Continental J. Applied Sciences
Osuagwu (2024) 19 (1): 106 – 125 Doi: 10.5281/zenodo.20583924

Heavy Metals in Food: Sources, Health Risks, Detection Technologies, and Sustainable Mitigation Strategies

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Abstract

Heavy metal contamination in food represents a global public health challenge that ranks among the top global food safety concerns. These inorganic contaminants are non-degradable once introduced into the environment, and they tend to bioaccumulate in food webs, ultimately posing a long-term threat to human health. Essential toxic heavy metals (e.g., Pb, Cd, Hg, As) can enter food systems through contaminated soils, irrigation water, industrial wastes and emissions, fertilizers, food processing methods, packaging materials, and transport practices. Long-term consumption has been shown to have effects on the nervous, cardiovascular, and renal systems, as well as on normal human development, and cause several cancers. Many studies are showing that rice, vegetables, seafood, cocoa, spices, and baby food products are key sources of heavy metals. This paper will review the sources of heavy metal contamination, exposure pathways, effects on human health, and the analysis and control measures of heavy metal contamination. Special focus will be given to those sustainable approaches that will control contamination without undermining the goals of global food security and public health.

Keywords: Food sources, food safety, food security, heavy metals, public health, framework, nanosensor

Received: 29 August 2024 Accepted: 18 October 2024

Citation: Osuagwu, I.M. (2024). Heavy Metals in Food: Sources, Health Risks, Detection Technologies, and Sustainable Mitigation Strategies. Continental J. Applied Sciences, 19(1), 106–125. Doi: 10.5281/zenodo.20583924

1. Introduction

Food safety is an integral part of sustainable development and public health. While microorganisms have long been identified as major sources of contamination, non-biological contaminations, primarily heavy metals, are increasingly gaining global attention as food quality and public health concerns (Gizaw, 1019; Tibebu et al., 2024). These heavy metals have high density and high atomic weight. Some metals like iron (Fe), zinc (Zn), copper (Cu), and manganese (Mn) are vital for human health in trace quantities (WHO, 2003). Other metals, however, like lead (Pb), mercury (Hg), arsenic (As), and cadmium (Cd) are non-biological and even a small dose has significant toxicity to humans.

Globalization, industrialization, urbanization, mining, farming intensification, and pollution have all contributed to widespread contamination of food by heavy metals. Unlike organic pollutants, heavy metals are persistent contaminants; they are neither degradable nor bio-transformable by living organisms and thus, can contaminate land, water, and air for long periods (Zhang et al., 2023). Through bioaccumulation in plants, animals, and even in aquatic species, these metals get transferred into food webs and hence the food chain, where they accumulate and result in human exposure through diet. The impact of heavy metals is a serious concern due to unavoidable food consumption by humans, and vulnerable groups like babies and pregnant women may be more at risk due to their physiological state and dietary needs (Olatona et al., 2023; Ambroży et al., 2023). Many international reviews have confirmed dietary intake to be one of the primary routes of toxic metal exposure globally.

Research Gaps

Despite the advancements made in understanding heavy metal contamination in food systems, certain knowledge gaps persist. Firstly, research often concentrates on individual metals, ignoring the complexity of simultaneous human exposure to multiple metals from varied food sources. The combined and synergistic effects of such exposures remain inadequately explored (Zhao et al., 2024). Secondly, the spatial variation of contamination levels has been unevenly studied. The majority of existing literature originates from North America, Europe, and Asia, leaving a substantial gap in the data from low and middle-income countries, especially those in Africa, as surveillance systems in these regions are underdeveloped. Therefore, data on contamination levels in a wide variety of food commodities are lacking, which hinders robust risk assessment and effective policy making (FAO/WHO, 2024). Thirdly, the emphasis on simply quantifying metal levels overlooks factors that influence their bioavailability and bioaccessibility. Metals in food do not necessarily mean they are readily absorbed by the human body. The effects of food composition, cooking techniques, and interaction with other nutrients need further investigation.

Fourthly, the link between climate change and heavy metals is still poorly understood. Shifting temperature and rainfall patterns, along with increased flooding or droughts, could alter heavy metal mobility, plant uptake, and contamination pathways in agricultural settings (Xiao et al., 2024). This is an area that warrants much more research. Another overlooked area is the integration of emerging technologies like artificial intelligence (AI), machine learning, blockchain for traceability, remote sensing, and Internet-of-Things (IoT) monitoring systems into food safety management systems. Monitoring tends to be reactive rather than predictive. The viability and effectiveness of certain mitigation approaches, such as phytoremediation, use of biochar, and soil amendments, are still relatively unproven under long-term field conditions. Much of the research to date has been conducted under controlled laboratory conditions, so translating these results

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into real-world applications has its challenges (American Society for Microbiology, 1998). Finally, there are limitations in translating global guidelines into practice. Although international organizations establish maximum permissible levels for metals in foods, national enforcement capacities vary enormously, with insufficient lab infrastructure, trained personnel, and funding leading to ineffective surveillance and compliance mechanisms.

Justification of the Review

Food consumption is a necessary daily activity that makes humans unavoidably exposed to the pervasive global threat posed by heavy metal contamination. Unlike organic compounds, heavy metals cannot be broken down and can persist in the environment and food chains for years. This persistent bioaccumulation poses serious health risks as foods such as cereals, rice, vegetables, fish, and cocoa are increasingly becoming significant carriers of heavy metals (Sarker et al., 2022). As the global food supply continues to expand due to a growing human population, urbanization, and intensive agriculture, the transfer of metal contaminants throughout the food chain continues to intensify. Modern agricultural practices, increased mining activities, industrialization, the use of wastewater in irrigation and land application, combined with overall environmental deterioration, have exacerbated metal contamination.

Vulnerable groups, including babies, the elderly, and pregnant women, are most at risk from the health impacts due to the increased physiological sensitivity they possess (Makinde et al., 2022). This review is therefore essential for providing a coherent summary of current research relating to the sources, pathways, health impacts, and management of heavy metal contamination in food, thereby serving as an evidence base for effective policy development, improved food safety practices, and achievement of sustainable development goals focusing on food security and health. This review supports the growing global recognition of the need for interdisciplinary efforts to address challenges at the confluence of agriculture, food, environment, and public health. By pinpointing existing knowledge gaps and areas of future inquiry, the paper provides guidance for researchers, policymakers, and practitioners to pursue a more efficient and sustainable approach to combatting heavy metal contamination.

Aim of the Study

This study aims to thoroughly investigate the occurrence, sources, health implications, analytical techniques, legal frameworks, and sustainable mitigation strategies of heavy metal contamination in food systems.

Objectives of the Study

1. To document the major heavy metals detected in foods and pinpoint the source(s) of contamination.
2. To characterize the various natural and anthropogenically induced pathways by which heavy metals gain access to the food chain.
3. To appraise the human health risk associated with dietary intake of toxic metals.

4. To review the analytical methods that are presently used for identifying heavy metals in food products.
5. To assess existing national and international regulations guiding heavy metal contamination in foods.
6. To look into promising technological, agricultural, and food processing techniques that will mitigate food contamination.
7. To highlight existing knowledge gaps and outline future research directions needed for the control of food contamination and promotion of sustainable food systems.

2. Major Heavy Metals Found in Food

Table 1. Common Heavy Metals in Food and Their Health Effects

Heavy Metal	Major Food Sources	Primary Health Effects
Lead (Pb)	Vegetables, spices, cereals, and chocolate	Neurotoxicity, developmental disorders
Cadmium (Cd)	Rice, cereals, leafy vegetables, cocoa	Kidney damage, bone disorders
Mercury (Hg)	Fish, shellfish, seafood	Nervous system toxicity
Arsenic (As)	Rice, groundwater-irrigated crops, seafood	Cancer, cardiovascular diseases
Chromium (Cr VI)	Industrially contaminated foods	Carcinogenic effects
Nickel (Ni)	Legumes, grains, processed foods	Allergic reactions, respiratory effects

Lead (Pb)

As a result of the widespread presence of lead and its serious health effects, it has been the subject of a multitude of studies. Unlike essential trace elements, lead has no positive roles in the human body. Exposure to lead in the diet occurs as a consequence of pollution, mostly as a result of man's activities and waste products; activities include mining and smelting, battery manufacturing and recycling, use of fossil fuels, and landfill disposal (Bouida et al., 2022). Soils situated near highways and industrial or urban areas are sometimes enriched with high levels of lead, which plants take up and absorb. Cereals, fruits, vegetables, spices, and food products may contain levels of lead resulting from uptake from soils or as atmospheric deposits (on their surfaces). Green vegetables, in particular, have a large surface area that facilitates the deposition of airborne particulate matter, and in some situations, food products may take up the metal from food packaging, storage, and cooking utensils. Children, more so than any other sector of the population, are affected by lead. Low levels of exposure have been found to retard intellectual development, decrease IQ, impair memory, and alter behavioral characteristics. All studies indicate that there is no completely safe level of exposure in children (CDC, 2024; WHO, 2024; IHME, 2024). The long-term effects in adults have been linked with the presence of cardiovascular disease, hypertension, renal damage, reproductive problems, etc. Lead Toxicity occurs via various mechanisms that interfere with normal cell functions, such as blocking calcium channels and disturbing normal transmission and storage of neurotransmitters. This accumulation occurs over the years in the bone and other soft tissues, leading to potentially life-long ill health following continuous dietary exposure even at low daily doses. Constant monitoring of lead levels in food has thus become an issue of global concern.

Cadmium (Cd)
Cadmium (Cd) is a highly toxic metal that commonly contaminates crops. The main source of cadmium pollution is mining, smelting, and refining of metal ores, and its emissions are released from industries as well as the use of sewage sludge and phosphate fertilizers in agriculture. Long-term use of fertilizers with phosphate, which also often contains traces of cadmium, will increase the concentration of this element in the soil, which will then be absorbed by the plants (Zhao et al., 2024). Cadmium is present in many types of food products; commonly reported food commodities containing cadmium include rice, cereals, leafy vegetables, potatoes, and cocoa products. Cultivated systems are susceptible, such as the system of growing rice, which is commonly found with saturated soil; flooding tends to release cadmium from soils and increase the mobility of metals. Certain crop varieties are more prone to cadmium uptake, and this is therefore an important aspect of the cultivation process. Toxicologically, cadmium represents a problem because once assimilated, cadmium binds tightly to proteins and therefore can remain in the organism for decades, primarily within the liver and kidney cells. Impaired renal function can occur after a prolonged accumulation, and this can reduce the kidney's filtering capacity. The cadmium binds to specific molecules, blocking and destroying calcium uptake and thus causing weakening of bones, with the possible development of osteoporosis. The ability to stimulate the production of reactive oxygen species makes cadmium a significant threat to cellular integrity. It has been associated with cardiovascular and immune system damage and cancer risk. As most non-smokers are exposed to cadmium by the ingestion of food, controlling the sources of food contamination is imperative.

Mercury (Hg)
Mercury (Hg) is a ubiquitous naturally occurring element, but in metallic forms it is non-toxic; it becomes extremely toxic once converted into methylmercury by aquatic microorganisms in rivers and other water bodies. Fish and seafood become a primary source of mercury exposure for humans (EFSA, 2024). Sources of mercury contamination include the release from industries, use of fossil fuels, artisanal mining of gold, and waste incineration. Deposits can make their way into rivers, lakes, and oceans, where mercury then bioaccumulates through the food chain. Fish from the higher trophic levels, such as swordfish, shark, and king mackerel, contain higher concentrations of methylmercury as they consume contaminated fish from lower levels. A population with high fish consumption rates may consequently have high mercury exposure levels. Methylmercury easily passes the blood-brain barrier and is therefore able to damage the nervous system. Fetal exposure to methylmercury has been found to cause brain development defects, decreased cognition and communication, and problems with motor function and balance. Symptoms in adults are tremors, memory loss, poor coordination, and sensory impairment.

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Mercury also generates oxidative stress in the body, and this damage to cardiovascular and immune systems. Damage to the nervous system can be irreversible, and therefore, monitoring of intake levels in food has become vital, particularly for pregnant women and infants.

Arsenic (As)
Arsenic (As) has gained prominence as a prevalent contaminant in the world's food supply owing to its widespread occurrence and well-established carcinogenicity. While naturally occurring in the earth's crust, contamination by arsenic can occur from man-made factors such as mining operations, industrial processes, and the extraction of underground water (Xing et al., 2024). The most significant dietary sources of inorganic arsenic are found in many parts of the world. Rice cultivations typically take place in inundated conditions, and it has been observed that this increases the arsenic mobility from the soil and from underground water sources of irrigation to the rice plant. People who consume large quantities of rice in their daily diet are exposed to more arsenic than others. There are two forms of arsenic, inorganic and organic, and it is inorganic arsenic that is more dangerous. Chronic exposure of arsenic to arsenic has been associated with the occurrence of various cancers such as skin cancer, bladder cancer, lung cancer, kidney cancer, and liver cancer. Besides carcinogenicity, it is also known to be linked to cardiovascular diseases, diabetes, immune system dysfunctions, and effects on childbearing. The toxic effects of arsenic are attributed to several factors, such as obstruction of cell respiration processes and the activity of enzymes, and induction of oxidative stress. Exposure to this element is also suspected to lead to damage to DNA, as well as epigenetic modification. Research on arsenic has lately focused on infant formulas, cereals, baby foods, and rice-based products as they were found to be relatively higher in arsenic content, prompting new limitations on the acceptable level of this contaminant in foodstuffs.

Chromium (VI)
There are different oxidation states of Chromium, Hexavalent Chromium [Cr(VI)] is of paramount importance in terms of toxicity. Unlike Cr(III), which is considered an essential nutrient used for glucose metabolism, Cr(VI) is a potent oxidizing agent and thus has a highly toxic nature (DesMarais and Costa, 2019). Contamination of food products by Cr(VI) most commonly arises from industrial waste generated by the production of various things, ranging from electroplating materials, leather, clothes (dyeing of clothes), pigments, metal surface finishing, etc. Waste can contaminate land and eventually water that will be used for the irrigation of crops. Crops can absorb chromium from the contaminated soil through their roots. While not at high levels as lead or cadmium, continuous ingestion can still be a concern due to the carcinogenic nature of the metal. Primarily, it exerts its toxic effect by creating reactive species in the cells of living organisms, thus causing damage to cells, proteins, and DNA. Long-term human exposure has been linked to renal and cardiovascular damage and to a higher risk of developing tumors. Cr(VI) compounds are classified as carcinogenic for humans by the International Agency for Research on Cancer (IARC), and hence, stringent industrial waste management processes are required to avoid widespread environmental and food contamination.

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Nickel (Ni)

Nickel is prevalent throughout the environment and can be found in soils, water sources, and bedrock. Industrial processes, combustion of fossil fuels, waste disposal, and the manufacture of metals release Nickel into the environment (Zhang et al., 2024). Nutrients such as leguminous products, cereal crops, nuts, vegetables, and processed foods all contain Nickel levels that can be measured. While it is known that low levels are not harmful, it can be a hazard when amounts are higher. Sources of contamination of food with Nickel can be from absorption from agricultural soils, machinery used in food production, and packaging materials used to store food. Conditions like acidic soil conditions cause increased absorption of Nickel from the soil.

Skin conditions associated with Nickel contamination can be of a form called allergic contact dermatitis, where people with an allergy to Nickel experience reactions when it is consumed. It is suggested that in large amounts, nickel can be bad for other areas like the respiratory system, cardiovascular system, and kidney functions. Cellular effects are shown as Nickel causing cellular oxidative stress and inflammatory responses, and as studies show that repeated exposures can alter DNA and the signaling pathways used in the cells. Nickel toxicity does not appear as severe as that associated with Lead, Cadmium, Mercury, or Arsenic, and it will need monitoring due to its abundance.

3. Sources of Heavy Metal Contamination in Food

3.1 Agriculture

Agricultural sources make a considerable contribution to the concentration of heavy metals found in foods. Repeated exposure to contaminated irrigation water sources, sewage sludge, pesticides, and phosphate fertilizers results in increased concentrations of metals in soils used for agriculture.

Fig. 1. Schematic diagram of heavy metal pathways through the environment to the human food chain. The sources include industrial emissions that represent the largest source of anthropogenic heavy metals. Metals from mining, smelting, manufacturing processes, and burning waste are released into the environment in industrial emissions. Metals enter the atmosphere and move over large areas by the action of wind before settling on land and in surface water systems. It explains why far away areas far from industrial development can have elevated levels. Heavy metals enter the soil system as they deposit onto soil, rivers, lakes, and ground water system. Soil acts both as a sink and source of heavy metal contamination because the majority of heavy metals don't break down in the soil even after decades of contamination. Heavy metals enter crop plants by root absorption from the contaminated soils and irrigation water. By foliar deposition, vegetables may have a large deposit from industrial emissions, particularly leafy vegetables. Rivers, lakes, and ponds represent the second most critical pathway for entry. The river and lake contain many heavy metals which are taken by algae, planktons, plunktons and other aquatic living beings. Heavy metals become bioaccumulated and biomagnified. In livestock, it may lead to metals entering meat, milk, and other products by consuming polluted feed and grass or polluted drinking water, and in fish and other aquatic animals through contamination in the

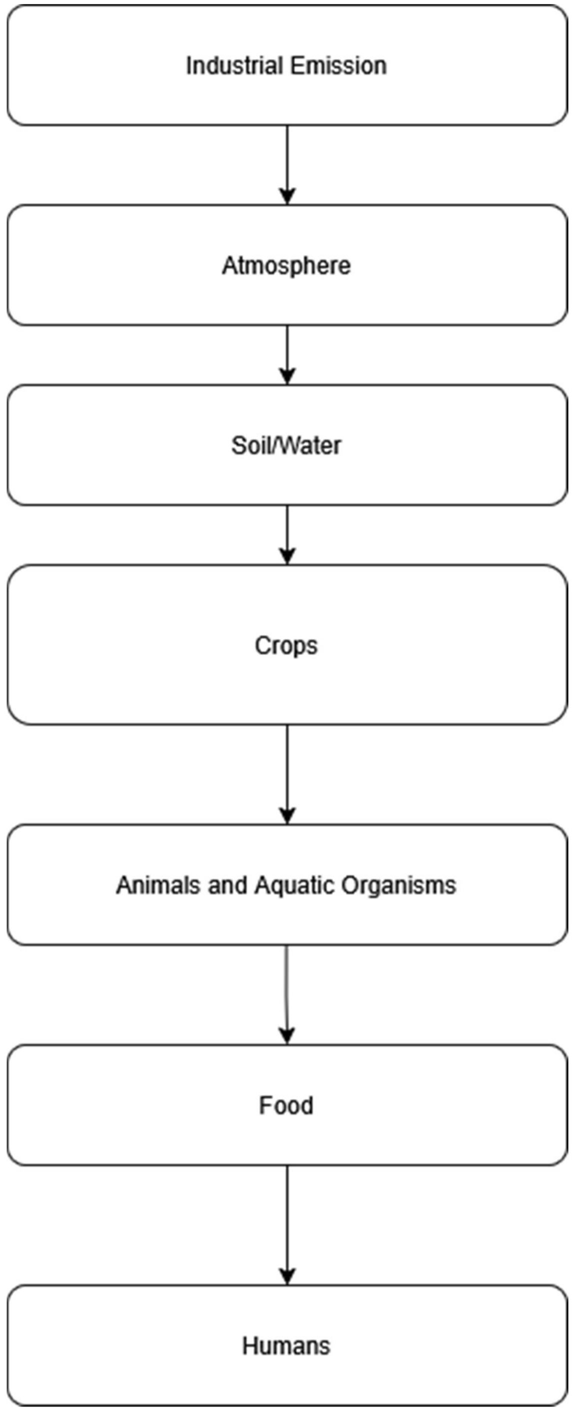

Figure 1. Pathways of Heavy Metals into Food Systems

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aquatic system (Afzal and Mahreen, 2024). Processing and packaging can also cause a source of contamination through industrial machines, storage places, containers, and materials. Humans are finally exposed to heavy metals through eating contaminated food. Unlike to occupational exposure, dietary exposure applies to almost all population groups and to people all lifelong. It emphasizes that the contamination of heavy metals in the food supply is no single point source but an integrated system between the environment, food, and health.

3.2 Industry Activities.
Mining, smelting, manufacture and disposal of waste contribute heavy metals to the environment. High concentrations of toxic metals is found in agricultural land near an industrial zone.

3.3 Transportation Activities.
Vehicle exhaust gases, wear of brakes and friction with tyres will put heavy metals (lead, zinc, copper, and cadmium etc) into the roadside environment. Vegetables grown alongside highways show high concentration.

3.4 Food Processing and Packaging.
Some processing equipment, containers, and packing materials can be responsible for the addition of metal to food. Recent studies report that contamination by migrating substances in food contact material is becoming an increasing concern.

4. Heavy Metals in Different Food Categories

Table 2. Food Categories Commonly Associated with Heavy Metal Contamination

Food Category	Typical Metals Detected
Rice	Arsenic, Cadmium
Leafy Vegetables	Lead, Cadmium
Seafood	Mercury, Arsenic
Cocoa Products	Cadmium, Lead
Spices	Lead, Arsenic
Infant Foods	Arsenic, Lead, Cadmium

Table 2 shows the important food categories responsible for major food chain exposure to heavy metals. It is important to note from the table that there is no restricted food type contaminated with metals, but diverse types of food commodities are being consumed regularly.

Rice is another primary dietary source of arsenic and cadmium. Because rice is commonly grown under flooded conditions, the bioavailability and plant uptake of arsenic are increased. The rice-consuming communities could be exposed to a higher level. Leafy vegetables, like spinach, lettuce, cabbage, etc., are common food sources for the accumulation of lead and cadmium. This

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is because they can easily accumulate these metals from the atmosphere due to the large surface area of the leaves and from root uptakes.

Mercury exposure at high levels comes from consuming fish. This is due to biomagnification within the aquatic food chain, where the bigger fishes consuming smaller fish will accumulate more mercury. Cocoa products are another source of cadmium and lead identified in the table. It varies in dependence upon factors such as soil characteristics, farming system, and post-harvest management in the cocoa-producing areas.

The potential role of spices should be highlighted, because contamination could be caused through all stages, including agricultural planting, growing, harvesting, drying, and food processing and storage. Although these products are consumed in relatively small amounts, the accumulation of high concentrations of metals can also cause exposure through their diets. Infant food should be paid attention to because infants are more susceptible physically than adults to the harmful effects. Low exposure levels can be significant for development and health. The table clearly indicates that different foods are contaminated by different groups of metals; this will differ according to the environmental conditions, agricultural system, and characteristics of the living things.

One of the key findings is that foods of one category could simultaneously be a carrier for two or more metals. The implication can be the additive/synergistic toxic effects of these metals toward human beings (Jaishankar et al., 2014). The variety of food categories implies a wide coverage of monitoring programs needed, which include plant-based and animal-based food. In general, Table 2 illustrates that heavy metal exposure by diet is determined by variety of sources related to the production, processing, and consumption.

5. Hazards to health

Oxidative stress, enzyme inhibition, damage to DNA, and interference with cell signaling pathways explain how heavy metals are able to harm the cell.

Table 3. Health Effects of Major Heavy Metals

Organ System	Potential Effects
Nervous System	Cognitive dysfunction, memory impairment
Cardiovascular System	Hypertension, cardiac illness
Renal System	Kidney malfunction
Skeletal System	Bone demineralization
Reproductive System	Reduced fertility
Immune System	Suppressed immunity
Respiratory System	Damage to the lungs
Cancer Risk	Carcinogenesis enhancement

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In Table 3, there is an overview of the broad range of effects heavy metals can have on health. As can be seen from this table, toxic metals can have an effect on nearly every major system of the human body.

The nervous system is one of the most susceptible targets. Lead and mercury are especially neurotoxic and cause impairment to memorization, thinking, learning ability, and behavior development (Schneider, 2023). Cardiovascular effects of EO exposure have included hypertension, arterial dysfunction, and an increased risk of cardiac disease. Recently, chronic exposure to systemic inflammation and oxidative stress has been suggested as a possible pathway leading to cardiovascular risk.

Cadmium and several other metals, for example, are known to prefer accumulation in the kidneys. Longer-term exposure may therefore facilitate compromised filtration and diminish renal function. Skeletal problems also have an association with heavy metal pollution. Cadmium impacts calcium metabolism, which can result in loss of minerals from bones.

Reproductive toxicology is yet another significant issue. It has been associated with decreases in fertility, negative effects on pregnancy and fetal development as well as endocrine dysruption.

Chronic exposure can lead to degradation of the immune system (Ebrahimi et al., 2020). Heavy metals can negatively impact immune responses, leading to a reduction in the ability of the immune system to fight off infections and inflammatory diseases. Not all respiratory effects occur only by inhalation exposure. It can also be contributed indirectly due to dietary exposure, such as systemic toxicity.

The table demonstrates the carcinogenicity of specific metals, especially arsenic and chromium(VI) metal compounds, where prolonged exposure increases the probability of various types of cancer. One important consequence of this is that the concern about health effects is that the effects can take a long time to develop and may be years away from being detected. This is because metals tend to build up over time in tissue. Thus, this table would also support the need for preventive techniques, ongoing food surveillance, dose estimation, and approaches in public health strategies to reduce toxic metal dietary consumption.

6. Analytical Techniques for Detection

In contemporary food safety laboratories, there are other methods for heavy metal determination.

Table 4. Analytical Methods Used in Heavy Metal Detection

Technique	Advantages	Limitations
Atomic Absorption Spectroscopy (AAS)	Economical Low sensitivity	Economical Low sensitivity
ICP-OES	Multi-element Moderate price	Multi-element Moderate price
ICP-MS	Ultra-trace Very expensive	Ultra-trace Very expensive
XRF Spectroscopy	Fast screening Low precision	Fast screening Low precision
Electrochemical Sensors	Field portable Calibration is an issue	Field portable Calibration is an issue

The latest progress in sensor technologies, nanomaterials, and artificial intelligence can provide improved ability in fast detection and surveillance.

7. Regulatory Frameworks

Regulatory frameworks are crucial for public health protection against heavy metal contamination. International organizations have developed standards aimed at reducing dietary exposure and establishing a coherent approach to food safety globally.

The main framework is provided by the Codex Alimentarius Commission (jointly administered by the Food and Agriculture Organization (FAO) and the World Health Organization (WHO)). Codex standards define maximum permitted concentrations for contaminants in food items and support international trade. Risk assessments performed by the Joint FAO/WHO Expert Committee on Food Additives form the basis for most regulations. In the EU, comprehensive evaluations of food contaminants and recommended safe limits are conducted by the European Food Safety Authority (EFSA).

Most countries have formulated their own national food safety regulations that are broadly based on Codex recommendations but consider specific local diets and environments. Typical components of regulatory frameworks include monitoring, laboratory accreditation, inspection programs, risk communication, and enforcement activities. Maximum Residue Levels (MRLs) are regularly updated with new scientific information in response to emerging concerns. Controls over food imports and exports are another regulatory aspect that helps prevent the entry of contaminated food products into the country.

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Traceability requirements are also increasingly important and allow for the tracking of contaminants and the identification of their source, facilitating the control process. Challenges remain concerning the implementation of the regulatory framework, especially in developing countries where financial and laboratory resources may be limited. Strengthening institutional capacity, developing monitoring networks, enhancing laboratory capabilities, and fostering cooperation between all relevant stakeholders will be critical. Future regulatory frameworks are expected to use digital technologies to achieve better food safety control.

8. Sustainable Mitigation Strategies

Agriculture

Agricultural interventions are the first line of defense against the introduction of heavy metals into food products because contamination often occurs on the farm. It is important to test soils for metal content before crop planting to identify contamination hot spots. Soil characteristics will influence the choice of crops and methods used.

The use of clean water for irrigation is vital as metals can easily enter the soil through groundwater, wastewater, and surface water. Regular testing of the water supply is beneficial to minimize the risks.

The choice of crop is another way of managing contamination. Different plant varieties accumulate metals to different extents. Breeding programs are developing crop varieties with a reduced ability to take up heavy metals.

Some soil amendments (biochar, compost, lime, organic matter) can immobilize metals in the soil, and their bioavailability decreases. The use of biochar in particular is getting a lot of attention, as it can both absorb heavy metals and improve soil quality (Saravanan et al., 2025).

Phytoremediation uses plants that accumulate high levels of contaminants and can be harvested. The plants then remove the pollutants from the soil over time.

Conservation agriculture (minimal cultivation, cover crops) will improve soil structure and reduce transport of contaminants.

Precision agriculture techniques that allow fine-tuned fertilizer management can reduce metal contamination from this source if not well-managed (e.g., phosphates can contain cadmium impurities).

Buffer zones established around agricultural lands and between agricultural land and pollution sources (e.g., industries) will help limit the atmospheric deposition of contaminants on farmland.

Farmer education also helps control contamination.
These agricultural interventions help us achieve sustainable food production while reducing both contamination and health risks.

Food Processing
Food processing techniques can also be used to reduce metal contaminants in food. There are conventional and newer food processing methods that can significantly lower the concentration of these metals.

Washing: one of the simplest methods that removes contamination from the surface of the food. Depends on how long the food is washed, the quality of the water, and the characteristics of the food.

Peeling: effective because many metals tend to accumulate in the outer layers of fruits, vegetables and tubers.

Blanching and boiling: have been shown to reduce levels of some metals. Metals can leach into the cooking water; discard it after cooking to improve the result.

Cooking of rice: studies have found that soaking rice prior to cooking and using plenty of water can greatly reduce the levels of arsenic in rice (Zhang et al., 2024).

Fermentation: changes the characteristics of the food and the metal. Microorganisms involved may either bind to or break down the metal, reducing its ability to be absorbed.

Milling and polishing: this technique removes outer grain layers. Excessive milling is detrimental to nutrient content.

Advanced technologies such as membrane filtration, adsorption technologies, and separation techniques can remove metals from food and beverages.

Use of adsorbent materials such as activated carbon, biochar-based materials, or nanomaterials for the removal of metals in food processing.

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Quality assurance system like Hazard Analysis and Critical Control Points (HACCP) are useful in identifying the potential for contamination in a food processing system.

Food packaging is another step towards preventing contamination.

Technological Innovations

Technological innovation is transforming the monitoring and management of heavy metal contamination in food systems around the world. Advanced analytical technologies improve the sensitivity, speed, and reliability of metal detection.

Portable sensors are among the most promising technologies. Portable analytical devices allow for real-time and rapid analysis of contaminants on-site, overcoming the need for expensive lab equipment.

Nanotechnology is used to enhance sensor sensitivity and selectivity of nanosensors. Nanosensors are able to detect trace levels of metals in a sensitive manner.

Artificial intelligence and machine learning are playing an increasingly significant role in forecasting food contamination and predicting risks before any real contamination has occurred. They are trained with a large amount of data on contamination patterns to forecast locations where contamination is likely to happen.

Remote sensing technologies provide information on soil characteristics and can contribute to predicting mobility and concentration of heavy metals. Satellite imagery can help in mapping contamination and planning land uses.

Internet of Things (IoT) technology allow real-time monitoring of contamination in agricultural fields and at all stages of food production.

Blockchain technology has the potential to enhance food traceability. Digital records will improve the visibility of the supply chain and help identify the source of contamination quickly.

Geographic Information Systems (GIS) allow mapping of contaminated areas for a better understanding of the dynamics of contamination and more effective resource allocation.

High-resolution analytical instruments such as Inductively Coupled Plasma - Mass Spectrometry (ICP-MS) improve our capability of detection to very low concentrations of contaminants.

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Lab-on-a-chip systems could offer a cost-effective method of rapid screening for contaminants in resource-limited settings.

Digital twin technology might be used in the future for modeling and simulating contaminant pathways in the food supply chain.

9. Future Research Priorities in Food System Heavy Metal Contamination

Concerns surrounding food safety, environmental pollution, and human health are increasing, and there is a growing need for scientific research focused on several areas of study. While progress has been made in elucidating the occurrence and impacts of heavy metals on food, critical gaps in knowledge exist that require attention in order to develop sound control strategies and sustainable food production systems.

Developing affordable and rapid detection methods remains a research priority. While ICP-MS and AAS offer highly accurate analyses, these techniques are expensive, labor-intensive, and generally unavailable in most developing countries. Innovative research in portable sensors, biosensors, and smartphone-aided detectors that are applicable at farms, markets, and during processing is critical to permit continuous monitoring of contaminants and facilitate on-the-spot testing (Boodhoo et al., 2024).

More information is needed about the simultaneous impacts of multiple heavy metals on food. The vast majority of toxicological studies evaluate the impact of individual metals alone, but exposure to various contaminant mixtures typically occurs through the diet, and the interactions among various metals like lead, cadmium, mercury, arsenic, nickel, and chromium can have synergistic, additive, or antagonistic effects. There are several long-term epidemiological and mechanistic studies required to ascertain these impacts (Boodhoo et al., 2024). Further studies are needed to understand the bioavailability and bioaccessibility of metals. The measured concentration of total metal may not correspond to actual human exposure, as metal absorption is affected by food properties, culinary practices, nutritional status of the consumers and gastrointestinal conditions. Future research should explore how various food components, such as fibers, proteins, vitamins, and minerals, can influence metal absorption and toxicity.

Future work is also urgently needed to understand how the impacts of global climate change, rising temperatures, altering rainfall patterns, flooding, droughts, and soil degradation may affect the distribution, transport, and plant uptake of heavy metals. Predictions regarding potential impacts on future food contamination require this critical data, which will permit development of robust agricultural management systems adapted to changing climates (Gomez-Zavaglia et al., 2020). Advanced data analytics and AI have a great potential to manage and predict contamination and they are of increased research interest. Machine learning tools capable of forecasting hotspots of contamination, identifying groups at risk and enabling decision-making are needed, and AI integration with GIS, remote sensing and monitoring stations can help identify vulnerable populations and target interventions (Cuadros et al., 2024).

ISSN: 1597 – 9928. Science and Education Development Inst., Nigeria

Another promising research area is the behavior of heavy metals within food systems under the presence of emerging contaminants (microplastics, pesticides, nanocoated particles, pharmaceutical compounds etc.). These emerging substances have poorly defined effects on mobility, bioavailability and toxicity of heavy metals. Finally, additional research into promising innovative remediation technologies (biochar, phytoremediation, bioremediation and nanotechnological approaches) are needed beyond the lab and pilot scale in various agricultural settings to confirm their real-world application. Identification of crop varieties tolerant to heavy metal accumulation through advanced genetic technologies can be another avenue to produce safer food in areas prone to heavy metal contamination. Cooking, fermentation, processing and packaging methods require continued assessment in terms of their impact on food safety for heavy metals and further human dietary exposure studies focused on vulnerable populations and long-term, longitudinal assessments of associated diseases are essential. Finally, policy research designed to evaluate regulatory programs and enhance the monitoring, risk communication, enforcement, and risk assessment practices to be incorporated into stronger governance frameworks is necessary. This requires an interdisciplinary research approach across agricultural, environmental, human health and social sciences to achieve safe and sustainable food systems.

Conclusion

Heavy metal contamination of foods represents a serious and persistent challenge for food safety, public health and the environment on a global scale. Persistent accumulation of toxic metals in food systems is likely to increase with intensification of industrial, agricultural and urban activities, alongside ongoing environmental degradation. Current data confirms that several common food groups such as rice, vegetables, sea foods, spices, cocoa products etc, are major sources of dietary exposure to heavy metals. While monitoring and regulatory controls have been significantly improved, a knowledge gap remains in terms of contaminant communication and effective control measures, warranting research. Sustainable food production practices, affordable testing technology, rigorous regulatory compliance and public education should be considered as the future research priorities for a safe global food system, a healthier humanity and the achievement of global sustainability targets.

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