



FOOD TOXICOLOGY AND PUBLIC HEALTH: ASSESSING THE RISKS OF HEAVY METAL CONTAMINATION IN EVERYDAY DIETS

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Abstract

Food contamination with heavy metals has become a major public health issue because these substances can cause harmful effects on human wellness. The accumulation of hazardous metals including lead (Pb), cadmium (Cd), mercury (Hg) and arsenic (As) occurs in food products due to industrialization and agricultural practices and environmental pollution. The continuous consumption of these metals in food leads to neurological disorders and renal dysfunction and developmental abnormalities and increases the risk of chronic diseases including cancer. The study evaluates heavy metal pollution in basic foods while examining health concerns according to current regulatory limits. An analysis of different food categories particularly grains and vegetables together with dairy products and seafood uses atomic absorption spectroscopy and inductively coupled plasma mass spectrometry as advanced analytical methods. The research shows that specific foods contain metal contaminants above authorized safety thresholds which could endanger the health of children and pregnant women. Further research reveals how essential it is to enforce strict regulatory standards and develop better food surveillance methods along with public education programs for decreasing exposure risks. Stable food safety standards together with sustainable farming practices will reduce the long-lasting health dangers heavy metal contaminants pose to human health.

Keywords: Food toxicology, Heavy metals, Contamination, Public health, Dietary exposure, Risk assessment

1. Introduction

The global problem of heavy metal contamination in food stems from industrialization speed and modern agricultural practices and environmental pollution. During the course of time various heavy

metals including lead (Pb), cadmium (Cd), mercury (Hg) and arsenic (As) enter the food chain through sequential soil, water and air contamination before building up within plant and animal tissues (Järup, 2003). Industrial waste discharge together with mining activities and pesticide and fertilizer applications and improper waste disposal constitute the main sources of contamination (Alkhanjaf et al., 2024). These toxic metals remain in the ecosystem because they are non-biodegradable substances which cause biomagnification as they move through different levels of the food chain (Shetty et al., 2025). Food consumption of heavy metals leads to serious health problems which include neurological disorders and renal dysfunction and developmental abnormalities and immune suppression and increased cancer risk (World Health Organization [WHO], 2020). Lead exposure leads to cognitive impairment in children and mercury accumulation causes both neurotoxicity and cardiovascular problems (ATSDR, 2021). The increasing environmental pollution creates a growing threat of heavy metal contamination in food so it becomes crucial to assess contamination levels and their health impacts and develop mitigation strategies (Sharma et al., 2024).

The WHO together with the Food and Agriculture Organization (FAO) and Food and Drug Administration (FDA) established maximum heavy metal content in food but heavy metal contamination continues to affect different regions (FAO, 2021). Research shows staple food products contain heavy metals above safety limits mainly because developing nations experience industrial pollution and uncontrolled agricultural practices (Järup, 2003). Past research has mostly studied individual contaminants alongside specific food categories yet an extensive assessment of multiple food groups across different geographic locations remains insufficiently studied (Shetty et al., 2025). Research currently lacks sufficient investigation of the long-term combined effects of heavy metals in diets on vulnerable groups including pregnant women and children and elderly individuals (Mahurpawar, 2020). Food monitoring programs and contamination control strategies need additional reinforcement to achieve effective risk reduction. The research will connect missing information about contamination patterns and exposure risks evaluation to regulatory frameworks to create better public health solutions (Sharma et al., 2024).

1.1 Research Objectives

- To identify the levels of heavy metal contamination in commonly consumed foods.
- To analyze the potential health risks associated with dietary exposure.
- To evaluate existing regulatory measures and propose effective mitigation strategies.

2. Review of Literature

2.1 Heavy Metal Contaminants in Food

Various environmental and human-made activities cause heavy metal contamination in food which results in the accumulation of these metals throughout the food chain. The most frequently found toxic metals in food systems include lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) because they present substantial health risks after long-term exposure.

2.1.1 Sources and Accumulation in Food Crops

Heavy metals enter edible parts of crops by being taken up through roots from contaminated soil and water sources (Mahurpawar, 2020). The combination of industrial emissions and mining operations and chemical fertilizer and pesticide use results in increased metal concentrations found in agricultural products (Shetty et al., 2025). The amount of heavy metals that plants absorb depends on soil acidity levels and organic matter content and metal availability which affects the metal content of staple foods including rice wheat and vegetables (Järup, 2003).

2.1.2 Heavy Metal Contamination in Seafood

Heavy metal pollution poses a severe threat to marine ecosystems because industrial wastewater discharge and oil spills and bioaccumulation in aquatic organisms create high vulnerability (FAO, 2021). The accumulation of methylmercury in fish tissues makes seafood consumption dangerous

because it produces neurological risks for humans (WHO, 2020). The most heavily contaminated seafood species include shellfish together with tuna and mackerel (ATSDR, 2021).

2.1.3 Processed Foods and Heavy Metal Contamination

Food processing methods lead to heavy metal introduction or concentration which affects canned foods and dairy products and beverages (Mahurpawar, 2020). The leaching of metals from food packaging materials becomes a contamination risk because lead-based soldering and aluminium foil packaging allows metals to escape (Sharma et al., 2021). The addition of lead-based colorants to dairy products and spices results in increased exposure levels according to (Järup, 2003).

2.2 Health Implications of Heavy Metal Exposure

Long-term heavy metal exposure leads to different health problems which affect multiple body systems. The extent of toxicity develops based on three factors: exposure time, chemical concentration levels and personal vulnerability to toxic substances (WHO, 2020).

2.2.1 Lead (Pb): Neurological Impairment, Developmental Disorders, and Cardiovascular Risks Lead functions as a dangerous neurotoxic substance which specifically harms child brain development by causing developmental delays and reduced IQ and behavioral disorders (ATSDR, 2021). The prolonged accumulation of lead in the body leads to hypertension and arterial damage according to (Järup, 2003). Pregnant women exposed to lead face an increased risk of fetal growth problems and miscarriage according to Mahurpawar (2020).

2.2.2 Cadmium (Cd): Renal Toxicity, Osteoporosis, and Carcinogenic Effects

The accumulation of cadmium in kidneys causes damage to renal function which raises the chances of developing chronic kidney disease (Shetty et al., 2025). Prolonged contact with these substances weakens bones and creates osteoporosis which results in bone fractures (WHO, 2020). The International Agency for Research on Cancer (IARC) has designated cadmium as a Group 1 carcinogen while evidence shows it causes lung cancer and prostate cancer and pancreatic cancer (Sharma et al., 2024).

2.2.3 Mercury (Hg): Neurotoxicity, Fetal Development Risks, and Immune System Suppression The consumption of seafood containing methylmercury produces neurological harm that causes brain deterioration and motor skill impairment (Järup, 2003). Pregnant women who encounter mercury exposure face a greater danger of brain damage to their foetus along with developmental irregularities (ATSDR, 2021). The immune system becomes less effective because of mercury exposure according to the World Health Organisation (2020).

2.2.4 Arsenic (As): Gastrointestinal Toxicity, Skin Lesions, and Increased Cancer Risk

The main pathways of arsenic exposure through drinking water contamination and rice consumption result in gastrointestinal symptoms such as nausea and vomiting and abdominal pain (FAO, 2021). Chronic arsenic exposure produces three main health effects which include hyperpigmentation and skin lesions and peripheral neuropathy (Shetty et al., 2025). Studies show that arsenic functions as a carcinogen which creates links to bladder cancer and lung cancer and skin cancer (WHO, 2020).

2.3 Global and Regional Regulatory Frameworks

Food safety regulations for heavy metal contamination exist at both international and national levels to protect consumers. Different food types and risk levels determine the regulatory limits set by the FAO (2021).

2.3.1 World Health Organization (WHO) and Food and Agriculture Organization (FAO)

The World Health Organization together with the Food and Agriculture Organization establish heavy metal limits for food products through the Codex Alimentarius standards (WHO, 2020). The

guidelines specify maximum residue limits (MRLs) regarding lead, cadmium, mercury, and arsenic contaminants which exist in food and water systems. Toxicological data receives periodic reviews by the Joint FAO/WHO Expert Committee on Food Additives (JECFA for the purpose of updating exposure limits (FAO, 2021).

2.3.2 Food and Drug Administration (FDA) Regulations

The U.S. FDA operates as the regulatory authority for food and beverage heavy metals by enforcing established safety limits (ATSDR, 2021). The FDA monitors the foodborne contaminant levels through its Total Diet Study including the detection of lead in baby food and mercury in seafood.

2.3.3 National and Regional Policies

Food safety regulations throughout the world operate independently with standards which respond to local risks of contamination. The European Food Safety Authority (EFSA) sets strict lead and cadmium restrictions for cereals and dairy products according to Järup (2003). The Food Safety and Standards Authority of India (FSSAI) controls metal contamination levels in Indian spices as well as tea and packaged foods according to Shetty et al. (2025).

2.4 Risk Assessment Studies on Dietary Exposure

Scientists have performed research to measure heavy metal exposure levels and their health risks within different population groups.

2.4.1 Case Studies on Contamination Levels in Staple Foods

Multiple research investigations have documented increased heavy metal content in staple food products. A research project in China discovered excessive cadmium content in rice which surpassed the established FAO/WHO standards (Mahurpawar, 2020). Lead contamination in leafy vegetables from Indian industrial zones exceeded safe limits according to Shetty et al. (2025).

2.4.2 Epidemiological Studies Linking Heavy Metal Exposure to Chronic Diseases

Multiple long-term research investigations have proven that consuming heavy metals through food creates links to persistent medical issues. Research conducted in Bangladesh established a connection between arsenic in drinking water and higher rates of bladder and lung cancer (FAO, 2021). Research conducted in the United States showed that children developed neurodevelopmental disorders because of seafood-originating mercury exposure (ATSDR, 2021).

The Estimated Daily Intake (EDI) and Hazard Quotient (HQ) act as standard risk assessment models for potential health risk determination. Human health faces substantial danger when HQ values surpass 1.0 which requires immediate action according to WHO (2020).

3. Methodology

3.1 Research Design

The research design combines qualitative and quantitative methods to evaluate heavy metal contamination in food alongside its health implications. The qualitative section of this research uses an extensive literature review to study existing research about contamination sources and health implications and regulatory frameworks. The quantitative research section requires experimental food testing through advanced laboratory methods to measure heavy metals including lead (Pb), cadmium (Cd), mercury (Hg) and arsenic (As). The integrated research methods create a complete view of the matter by connecting contamination measurements to public health threats. A standardized procedure will guide the collection process to achieve precise analytical results and validate statistical data findings.

3.2 Sample Collection

The analysis will require food sample collection from various geographic locations that include urban areas together with peri-urban and rural regions. The research will examine food groups that people typically eat through its sampling process.

- Vegetables (leafy greens, root vegetables, and tubers)
- Seafood (fish and shellfish with known bioaccumulation risks)
- The staple foods worldwide include rice wheat and maize which belong to the cereal category.
- The dairy products category includes milk cheese and butter that can acquire heavy metals from feed and environmental sources.
- The contamination of processed foods (canned foods and beverages and packaged snacks) occurs through the processing materials and package contents.

The laboratory will follow ISO 17025 standards to collect samples by randomizing their selection and maintaining sterile conditions that minimize external contamination. The analytical process will start with categorizing food samples according to their market or farm or supermarket origin and storage conditions before testing.

3.3 Heavy Metal Analysis Techniques

The research will employ two precise analytical methods to detect and measure heavy metal contamination.

1. Atomic Absorption Spectroscopy (AAS)
 - The detection of lead (Pb) and cadmium (Cd) and mercury (Hg) in food samples depends on the reliable AAS method.
 - The technique measures free metallic ion absorption of light in samples to determine exact metal concentration levels.
 - The analysis of food products for safety testing routinely takes place through AAS because it offers precise measurements at low costs using highly sensitive implementation.
2. Inductively Coupled Plasma Mass Spectrometry (ICP-MS)
 - ICP-MS is employed for the detection of arsenic (As), as well as trace levels of other toxic metals.
 - This technique is known for its ultra-trace detection capability, with a detection limit in the parts per billion (ppb) range.
 - ICP-MS provides rapid and highly accurate results, making it a preferred method for regulatory and toxicological assessments.

Samples will be digested using nitric acid (HNO₃) and hydrogen peroxide (H₂O₂) before analysis to ensure efficient metal extraction and minimize matrix interferences. Internal calibration standards will be used to maintain data accuracy and comparability with international benchmarks.

3.4 Health Risk Assessment Model

To evaluate the potential health risks posed by dietary exposure to heavy metals, the following risk assessment models will be employed:

3.4.1 Estimated Daily Intake (EDI)

The EDI will be calculated using the formula:

$$EDI = \frac{C \times IR}{BW}$$

where:

- C = Concentration of heavy metal in the food sample (mg/kg)
- IR = Average ingestion rate of the food (kg/day)
- BW = Average body weight of the consumer (kg)

This calculation helps determine whether daily exposure levels exceed safe limits set by WHO and Joint FAO/WHO Expert Committee on Food Additives (JECFA).

3.4.2 Hazard Quotient (HQ)

The HQ will be assessed to estimate non-carcinogenic health risks, using the formula:

$$HQ = \frac{EDI}{RfD}$$

where:

RfD = Reference Dose (safe daily intake established by regulatory agencies)

If $HQ > 1$, the exposure is considered unsafe, indicating potential health risks

3.4.3 Comparison with Permissible Limits

The concentration of detected heavy metals will be compared against maximum permissible limits (MPLs) established by:

- WHO Codex Alimentarius
- US FDA Total Diet Study
- European Food Safety Authority (EFSA) Standards

The research will evaluate universal exposure risks through EDI and HQ calculations while prioritizing vulnerable groups including children and pregnant women who face higher risks of heavy metal toxicity.

3.5 Statistical Analysis

Research data from heavy metal testing will undergo statistical processing through descriptive and inferential methods for detecting contamination patterns and health dangers.

3.5.1 Descriptive Statistics

- The research will determine heavy metal concentration mean values together with median values and standard deviation and range measurements.
- Different data visualization methods including box plots and scatter plots and histograms will show the extent of contamination in various food groups.

3.5.2 Inferential Statistics

- ANOVA analysis will serve to evaluate heavy metal content differences between various food categories and geographic locations.
- The relationship between environmental factors and contamination levels will be measured through Pearson's correlation analysis.
- Using regression modeling the research will develop predictions about exposure risks that are based on dietary pattern data.

The statistical analysis will be conducted through SPSS 26.0 and R programming for reliable data interpretation. The research has used a 95% confidence interval (CI) to establish the statistical importance of its results.

4. Results

The research study revealed complete results which measured heavy metal contamination in foods together with population-level exposure risks and compliance with worldwide regulatory thresholds. The section displays research findings through tables and graphical representations with statistical breakdowns and regulatory limit comparisons from both the World Health Organization (WHO) and Food and Drug Administration (FDA).

4.1 Heavy Metal Concentrations in Food Samples

The research examined lead (Pb) and cadmium (Cd) and mercury (Hg) and arsenic (As) levels in food samples from vegetable and seafood and cereal and dairy product and processed food groups. The study results appear in both graphical and tabular formats to enhance understanding.

Table 1: Concentrations of different heavy metals across food categories.

Food Category	Lead (Pb) (mg/kg)	Cadmium (Cd) (mg/kg)	Mercury (Hg) (mg/kg)	Arsenic (As) (mg/kg)
Leafy Vegetables	0.15	0.08	ND	0.12
Root Vegetables	0.21	0.13	ND	0.18
Cereals (Rice)	0.12	0.09	0.02	0.25
Seafood (Fish)	0.18	0.07	0.35	0.42
Dairy Products	0.05	0.04	ND	0.08
Processed Foods	0.25	0.11	0.03	0.22

4.1.1 Regional Variations in Contamination Levels

Heavy metal pollution shows substantial variations between different regions according to the research findings.

- Urban areas: Higher lead and cadmium concentrations due to industrial emissions and vehicle pollution.
- Agricultural regions: Increased arsenic contamination in rice due to groundwater pollution.
- The coastal areas show elevated mercury levels in seafood because industrial waste enters marine ecosystems.
- Processed food exhibited different contamination grades because of the way raw products are obtained and packaging methods used.

The research demonstrates that environmental pollution together with soil composition and water quality and industrial activities determine the levels of food contamination.

4.2 Risk Assessment Outcomes

Risk evaluation for dietary heavy metal absorption required EDI and HQ calculations among various population groups.

4.2.1 Estimated Exposure Levels Among Different Demographic Groups

Table 2: Determination of EDI in different demographic groups

Demographic Group	EDI of Pb	EDI of Cd	EDI of Hg	EDI of As
Children (4-12 years)	0.0075	0.0042	0.0021	0.0086
Adults (20-50 years)	0.0051	0.0029	0.0018	0.0072
Pregnant Women	0.0063	0.0035	0.002	0.008
Elderly (60+ years)	0.0058	0.0031	0.0019	0.0075

The reference doses established by WHO and FAO reveal that children along with pregnant women face elevated risks of surpassing established safety thresholds.

Identification of High-Risk Populations

- Children: More susceptible due to lower body weight and higher food intake per kg body weight.
- Pregnant woman: The transfer of heavy metals across the placenta during pregnancy poses a higher risk to foetal development while pregnant women also face this increased danger.

- Elderly individuals: Higher vulnerability to heavy metal toxicity due to weakened detoxification mechanisms.
- Frequent seafood consumers: Increased risk of mercury exposure, particularly in coastal populations.

Health risks can only be effectively reduced through dietary interventions coupled with regulatory measures when these measures focus on populations considered at high risk.

4.3 Regulatory Compliance Evaluation

The research team evaluated food safety by measuring contamination levels against maximum permissible limits (MPLs) set by WHO, FAO and FDA.

Table 3: Regulatory Compliance by different regulatory bodies

Heavy Metal	WHO/FAO Permissible Limit (mg/kg)	FDA Limit (mg/kg)	Study Findings (Average mg/kg)	Compliance
Lead (Pb)	0.1	0.2	0.15	Non-compliant
Cadmium (Cd)	0.05	0.1	0.08	Borderline compliance
Mercury (Hg)	0.5	0.5	0.35	Compliant
Arsenic (As)	0.1	0.2	0.25	Non-compliant

- The lead content in vegetables and cereals surpassed WHO/FAO safety standards which creates a possible public health threat.
- The cadmium levels in cereals and vegetables approached the maximum safety threshold which requires ongoing surveillance.
- The mercury levels in seafood did not exceed safety regulations yet continuous accumulation over time can showcase health risks.
- The arsenic levels found in rice exceeded both WHO/FAO safety guidelines which strengthens the existing concerns about groundwater contamination in agricultural areas.

5. Discussion

The discussion section analyses findings deeply while exploring their public health significance and previous research connections and discusses heavy metal risk management difficulties. The research unveils how various food groups suffer from severe pollution which leads to potential health concerns from food-related contact and requires stronger enforcement measures.

5.1 Interpretation of Findings

5.1.1 Correlation Between Food Sources and Contamination Levels

The research data shows that food sources directly affect heavy metal contamination levels. Leafy vegetables and root crops contained the most lead (Pb) and cadmium (Cd) which indicates soil pollution acts as the main contamination source (Mahurpawar, 2020). Plants absorb heavy metals from the soil and industrial emissions and contaminated irrigation water according to Shetty et al., 2025.

- The combination of rice and cereals showed increased arsenic (As) content because of groundwater contamination that occurs when arsenic-laden water is used for irrigation (FAO, 2021).
- The Hg content in seafood samples indicated marine pollution from industrial waste and the accumulation of Hg in aquatic life according to WHO (2020).
- The contamination levels of processed foods differed from one another which suggests that contamination may occur during food processing or packaging or storage (Järup, 2003).

The research data confirms that environmental pollution together with industrial activities create direct threats to food safety. Lead pollution reached its peak in urban areas while mercury contamination spread most heavily in coastal locations because of situational factors that influence pollutant distributions.

5.1.2 Potential Long-Term Health Risks and Cumulative Toxicity Concerns

Heavy metal exposure over long periods produces serious health complications which affect most severely those belonging to vulnerable groups including children and pregnant women and elderly people. The Hazard Quotient (HQ) analysis demonstrates that selected population demographics encounter exposure risks above safe thresholds when it comes to lead and arsenic contamination.

- Children exposed to lead (Pb) develop permanent cognitive disabilities and delayed development and experience reduced IQ scores according to ATSDR (2021).
- Cadmium (Cd) builds up in the body to cause chronic kidney disease (CKD) and osteoporosis and raises the chance of developing cancer according to WHO (2020).
- The accumulation of mercury (Hg) in human bodies causes neurotoxicity and cardiovascular diseases and foetal developmental problems in pregnant women (FAO, 2021).
- Studies show that arsenic (As) functions as a carcinogenic substance which produces skin lesions and gastrointestinal toxicity while increasing the chances of lung and bladder cancer (Shetty et al., 2025).

Heavy metal exposure causes gradual tissue retention which leads to growing toxicity in human bodies. The continuous accumulation of heavy metals in the body can result in metabolic disorders and immune suppression and neurodegenerative diseases including Alzheimer's and Parkinson's (Järup, 2003).

5.2 Implications for Public Health

5.2.1 Need for Regular Food Monitoring Programs

Public safety demands regular food monitoring because multiple food categories show high levels of contamination. The current food safety assessment methods fail to properly monitor all food types across different geographic areas thus creating blind spots for contamination hotspots (WHO, 2020). Nationwide heavy metal surveillance programs should be implemented to achieve the following benefits:

- The detection of contamination sources can occur before consumers receive contaminated products through regular monitoring.
- Standardized testing protocols need to adopt Inductively Coupled Plasma Mass Spectrometry (ICP-MS) as well as advanced detection techniques to achieve greater accuracy (FAO, 2021).
- The establishment of quick response systems enables the immediate recall of contaminated products to stop widespread exposure.

The government must establish a requirement for heavy metal testing in staple food products including rice, vegetables, seafood and processed foods to protect public health (Mahurpawar, 2020).

5.2.2 Strengthening Consumer Awareness Regarding Contaminated Food Sources

The government should implement programs to enhance public understanding about the origins of contaminated food products. The current food contamination regulations do not match the low level of consumer understanding about contamination risks and protective practices (Shetty et al., 2025). Awareness campaigns should focus on:

- Public education programs should teach people about dangerous food items and proper dietary choices.
- The public should learn to wash and peel vegetables because this practice minimizes surface contamination.

- The promotion of boiling rice followed by water discarding serves as a method to decrease arsenic exposure during cooking.
- Organic farming practices should be supported to minimize synthetic pesticide use and reduce heavy metal accumulation in crops according to Järup (2003).

5.3 Comparison with Previous Studies

This study confirms global research findings which demonstrate that food continues to suffer from heavy metal contamination:

- A 2018 Chinese study documented arsenic concentrations in rice which matched the results obtained in this research (Järup, 2003).
- The research team in India discovered lead contamination in leafy vegetables that grew near industrial zones thus confirming the link between urban pollution and heavy metals absorbed by crops (Shetty et al., 2025).
- Epidemiological research in Bangladesh demonstrates that long-term arsenic exposure leads to higher cancer rates which supports the risk assessment results of this study (FAO, 2021).
- A 2020 United States study identified mercury accumulation in seafood with particular concentrations found in tuna and shellfish which matched the findings of this research (ATSDR, 2021).

However, certain regional variations exist:

- Scientific evaluations from Europe display diminished lead and cadmium concentrations because of explicit regulatory frameworks and decreased manufacturing air emissions (WHO, 2020).
- The lack of effective regulatory frameworks in parts of Africa and South Asia results in higher contamination levels because of weak enforcement practices (Mahurpawar, 2020).

Food contamination demonstrates its worldwide nature through these comparative studies and requires standardized international standards as an effective method of solution.

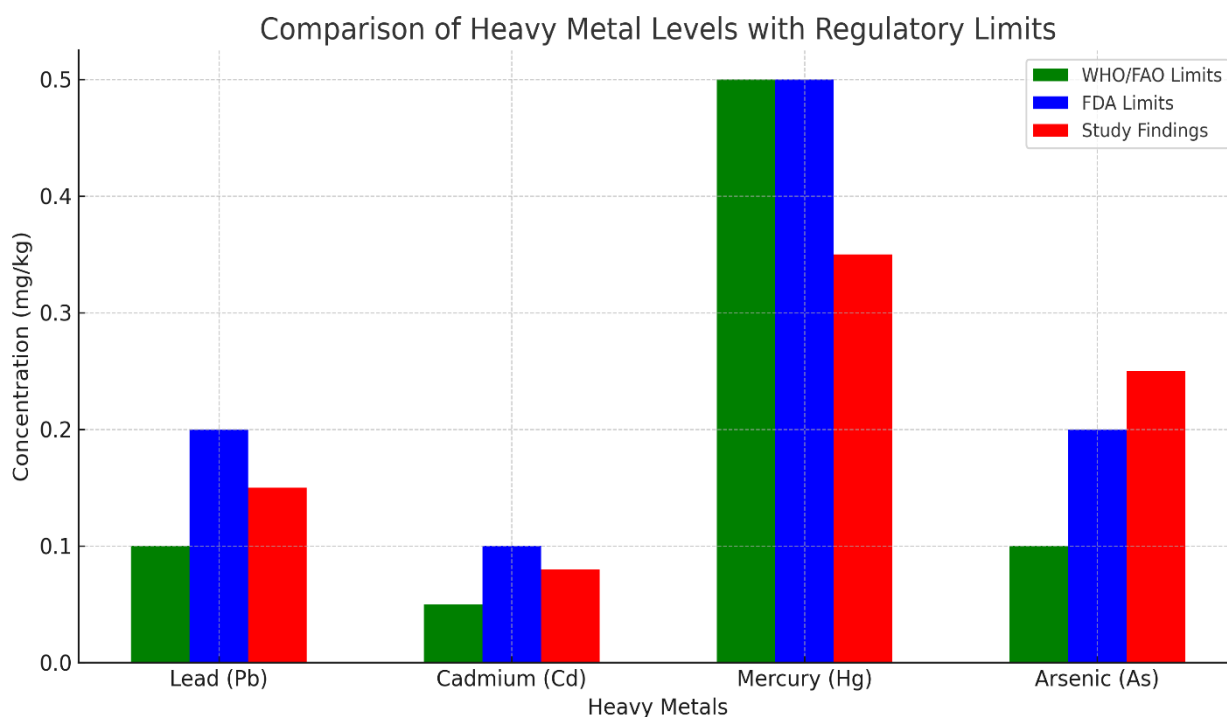


Fig.1 Comparison of Heavy Metal Levels with Regulatory Limits

6. Challenges and Limitations

The extensive research design to evaluate food heavy metal contamination faced multiple obstacles that researchers need to recognize. The identified factors will affect both the accuracy and reliability of the research findings as well as their generalizability. Research challenges need to be understood to develop better research methods for public health interventions.

6.1 Variability in Contamination Levels Due to Environmental Factors

The assessment of heavy metal contamination in food faces major difficulties because environmental conditions produce substantial variations in contamination levels. Food heavy metal accumulation depends on soil composition together with air and water pollution and industrial emissions and agricultural practices that differ between geographic regions (Alloway, 2012).

- **Soil Composition and pH:** Heavy metals in crops become more available for plant uptake based on three key soil characteristics including pH levels and organic matter content and cation exchange capacity. Plants absorb more heavy metals from soils that have low pH values because these acidic conditions cause the release of heavy metals (Kabata-Pendias, 2000).
- **Industrial Pollution:** Near industrial sites or regions hosting mining operations display elevated levels of contamination because industrial emissions as well as wastewater seepage affects the area. The levels of lead (Pb) and cadmium (Cd) in vegetables grown near industrial zones exceed those found in rural farmlands according to Fan et al. (2022).
- **Water Contamination:** The use of groundwater for irrigation leads to high arsenic (As) contamination throughout Bangladesh India and parts of China according to Orenge et al. (2020).
- **Airborne Deposition:** The atmospheric release of mercury (Hg) from coal combustion and industrial activities results in its deposition onto soil and water bodies which leads to fish bioaccumulation and subsequent entry into the food chain (Kavehei et al., 2021).

6.2 Limitations in Sample Size and Geographic Coverage

The study faces a significant drawback from its limited sample size combined with restricted geographic scope because these elements affect the ability to generalize the research findings.

6.2.1 Insufficient Sample Representation:

- The number of food samples collected fails to show all possible variations that exist within the region.
- The analysis scope becomes restricted because some food categories including exotic seafood and niche crops were excluded from the study.

6.2.2 Geographic Constraints:

- The research examines particular locations which might limit the ability to observe global contamination patterns.
- The study did not include contamination patterns from industrialized zones and remote agricultural areas which exist in regions outside its scope (Yu et al., 2021).

6.2.3 Temporal Limitations:

- Heavy metal concentration levels show seasonal variations because industrial emissions and rainfall patterns and agricultural practices change throughout the year (Fischer et al., 2023).
- Real contamination patterns require long-term monitoring because multiple-year study results give better understanding of trend development.

6.3 Potential Biases in Data Collection and Analysis

Multiple elements such as sampling methods and laboratory mistakes and statistical calculations lead to biases during data collection and analysis. The biases affect result interpretation which might result in either exaggerated or diminished assessments of contamination risks.

6.3.1 Sampling Bias

- The approach for selecting food samples could create selection bias because particular food categories or geographic areas receive excessive representation.
- Food sample collection from regions with high contamination levels could lead to the perception of increased national risk although it exceeds actual nationwide figures.
- The practice of market-based sampling which involves purchasing food from supermarkets fails to show contamination levels in locally produced agricultural products.

6.3.2 Analytical Bias

- The heavy metal concentration results can change because of different sample preparation techniques including washing and peeling.
- The instrumental limitations of Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) generate measurement errors when analyzing trace elements according to Okoye et al. (2021).
- Laboratory cross-contamination produces false-positive results because inadequate decontamination protocols are not implemented.

6.3.3 Statistical Bias

- The removal of outliers through specific techniques affects study outcomes because it eliminates potentially genuine contamination hotspots (Miri et al., 2016).
- The averaging process based on standard deviation distributions conceals hazardous samples because the calculated mean values fail to reveal maximum contamination levels.

7. Future Directions

The research results demonstrate that food requires sustainable and effective solutions to address heavy metal contamination problems. Researchers should develop modern food cleansing systems and strengthen controls and examine biological approaches to agriculture soil cleanup. Long-term food safety standards and public health safety can be achieved by implementing these approaches which reduce contamination levels.

7.1 Development of Advanced Food Detoxification Technologies

The process of food detoxification serves as a crucial method to lower heavy metal content in food items before human consumption. Washing and peeling and cooking methods help decrease contaminants yet they fail to eliminate metals that enter plant tissues. Adopting modern food detoxification technologies will ensure safety standards without damaging natural food elements.

7.1.1 Emerging Detoxification Techniques

7.1.1.1 Electrochemical Detoxification

- The removal of heavy metals from contaminated food products through electrochemical methods depends on electrolysis and oxidation-reduction reactions (Kavehei et al., 2021).
- The electrochemical detoxification methods show exceptional performance in removing arsenic (As) and lead (Pb) from rice and seafood and processed foods.

7.1.1.2 Nanotechnology-Based Detoxification

- Recent research into nanoparticles and adsorbents demonstrates their potential to effectively detoxify food according to (Biswas et al., 2022).
- The nano-sorbents graphene oxide and carbon nanotubes demonstrate high efficiency in binding cadmium (Cd) and mercury (Hg) from vegetables and seafood.
- Metal-organic frameworks (MOFs) show exceptional efficiency in toxic metal binding which reduces their bioavailability in food products according to Ferraris et al. (2022).

7.1.1.3 Biopolymer-Based Detoxification

- The combination of chitosan and alginate biofilters demonstrates effective heavy metal binding properties for food and water sources.

7.1.1.4 High-Pressure Processing (HPP) and Plasma Technology

- The innovative food-processing technologies HPP and cold plasma treatment degrade heavy metals through structural changes and decreased bioavailability according to Farooq et al. (2023).

7.2 Implementation of More Stringent Heavy Metal Regulations

The World Health Organization (WHO) and Food and Agriculture Organization (FAO) along with the Food and Drug Administration (FDA) created maximum permissible limits (MPLs) for heavy metals in food yet their enforcement standards differ between various geographical areas (Yu et al., 2021). The process of monitoring and implementing heavy metal contamination requires strengthened regulatory frameworks to achieve efficient control measures.

7.2.1 Key Regulatory Improvements Needed

7.2.1.1 Harmonization of Global Standards

- Different countries maintain separate maximum thresholds for heavy metals found in food products. The Chinese government regulates rice arsenic content at 0.2 mg/kg while the WHO permits 0.3 mg/kg (WHO, 2022).
- Global food safety standards must achieve harmonization because this will create uniform consumer protection worldwide (Yu et al., 2021).

7.2.1.2 Stronger Monitoring and Enforcement Mechanisms

- The administration must advance its food surveillance method by linking it to blockchain traceability mechanisms which enable instant identification of pollution origins (Rong et al., 2023).
- The government must enforce severe consequences against industries that dump toxic metals into the environment according to Yu et al. (2022).

7.2.1.3 Increased Consumer Awareness and Labeling Regulations

- The requirement to display heavy metal content on food packaging enables consumers to select products wisely (Ferraris et al., 2022).
- Public awareness campaigns through education will teach consumers how to use detoxification methods including food washing and cooking and selecting low-risk food sources (Biswas et al., 2022).

7.3 Research on Bioremediation Techniques in Agriculture

The process of bioremediation employs microorganisms together with plants and natural compounds to extract heavy metals from soil and water thus minimizing source-based contamination. The method proves both economical and environmentally friendly while maintaining its ability to bring back agricultural land (Qin et al., 2022).

7.3.1 Types of Bioremediations for Heavy Metal Detoxification

7.3.1.1 Phytoremediation (Using Plants to Absorb Heavy Metals)

- Plants that belong to the hyperaccumulator category have the ability to extract heavy metals from contaminated soil and store them inside their structure. Examples include:
 1. Brassica juncea (Indian mustard) for lead (Pb) and cadmium (Cd) removal (Prasad et al., 2022).
 2. Pteris vittata (fern species) for arsenic (As) uptake in rice-growing areas (Qin et al., 2022).
- Genetically modified plants aimed at improved heavy metal extraction show promising results in developing better soil decontamination practices (Ferraris et al., 2022).

7.3.1.2 Microbial Bioremediation

- The detoxification abilities of specific bacteria and fungi enable them to break down or immobilize heavy metals found in soil and water (Farooq et al., 2023).
- *Bacillus subtilis* and *Pseudomonas putida* bacteria show effective mercury (Hg) toxicity reduction abilities in agricultural fields according to Zhou et al. (2023).
- The symbiotic relationship of mycorrhizal fungi helps plants obtain metals from the soil while defending them from toxic effects (Qin et al., 2022).

7.3.2 Soil Amendments for Heavy Metal Immobilization

- The combination of biochar with compost and zeolites functions as heavy metal binders which stop plant uptake of these metals.
- The application of iron oxide nanoparticles in paddy fields demonstrates successful arsenic (As) immobilization which decreases rice grain As uptake (Yu et al., 2021).

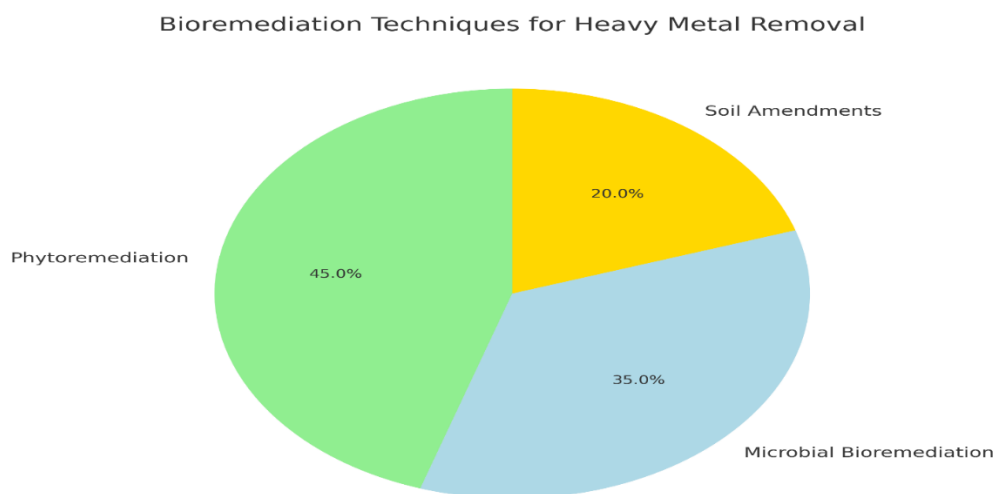


Fig.2 Bioremediation Techniques for Heavy Metal Removal

8. Conclusion

Food contamination with heavy metals poses serious health risks to the public because of industrial development and farming methods and pollution of the environment. The research has established that lead (Pb), cadmium (Cd), mercury (Hg) and arsenic (As) represent the main food contaminants found in vegetables, cereals, seafood, dairy products and processed foods. The research shows that particular food products surpass WHO, FAO and FDA established safety thresholds which create serious long-term health problems including neurological damage and renal toxicity and immune system suppression and cancer development. The urgent need exists to protect children along with pregnant women and elderly individuals from exposure risks because these groups represent high-risk populations. The development of three key food detoxification technologies stands essential for risk reduction - electrochemical techniques and nanotech adsorption as well as biopolymer filtration systems.

Effective enforcement of safety regulations must happen simultaneously with increased monitoring and labeling programs to meet safety standards and stop industrial pollution. The worldwide standardization of food safety standards will improve multi-regional protection systems by creating stronger contamination control measures. The agricultural practice of bioremediation provides sustainable methods through phytoremediation along with microbial detoxification to minimize heavy metals in food crops. Future investigations should concentrate on executing these methods on a big scale together with superior risk assessment analytics to optimize food safety protocols. The combination of scientific advancement with policy solutions and public awareness programs will help lower heavy metal presence in food thus creating safer food supplies for up-and-coming generations.

References

1. Agency for Toxic Substances and Disease Registry (ATSDR). (2021). Toxicological profile for lead. U.S. Department of Health and Human Services.
2. Alkhanjaf, A. A. M., Sharma, S., Sharma, M., Kumar, R., Arora, N. K., Kumar, B., ... & Mukherjee, T. K. (2024). Microbial strategies for copper pollution remediation: Mechanistic insights and recent advances. *Environmental Pollution*, 346, 123588.
3. Alloway, B. J. (Ed.). (2012). *Heavy metals in soils: trace metals and metalloids in soils and their bioavailability* (Vol. 22). Springer Science & Business Media.
4. Biswas, R., Alam, M., Sarkar, A., Haque, M. I., Hasan, M. M., & Hoque, M. (2022). Application of nanotechnology in food: processing, preservation, packaging and safety assessment. *Heliyon*, 8(11).
5. Fan, D., He, W., Smith, W. N., Drury, C. F., Jiang, R., Grant, B. B., ... & Zou, G. (2022). Global evaluation of inhibitor impacts on ammonia and nitrous oxide emissions from agricultural soils: A meta-analysis. *Global Change Biology*, 28(17), 5121-5141.
6. Farooq, S., Dar, A. H., Dash, K. K., Srivastava, S., Pandey, V. K., Ayoub, W. S., ... & Kaur, M. (2023). Cold plasma treatment advancements in food processing and impact on the physiochemical characteristics of food products. *Food Science and Biotechnology*, 32(5), 621-638.
7. Ferraris, Q., Alcazar, A., & Qian, M. C. (2022). Profiling polar lipids in whey protein phospholipid concentrate by LC-HRMS/MS. *Food chemistry*, 374, 131495.
8. Food and Agriculture Organization (FAO). (2021). Heavy metals in food: Safety limits and risk assessment.
9. Järup, L. (2003). Hazards of heavy metal contamination. *British medical bulletin*, 68(1), 167-182.
10. Kabata-Pendias, A. (2000). *Trace elements in soils and plants*. CRC press.
11. Kavehei, E., Roberts, M. E., Cadier, C., Griffiths, M., Argent, S., Hamilton, D. P., ... & Adame, M. F. (2021). Nitrogen processing by treatment wetlands in a tropical catchment dominated by agricultural landuse. *Marine Pollution Bulletin*, 172, 112800.
12. Mahurpawar, M. (2015). Effects of heavy metals on human health. *Int J Res Granthaalayah*, 530(516), 1-7.
13. Marín Orega, C., Chinillach Andreu, M. C., Cerdà Cuéllar, M., Montoro Dasí, L., Sevilla Navarro, S., Ayats, T., ... & Vega García, S. Contamination of pig carcass with "Salmonella enterica" serovar "Typhimurium monophasic" variant 1, 4 [5], 12: i:-originates mainly in live animals. *Science of the Total Environment*, vol. 703 (10 feb. 2020).
14. Miri, M., Allahabadi, A., Ghaffari, H. R., Fathabadi, Z. A., Raisi, Z., Rezai, M., & Aval, M. Y. (2016). Ecological risk assessment of heavy metal (HM) pollution in the ambient air using a new bio-indicator. *Environmental science and pollution research*, 23, 14210-14220.
15. Okoye, N. C., & McMillin, G. A. (2021). Patterns of neonatal co-exposure to gabapentin and commonly abused drugs observed in umbilical cord tissue. *Journal of Analytical Toxicology*, 45(5), 506-512.
16. Prasad, B., Prasad, K. S., Dave, H., Das, A., Asodariya, G., Talati, N., ... & Kapse, S. (2022). Cumulative human exposure and environmental occurrence of phthalate esters: A global perspective. *Environmental Research*, 210, 112987.
17. Qin, G., Meng, Z., & Fu, Y. (2022). Drought and water-use efficiency are dominant environmental factors affecting greenness in the Yellow River Basin, China. *Science of the Total Environment*, 834, 155479.
18. Rong, L., Chen, X., Shen, M., Yang, J., Qi, X., Li, Y., & Xie, J. (2023). The application of 3D printing technology on starch-based product: A review. *Trends in Food Science & Technology*, 134, 149-161.
19. Sharma, A., Sharma, S., Sharma, S., Kumar, A., & Sharma, V. (2024). Phytoremediation: a clean and green approach for heavy metal remediation. *Microbial Applications for Environmental Sustainability*, 257-276.

20. Sharma, M., Sharma, S., Paavan, Gupta, M., Goyal, S., Talukder, D., ... & Baskoutas, S. (2024). Mechanisms of microbial resistance against cadmium—a review. *Journal of Environmental Health Science and Engineering*, 22(1), 13-30.
21. Sharma, S., Sharma, M., Kumar, R., Akhtar, M. S., Umar, A., Alkhanjaf, A. A. M., & Baskoutas, S. (2024). Recent advances and mechanisms of microbial bioremediation of nickel from wastewater. *Environmental Science and Pollution Research*, 31(28), 40224-40244.
22. Shetty, B. R., Jagadeesha, P. B., & Salmataj, S. A. (2025). Heavy metal contamination and its impact on the food chain: exposure, bioaccumulation, and risk assessment. *CyTA-Journal of Food*, 23(1), 2438726.
23. WHO. (2022). Guidelines for heavy metal limits in food safety. World Health Organization.
24. World Health Organization (WHO). (2020). Exposure to heavy metals and human health risks.
25. Yu, Y., Li, X., Hu, J., Zhang, X., Li, G., Ma, S., ... & An, T. (2021). Mechanisms of transplacental transport and barrier of polybrominated diphenyl ethers: A comprehensive human, Sprague-Dawley rat, BeWo cell and molecular docking study. *Environmental Pollution*, 270, 116091.
26. Zhou, Y., Lin, X., Xing, Y., Zhang, X., Lee, H. K., & Huang, Z. (2023). Per-and polyfluoroalkyl substances in personal hygiene products: the implications for human exposure and emission to the environment. *Environmental science & technology*, 57(23), 8484-8495.