonetheless, as a sustainable and low-cost approach, phytoremediation is particularly suited to large-scale agricultural lands near industrial complexes.

5.2 Soil Amendments

Soil amendments represent another widely used strategy to mitigate heavy metal risks. By altering soil chemistry, amendments immobilize metals, reducing their solubility and uptake by plants.

Lime is commonly applied to raise soil pH, thereby precipitating metals as less soluble hydroxides or carbonates. For example, lime treatment has been shown to reduce Cd and Pb uptake in leafy vegetables cultivated in acidic soils.

Organic amendments such as compost and manure enhance soil organic matter, which binds heavy metals into stable complexes. This not only reduces bioavailability but also improves soil fertility and microbial activity. However, care must be taken to avoid using contaminated composts that may inadvertently introduce additional metals.

Zeolites are naturally occurring aluminosilicate minerals with high cation exchange capacity, effective in adsorbing Cd, Pb, and Ni. They are increasingly applied in contaminated soils to trap metals and reduce their bioavailability.

Biochar, produced from pyrolyzed biomass, has gained considerable attention due to its porous structure, high surface area, and stability in soils. Biochar amendments enhance metal immobilization by adsorption, ion exchange, and surface complexation. Additionally, biochar improves soil aeration, water retention, and microbial activity, offering co-benefits for crop productivity. Recent studies highlight its effectiveness in reducing arsenic uptake in rice and Cd in leafy vegetables [9].The choice of amendment depends on local soil properties, target contaminants, and crop types. Combining multiple amendments—such as biochar with compost or lime—has shown synergistic effects in reducing plant uptake of heavy metals.

5.3 Policy and Monitoring

Technological and agronomic solutions alone are insufficient without robust governance and monitoring frameworks. Effective policy interventions are critical to prevent contamination at its source and safeguard agricultural ecosystems.

Industrial complexes must implement strict regulations to minimize the release of heavy metals through dust, effluents, and solid waste. Adoption of cleaner production technologies, dust suppression systems, and proper waste disposal can significantly reduce soil loading.Wastewater treatment is essential in peri-urban agricultural areas where untreated industrial effluents are often used for irrigation. Advanced treatment systems—such as membrane filtration, constructed wetlands, or electrocoagulation—can remove metals before wastewater is discharged into fields.

Permissible limits for heavy metals in soils and food crops must be clearly established and regularly updated in line with international guidelines, such as those by the Codex Alimentarius Commission and World Health Organization. National governments should enforce compliance through regular inspections and penalties for violations.Periodic testing of soils and crops in industrial zones can identify hotspots of contamination and guide targeted interventions. Incorporating geospatial mapping and remote sensing technologies can further enhance surveillance and inform risk-based land-use planning.

5.4 Integrated Approaches

The most effective strategy often combines biological, chemical, and policy measures. For example, phytoremediation coupled with biochar amendments can simultaneously extract and immobilize metals, while policy frameworks ensure that contamination sources are controlled. Public awareness campaigns, farmer training, and community-based monitoring also play pivotal roles in reducing risks, mitigation and remediation of heavy metal contamination near industrial complexes require a multifaceted approach. Phytoremediation offers sustainable long-term benefits, soil amendments provide immediate risk reduction, and policy enforcement ensures prevention at the source. Integrating these strategies represents the most viable pathway to safeguarding food safety and protecting human health in contaminated regions.

6. Future Perspectives

The growing recognition of heavy metal contamination in soils near industrial complexes and its transfer into edible crops underscores the urgent need for forward-looking solutions. While remediation strategies such as phytoremediation, soil amendments, and regulatory enforcement offer partial relief, future efforts must integrate advanced scientific tools with systemic monitoring and governance to achieve long-term food safety.One promising direction lies in biotechnology and molecular biology. The development of genetically engineered or gene-edited crops with reduced heavy metal uptake represents a viable strategy to mitigate dietary exposure. By modifying the expression of transporters responsible for metal absorption or enhancing root sequestration mechanisms, crops could be engineered to limit translocation of toxic metals into edible tissues.

Recent advances in CRISPR/Cas technologies provide a precise and efficient platform to target these pathways, offering significant potential for crop improvement in contaminated regions.

Omics-based approaches—including transcriptomics, proteomics, and metabolomics—are revolutionizing our understanding of plant responses to metal stress. These tools enable researchers to unravel complex molecular networks governing metal uptake, detoxification, and tolerance. Insights from such studies can inform both conventional breeding and biotechnological interventions, accelerating the development of crop varieties with enhanced resistance to metal stress while maintaining productivity and nutritional value.Equally critical is the establishment of standardized risk assessment frameworks. Current guidelines for permissible heavy metal levels in soils and crops vary across countries, leading to inconsistencies in food safety regulation. Harmonized international standards, grounded in evidence-based thresholds for chronic exposure, are essential to protect consumers in both industrialized and developing nations [12-13].Future progress also depends on integrated monitoring systems that combine geospatial mapping, remote sensing, and high-throughput analytical technologies. Such systems would enable real-time surveillance of contamination hotspots and facilitate risk-based land-use planning, these monitoring tools with community-based initiatives can empower local stakeholders and farmers to make informed decisions about crop cultivation in contaminated soils.In rapidly industrializing regions, where urban expansion and agriculture often intersect with industrial activities, proactive measures are urgently required. The uniting advances in biotechnology, systems biology, and regulatory science, alongside community engagement, future strategies can mitigate risks, safeguard food security, and ensure sustainable agricultural development in contaminated landscapes.

Conclusion

Soils in the vicinity of industrial complexes are highly susceptible to heavy metal contamination, which poses serious concerns for food safety, environmental quality, and human health. Industrial activities release metals such as lead, cadmium, mercury, and arsenic into the surrounding environment, which can accumulate in agricultural soils over time. The uptake of these metals by crops varies depending on species, with leafy vegetables and root crops demonstrating higher accumulation rates compared to cereals and legumes. This differential uptake significantly influences the risk of chronic exposure for consumers, as continuous ingestion of contaminated food can lead to a range of adverse health effects, including neurological disorders, kidney damage, and developmental impairments in children.Effective mitigation strategies are essential to reduce these risks. Phytoremediation, involving the use of metal-accumulating plants, offers a cost-effective and environmentally friendly approach to remove contaminants from soils. Soil amendments, such as organic matter, lime, and biochar, can immobilize metals and reduce their bioavailability to crops, stringent regulatory enforcement, regular soil monitoring, and the implementation of safe agricultural practices are critical to prevent further contamination and safeguard food production systems, heavy metal accumulation near industrial hubs requires a holistic, multidisciplinary approach involving environmental scientists, agronomists, public health experts, policymakers, and local communities. Only through coordinated efforts can the persistent challenge of soil contamination be managed effectively, ensuring sustainable agricultural productivity and minimizing health risks. Proactive intervention and long-term monitoring are indispensable to protect both ecosystems and human populations from the insidious effects of industrial pollution on agroecosystems.

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