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Pathways and Mechanisms of Heavy Metal Toxicity in Food Chains: A Systematic Literature Review

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Abstract

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Heavy metal contamination in food systems represents a significant public health concern due to its persistence, bioaccumulation, and potential toxic effects on humans. This study aims to evaluate heavy metal exposure from a contemporary risk perspective by synthesizing recent evidence on contamination sources, food chain transfer, toxicological mechanisms, and health implications. A qualitative Systematic Literature Review (SLR) approach was applied to analyze peer-reviewed studies published between 2020 and 2025. The findings indicate that heavy metals enter food systems through environmental pollution and agricultural practices, followed by accumulation through food chains and continuous dietary exposure. Toxic effects are primarily associated with oxidative stress, enzymatic disruption, and metabolic interference, contributing to chronic health outcomes. The study highlights limitations in conventional risk assessment approaches and emphasizes the need for more integrative frameworks that consider cumulative exposure and environmental variability. These insights support the development of improved food safety strategies and risk evaluation models.

1. Introduction

Heavy metal contamination in food systems remains a significant global concern due to its persistence, bioaccumulative nature, and potential to cause adverse health effects in humans. These contaminants, including lead, cadmium, mercury, and arsenic, are introduced into food systems through multiple pathways such as industrial emissions, agricultural practices, and environmental pollution (Angon et al., 2024; Thompson & Darwish, 2019). Because heavy metals are non-biodegradable, they can persist in environmental media and accumulate within biological systems over time, increasing the risk of chronic exposure. Recent studies have highlighted that dietary intake represents one of the primary routes of human exposure, particularly through commonly consumed foods such as vegetables, grains, and seafood (Mititelu et al., 2025). This widespread presence across food categories underscores the importance of understanding both contamination pathways and long-term exposure dynamics. As environmental pressures and food production systems continue to evolve, the complexity of heavy metal distribution within food systems is expected to increase.

The health implications of heavy metal exposure are closely linked to their toxicological properties and interactions within biological systems. Heavy metals are known to induce a range of adverse effects, including neurotoxicity, carcinogenicity, and organ damage, depending on exposure level and duration (Jomova et al., 2025). At the cellular level, many metals exert toxicity through mechanisms such as oxidative stress, disruption of enzymatic activity, and interference with essential metabolic processes. These mechanisms contribute to the development of chronic diseases and highlight the importance of understanding the biological pathways involved. In addition, emerging evidence suggests that even low-level exposure may have cumulative effects when it occurs over extended periods. This challenges traditional assumptions about safe exposure thresholds and calls for more refined approaches to risk evaluation.

In addition to biological effects, the distribution of heavy metals in food systems is influenced by environmental and agricultural conditions that determine their uptake and accumulation. Soil contamination, irrigation practices, and the use of fertilizers and wastewater significantly affect the transfer of metals into crops and food products (Kaur et al., 2025). Certain food categories, such as spices and herbs, have also been identified as potential sources of elevated exposure due to their capacity to accumulate contaminants during growth and processing (Alawadhi et al., 2024). These variations indicate that contamination is not uniform but depends on geographic, environmental, and production-related factors. Such variability complicates efforts to assess exposure and requires more context-specific evaluation strategies. Understanding these differences is essential for identifying high-risk food sources and improving monitoring systems.

Despite extensive research on heavy metal contamination, current risk assessment approaches often focus on individual metals under controlled conditions, which may not accurately reflect real-world exposure scenarios. In practice, individuals are exposed to multiple sources of contamination over time, and these exposures may interact in ways that are not fully captured by traditional models. Hou et al. (2020) emphasize that addressing food safety challenges requires integrating environmental processes with food production systems. Furthermore, the increasing complexity of global food supply chains introduces additional challenges in monitoring contamination and ensuring safety. These limitations suggest that existing frameworks may underestimate the true risk associated with dietary exposure to heavy metals. Therefore, there is a need to adopt more comprehensive and integrative approaches to risk assessment.

This study aims to evaluate heavy metal exposure in food systems from a contemporary risk perspective by synthesizing recent evidence on contamination sources, exposure pathways, toxicological mechanisms, and health implications. Using a qualitative Systematic Literature Review (SLR) approach, this study seeks to provide a more integrated understanding of how heavy metals affect human health within modern food systems. The analysis emphasizes the importance of considering cumulative exposure, environmental variability, and biological mechanisms in assessing risk. By addressing these dimensions, the study contributes to advancing current knowledge and supporting the development of more effective food safety strategies.

2. Literature Review

2.1. Sources and Pathways of Heavy Metal Contamination in Food Systems

Heavy metal contamination in food systems arises from multiple interconnected sources that influence how these contaminants enter and spread within the food chain. Environmental pollution from industrial activities, mining operations, and urban emissions contributes significantly to the accumulation of heavy metals in soil and water systems (Angon et al., 2024). These contaminants are then transferred into agricultural systems, where crops absorb metals through root uptake, creating a direct pathway into human diets. Agricultural practices further intensify this process, particularly through the use of contaminated irrigation water, fertilizers, and pesticides. In many regions, wastewater irrigation has been identified as a key contributor to elevated metal concentrations in vegetables and other food products (Kaur et al., 2025). In addition to primary production, processing and handling stages may also influence contamination levels, especially in food categories such as spices and herbs (Alawadhi et al., 2024). These findings indicate that contamination pathways are continuous and influenced by both environmental and human-driven factors.

2.2. Bioaccumulation and Food Chain Transfer

The movement of heavy metals through food systems is largely governed by processes of bioaccumulation and biomagnification, which increase contaminant concentrations at higher trophic levels. Plants act as the primary entry point by absorbing metals from contaminated soil and water, while animals accumulate these metals through dietary intake. Over time, repeated exposure leads to the retention of metals within biological tissues, resulting in higher internal concentrations in organisms. Hou et al. (2020) highlight that soil contamination plays a central role in facilitating this transfer, linking environmental pollution directly to food safety concerns. The extent of accumulation varies depending on factors such as metal type, environmental conditions, and species-specific characteristics. This variability complicates efforts to estimate exposure levels across different populations and ecosystems. As a result, understanding food chain dynamics is essential for accurately assessing long-term exposure risks.

2.3. Toxicological Mechanisms of Heavy Metals

Heavy metals exert their toxic effects through multiple biological mechanisms that disrupt normal cellular and physiological functions. One of the most significant mechanisms is oxidative stress, where an imbalance between reactive oxygen species and antioxidant defenses leads to cellular damage. Jomova et al. (2025) explain that heavy metals can induce oxidative stress by generating free radicals, which damage lipids, proteins, and DNA. In addition to oxidative stress, these metals can interfere with enzymatic activity and disrupt essential metabolic pathways. Such disruptions may contribute to the development of chronic conditions, including neurological disorders and cancer. The severity of these effects depends on factors such as exposure level, duration, and individual susceptibility. This highlights the importance of understanding both exposure and mechanism in evaluating health risks.

2.4. Health Risk Assessment and Emerging Perspectives

Traditional risk assessment approaches for heavy metals have primarily focused on evaluating individual contaminants based on established safety thresholds. While these methods provide useful benchmarks, they may not fully reflect the complexity of real-world exposure scenarios. Mititelu et al. (2025) emphasize that dietary exposure often involves multiple sources and varying concentrations, which can influence overall risk levels. In addition, differences in dietary habits and environmental conditions contribute to variability in exposure across populations. Thompson and Darwish (2019) note that contamination patterns vary globally, further complicating standardized assessments. Recent studies have therefore highlighted the need to incorporate more comprehensive frameworks that consider cumulative exposure and population variability. These developments suggest a shift toward more realistic and integrative approaches to risk evaluation.

2.5. Limitations and Research Gaps

Despite substantial progress in understanding heavy metal contamination, several limitations remain in current research and assessment practices. Many studies focus on specific metals or individual food categories, which may limit the ability to capture broader system-level interactions. This fragmented approach can result in incomplete assessments of how contamination pathways interact within food systems. In addition, there is often limited integration between environmental monitoring and human health studies, even though these areas are closely interconnected. Sarker et al. (2022) highlight that food web dynamics play a crucial role in shaping exposure, yet they are not always fully incorporated into risk assessments. The increasing complexity of global food systems further complicates efforts to monitor and control contamination. These gaps indicate the need for more interdisciplinary and integrative research approaches moving forward.

3. Methods

This study employs a qualitative Systematic Literature Review (SLR) approach to evaluate heavy metal exposure in food systems and its implications for human health from a contemporary risk perspective. The SLR method is used to systematically collect, analyze, and synthesize existing scientific literature across relevant disciplines, including environmental toxicology, food safety, and public health, without generating new experimental data. The literature search was conducted using academic databases. Keywords such as "heavy metals," "food contamination," "bioaccumulation," "food chain," "oxidative stress," and "risk assessment" were used in various combinations to identify relevant publications. The inclusion criteria were limited to peer-reviewed articles published between 2020 and 2025, focusing on studies that address contamination sources, exposure pathways, toxicological mechanisms, and health outcomes related to food systems. Studies that focused exclusively on non-food exposure pathways or lacked relevance to human health implications were excluded, and the selected literature was analyzed through thematic synthesis to identify key patterns and relationships.

4. Results

This section presents the synthesized findings on heavy metal exposure in food systems, focusing on contamination sources, food chain transfer, toxicological mechanisms, and associated health risks. The results indicate that heavy metal contamination is driven by a combination of environmental, agricultural, and industrial factors that interact across different stages of food production. These interactions create multiple pathways through which contaminants enter food systems and ultimately reach consumers. The analysis also shows that contamination levels vary depending on geographic location, food type, and production practices. Such variability highlights the complexity of assessing exposure and the need for context-specific evaluation approaches. Overall, the findings emphasize that heavy metal exposure is a dynamic process influenced by both environmental conditions and human activities.

4.1. Sources and Distribution of Heavy Metals in Food Systems

The findings show that heavy metals originate from diverse sources, including industrial emissions, agricultural inputs, and environmental contamination, which together influence their distribution in food systems. Industrial activities release metals into air, soil, and water, creating primary sources of contamination that affect agricultural production (Angon et al., 2024). Agricultural practices, particularly the use of contaminated irrigation water and fertilizers, further contribute to the transfer of metals into crops. Wastewater irrigation has been identified as a significant factor in increasing metal accumulation in vegetables and other edible plants (Kaur et al., 2025). In addition, certain food categories such as spices and herbs may contain elevated levels of metals due to both environmental exposure and processing conditions (Alawadhi et al., 2024). These variations indicate that contamination patterns differ across food types and regions, complicating efforts to assess exposure uniformly.

Table 1. Sources and Distribution of Heavy Metals in Food Systems

Source Category	Metal Type	Environmental Medium	Pathway to Food
Industrial emissions	Lead, cadmium	Air, soil	Deposition on crops
Agricultural inputs	Mixed metals	Soil, water	Uptake by plants
Wastewater irrigation	Cadmium, arsenic	Water	Accumulation in vegetables
Environmental persistence	Mercury, arsenic	Soil, water	Entry into food chain

4.2. Food Chain Transfer and Bioaccumulation

The results indicate that heavy metals are transferred through food systems via processes of uptake, accumulation, and trophic transfer, leading to increased exposure in humans. Plants absorb metals from contaminated soil and water, acting as the primary entry point into the food chain, while animals accumulate these metals through dietary intake. Over time, repeated exposure results in the accumulation of metals in biological tissues, increasing internal concentrations. Hou et al. (2020) emphasize that soil contamination plays a crucial role in facilitating this transfer, linking environmental pollution directly to food safety concerns. The extent of bioaccumulation varies depending on environmental conditions, species characteristics, and metal type. This variability makes it challenging to predict exposure levels across different populations and food systems. These findings highlight that bioaccumulation is a key mechanism driving long-term exposure.

4.3. Toxicological Mechanisms and Health Effects

The findings show that heavy metals exert their toxic effects through multiple biological mechanisms that disrupt normal cellular and systemic functions. One of the primary mechanisms is oxidative stress, which results from an imbalance between reactive oxygen species and antioxidant defenses, leading to cellular damage. Jomova et al. (2025) explain that this process can affect lipids, proteins, and DNA, contributing to disease development. In addition to oxidative stress, heavy metals can interfere with enzymatic activity and disrupt essential metabolic pathways. These effects are associated with a range of health outcomes, including neurological disorders, cardiovascular diseases, and cancer. The severity of these outcomes depends on factors such as exposure level, duration, and individual susceptibility. Understanding these mechanisms is essential for evaluating the health risks associated with heavy metal exposure.

Table 2. Integrated Framework of Cumulative Chemical Exposure and Health Risks

Process Stage	Description	Mechanism	Health Outcome
Environmental contamination	Release of metals into soil and water	Persistence and accumulation	Initial exposure risk
Food chain transfer	Uptake by plants and animals	Bioaccumulation and biomagnification	Increased internal dose
Dietary exposure	Consumption of contaminated food	Continuous intake	Chronic exposure
Cellular interaction	Interaction with biological systems	Oxidative stress and enzymatic disruption	Cellular damage
Systemic effect	Impact on organs and systems	Inflammation and metabolic disruption	Disease development

4.4. Health Risk Implications and Exposure Variability

The results indicate that health risks associated with heavy metal exposure are influenced by both exposure levels and variability in dietary patterns and environmental conditions. Dietary intake has been identified as a major pathway of exposure, particularly in populations that consume contaminated food regularly (Mititelu et al., 2025). In addition, the presence of metals in commonly consumed foods suggests that exposure is continuous rather than occasional. Differences in geographic location and food production systems further contribute to variability in exposure levels. Thompson and Darwish (2019) highlight that contamination patterns differ globally, making standardized risk assessments challenging. Even low concentrations in frequently consumed foods can contribute to cumulative exposure over time. These findings indicate that both concentration and consumption frequency must be considered in evaluating health risks.

4.5. Interpretation of Key Findings

The synthesis demonstrates that heavy metal exposure in food systems is shaped by the interaction of multiple factors, including environmental contamination, food production practices, and biological mechanisms. These interactions create complex exposure patterns that vary across regions and populations. A key insight is that exposure cannot be fully understood by examining individual sources in isolation, as multiple pathways contribute simultaneously to overall intake. The findings also highlight the importance of bioaccumulation and persistence in shaping long-term exposure. In addition, shared toxicological mechanisms provide a framework for understanding the effects of different metals. These insights suggest that more integrative approaches are needed to evaluate exposure and risk effectively. This interpretation reinforces the importance of system-level perspectives in food safety research.

5. Discussion

The findings indicate that heavy metal contamination in food systems is shaped by a combination of environmental conditions and human activities, rather than a single dominant source. Industrial emissions, agricultural practices, and environmental persistence interact to create continuous pathways of contamination that influence food safety over time. This interconnected structure suggests that addressing contamination requires a broader perspective that considers the entire food production system. In addition, the variability observed across regions and food types highlights that exposure is not uniform and must be evaluated within specific contexts. The role of agricultural practices, particularly irrigation and soil management, appears to be especially important in determining contamination levels. These insights suggest that effective mitigation strategies must integrate both environmental management and food production practices.

Another important implication is that health risks associated with heavy metal exposure are influenced by cumulative and long-term exposure rather than isolated intake events. The persistence of heavy metals and their ability to accumulate in biological systems mean that even low-level exposure may contribute to adverse health outcomes over time. This challenges traditional risk assessment models that rely primarily on fixed thresholds and short-term exposure evaluations. In addition, differences in dietary habits and individual susceptibility further complicate the assessment of risk. These factors indicate that current approaches may underestimate the true impact of exposure in real-world conditions. A more integrative framework that considers exposure duration, accumulation, and variability is therefore necessary. Such an approach would provide a more accurate basis for improving food safety and protecting public health.

6. Conclusion

This study demonstrates that heavy metal exposure in food systems is a complex issue shaped by multiple interacting environmental and human-related factors. The findings show that contamination originates from industrial activities, agricultural practices, and environmental persistence, which together influence how metals are distributed across food systems. These contaminants are transferred through food chains via processes such as bioaccumulation and biomagnification, resulting in continuous human exposure through dietary intake. The persistence of heavy metals and their ability to accumulate in biological systems increase the risk of long-term health effects. This indicates that food safety cannot be evaluated solely at the point of consumption but must consider the entire production and environmental context. Overall, a system-level perspective is essential for understanding the dynamics of heavy metal contamination.

From a toxicological perspective, the study highlights the importance of understanding the mechanisms through which heavy metals affect human health. The findings indicate that processes such as oxidative stress, enzymatic disruption, and metabolic interference play key roles in mediating toxicity. These mechanisms are associated with a range of health outcomes, including neurological disorders, cardiovascular diseases, and cancer. The impact of heavy metals is influenced not only by exposure levels but also by duration and individual susceptibility. This suggests that even low-level exposure may have significant effects when it occurs over long periods. Understanding these mechanisms is therefore essential for improving risk assessment and health protection strategies.

In practical terms, the findings emphasize the need to improve current approaches to food safety and risk assessment. Traditional models that focus on individual contaminants and fixed thresholds may not fully capture the complexity of real-world exposure. Future research should focus on developing more integrative frameworks that consider cumulative exposure, environmental variability, and biological mechanisms. Strengthening monitoring systems and improving regulatory controls are also important for reducing contamination risks. In addition, promoting sustainable agricultural practices can help limit the transfer of heavy metals into food systems. These efforts require collaboration across disciplines to ensure effective implementation. By addressing these challenges, it is possible to enhance food safety and better protect human health.

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