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HEAVY METAL CONTAMINATION IN CEREALS AND LEGUMES: GLOBAL TRENDS, HEALTH RISKS, AND MITIGATION STRATEGIES

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Abstract
Cereals and legumes form the foundation of global diets, contributing substantially to daily caloric and protein intake. However, heavy metal contamination primarily from agricultural inputs, industrial activities, and environmental pollution has emerged as a critical food safety concern. Lead (Pb), cadmium (Cd), arsenic (As), chromium (Cr), and mercury (Hg) are among the most frequently reported contaminants. These toxic elements enter food chains through pesticide residues, phosphate fertilizers, wastewater irrigation, and mining effluents, accumulating in edible crops. Their persistence and bioaccumulation present both acute and chronic health risks, including neurotoxicity, kidney dysfunction, cardiovascular disorders, and carcinogenesis.
This review synthesizes global evidence on heavy metal contamination in cereals and legumes, drawing comparisons across regions where weak regulatory systems exacerbate risks. In contrast, countries in North America, Europe, and Australia report lower contamination levels due to stricter pesticide regulations and continuous monitoring, though legacy pollution persists. Mitigation strategies such as phytoremediation, integrated pest management, soil amendments, low-uptake crop breeding, and regulatory reforms are discussed. Addressing this contamination requires multidisciplinary approaches that combine scientific innovation, farmer education, and policy enforcement. Safeguarding food security demands robust, context-specific interventions to reduce exposure globally.
Keywords: heavy metals, cereals, legumes, contamination, pesticides, risk assessment

INTRODUCTION

Food serves a dual role in society: satisfying hunger and sustaining physiological processes. This makes a balanced diet essential, encompassing all six key food classes; carbohydrates, proteins, fats and oils, vitamins, minerals, and water (Olugbire *et al.*, 2021). Among these, carbohydrates dominate global diets, primarily because they fuel body systems, particularly the brain. Cereals, grain-based crops from the grass family Gramineae; are prime carbohydrate sources offering energy-rich nutrition but limited other nutrients (Wrigley, 2016). Common cereals include rice, wheat, maize, sorghum, barley, and millet. These grains serve as staple foods worldwide: rice in Asia and Africa, maize in the Americas and Africa, sorghum in Africa, and wheat in China, India, and the USA (FAO, 2004). In low-income countries, cereals can contribute up to 60% of caloric intake, while in high-income regions, they provide around 30% (Awika, 2011).
Yet, cereals' widespread consumption and role in food security make them susceptible to contamination, especially by pesticides and heavy metals (Hakme *et al.*, 2024; Tsagkaris *et al.*, 2021; Yu & Pedroso, 2023).

These safety risks demand strict monitoring and regulatory interventions to ensure that grains remain safe from field to fork (Saeed *et al.*, 2023). Food safety is especially critical in the cereal industry given their global dietary relevance (Bendekovic & Naletina, 2015; Assuncao *et al.*, 2021). Similarly, legumes are valuable due to their high protein content; typically 20–25% compared to 6–10% in cereals. They also provide essential amino acids, particularly lysine and methionine, making them complementary to cereal proteins. Rich in fiber and low in fat, legumes are staples for vegetarians and are culturally entrenched in global cuisines. Recent dietary trends in developed nations now regard legumes as "health foods" (Ipsos Reid, 2010; USDA-ERS, 2011). Grown across over 100 countries on more than 70 million hectares, legumes are vital in South Asia, Africa, and the Americas (Olawale & Confidence, 2020). As agricultural demands rise with population growth, so too does the reliance on chemical inputs like pesticides to boost crop yield (Olawale & Confidence, 2020). While these substances aid productivity, they introduce environmental contaminants into food systems (Litmans & Miller, 2004). Pesticides can carry heavy metal impurities like arsenic, cadmium, mercury, and lead (Yadav & Devi, 2017). Though naturally occurring, these metals become hazardous when introduced in excess through human activity (Singh *et al.*, 2010). Unlike microbial or enzymatic hazards, heavy metals are non-degradable, long-lasting, and bioaccumulative, making them particularly difficult to manage in the food supply chain (Zhou *et al.*, 2022; Shahjahan *et al.*, 2023). These contaminants harm ecosystems, reduce biodiversity, and enter the human food web, raising significant food safety issues (Bawa *et al.*, 2020; Jallow *et al.*, 2017).
This review explores the global consumption of cereals and legumes, types and sources of chemical contaminants, research trends on heavy metals in food crops and global mitigation strategies to improve food safety and protect public health.

Global Utilization of Cereals and Legumes

Cereals and legumes are among the earliest domesticated crops, sustaining civilizations for millennia. Today, rice, maize, and wheat dominate diets across Asia, Africa, and the Americas (Neupane et al., 2022). Whole grains offer health benefits, including reduced risks of cardiovascular diseases and diabetes, while legumes provide complementary proteins and bioactive compounds (Kouris-Blazos & Belski, 2016; Rebello et al., 2014). Beyond food, cereals are used in industrial sectors for biofuels, packaging, and paper, while legumes support soil fertility through nitrogen fixation (Chibudike & Udohitinuh, 2009; Kalidas & Mahapatra, 2014). Traditional meals worldwide such as rice and beans in Latin America, maize and cowpeas in Africa, and dhal and rice in South Asia demonstrate the nutritional synergy between cereals and legumes (FAO, 2016). Rising populations and urbanization continue to drive demand, leading to intensified agricultural practices that increase chemical input use. This intensification heightens risks of heavy metals contamination in food systems (Olawale & Confidence, 2020).

Chemical Contaminants in Cereals and Legumes

Heavy metal contamination in cereals and legumes is strongly influenced by agricultural inputs, particularly pesticides and fertilizers, alongside atmospheric deposition. Pesticides, though essential for controlling agricultural pests and increasing yields, pose risks when misused. Improper application or failure to observe safety intervals can result in residual chemicals remaining on food crops (Tudi et al., 2021). Globally, pesticide classes such as organochlorines, organophosphates, carbamates, and metal-based fungicides contribute to contamination either directly through trace metal impurities (e.g., Cu, Zn, As) or indirectly by modifying soil physicochemical properties and enhancing metal bioavailability (Alengebawy et al., 2021; Sharma et al., 2022; Wan et al., 2024). However, consistent evidence indicates that phosphate fertilizers represent the dominant agricultural source of heavy metals, especially cadmium (Cd), due to their geological origin, while additional inputs from sewage sludge, manure, and industrial emissions further exacerbate accumulation in agroecosystems (Alloway, 2013; Nziguheba & Smolders, 2008; Rashid et al., 2023). Cereals such as rice and wheat preferentially accumulate Cd and arsenic (As), whereas legumes exhibit variable accumulation patterns influenced by soil chemistry and cropping systems (Grant et al., 2008). Among the contaminants, cadmium poses the greatest ecological and human health risk due to its high mobility, plant uptake efficiency, and chronic toxicity, followed by arsenic and lead, which are associated with carcinogenic and neurotoxic effects, respectively (Clemens et al., 2013; EFSA, 2012; Jaishankar et al., 2014; Tchounwou et al., 2012).

Commonly Studied Heavy Metals in Cereal and Legume Research

Research across continents consistently reports Pb, Cd, As, Cr, and Hg as the most critical contaminants (Ravindran et al., 2016). These elements are of particular concern due to their toxicity, environmental persistence, and their common presence in pesticide formulations (Ravindran *et al.*, 2016). As a result, considerable research has focused on understanding their occurrence, toxicological effects, and strategies for reducing human exposure through contaminated food crops.

In Asia, the most frequent studied heavy metals are; Pb, Ar, Cd, Hg, Cr, Ni, Cu, Zn (Khan *et al.,* 2022). In Australia, Pb, As, Cd, Hg and Cr were the most common researched heavy metals (Zhang *et al.,* 2019, Brooks *et al.,* 2020). In Africa, Pb, Hg, Cd, As, Zn, Cu were the commonly researched metals (Abdulaziz *et al.,* 2022, Yaw *et al.,* 2024, Micah *et al.,* 2024, Ovonramwen *et al.,* 2023). Whereas Europe, North and South America focused on Pb, Hg, Cd, As (Ogunleye *et al.,* 2021, Kobal *et al.,* 2020, Pérez *et al.,* 2021, EPA, 2020).

Health Risks of Heavy Metals in Humans

Acute Effects

Short-term dietary exposure can cause headaches, seizures, nausea, and gastrointestinal distress. High Pb exposure may induce convulsions, while acute Cu poisoning leads to jaundice and liver failure (Oe et al., 2016).

Chronic Effects

Chronic Cd intake causes kidney dysfunction, osteoporosis, and cancer. Lead disrupts neurodevelopment in children and impairs fertility. Arsenic is linked to multiple cancers and cardiovascular diseases. Mercury affects memory, coordination, and neurological functions (Islam et al., 2017; El-Kady & Abdelwahab, 2018).

Mechanisms of Toxicity

Many metals induce oxidative stress, DNA damage, and interference with enzyme systems, leading to carcinogenesis and systemic organ damage (Alengebang et al., 2021).

Global Trends in Heavy Metal Contamination

The degree of heavy metal contamination in cereals and legumes differs significantly across regions, largely due to environmental and agricultural factors such as the use of polluted irrigation water and the application of contaminated fertilizers and pesticides (Yu & Pedroso, 2023).

In countries like China, India, Italy, and many parts of Africa, agricultural soils have been severely affected by both natural processes and human activities. These include the use of untreated sewage and industrial wastewater for irrigation, as well as the indiscriminate use of chemical pesticides (Wu *et al.*, 2021). In these areas, toxic metals such as cadmium (Cd) and arsenic (As) can infiltrate soil and water, leading to the contamination of crops like vegetables, cereals, and legumes (Nemes *et al.*, 2022).

In Asian countries like Bangaladesh, India, China, Pakistan and Malaysia, heavy metals contamination were as a result of Hydrogeological conditions causing extensive release and mobilization of this toxic metal in the groundwater as well as the use of agrochemicals such as phosphate-based fertilizers and certain pesticides (Oluboyo *et al.,* 2020, Wu *et al.,* 2020, FSANZ, 2021 and EC, 2020). In Africa; Nigeria, Kenya, Ghana and Egypt, Increasing contamination was due to the use of untreated wastewater and industrial pollutants and indiscriminate pesticides application (Abdulaziz *et al.,* 2022, yaw *et al.,* 2024 and Micah *et al.,* 2024). While in Europe; southern Europe and coastal areas, decreasing contamination was due to the regulations on phosphate fertilizers, but localized issues persist (Kobal *et al.,* 2020 and Perez *et al.,* 2021). In Australian countries like Western Australia and Northern Territory, there is moderate contamination, but decreasing due to strict regulations (Sanchez *et al.,* 2021). Countries like Canada, Mexico and United States (industrial zones) in North America heavy metal contamination of cereals and legumes has been linked in part to the historical and ongoing use of certain pesticides and phosphate fertilizers that contain or mobilize toxic elements such as cadmium (Cd), arsenic (As), and lead (Pb) (Ma *et al*., 2016) and the contamination was a mixed trend, reductions in cadmium but ongoing concerns with mercury and lead in industrial areas (Perez *et al.,* 2021, WHO, 2020). But in South America; countries like Brazil, Argentina, Peru and Chile, there was increasing contamination, particularly due to industrialization and irrigation with contaminated water and extensive use of phosphate fertilizers and pesticide formulations containing or mobilizing heavy metals (Chávez-Capilla *et al*., 2020 and Nouru *et al.,* 2017).

Mitigation strategies to address heavy metals contamination

Effective mitigation strategies must be context-specific rather than generic. Soil amendments such as biochar, lime, and phosphates are particularly effective for immobilizing Cd and Pb in cereal systems (Beesley et al., 2011; Bolan et al., 2014). Phytoremediation is suitable for moderately contaminated soils and is often integrated into legume-based cropping systems, though it is slower in large-scale applications (Ali et al., 2013). Crop selection and breeding of low-metal-accumulating varieties represent one of the most sustainable long-term solutions, especially for cereals (Clemens et al., 2013). In arsenic-prone regions, particularly in Asia, irrigation management techniques such as alternate wetting and drying significantly reduce uptake in rice (Norton et al., 2015). In contrast, in regions such as sub-Saharan Africa, improving fertilizer quality, regulating pesticide use, and adopting organic soil amendments are more practical and impactful interventions.

Conclusion

Heavy metal contamination of cereals and legumes is a global challenge, disproportionately affecting developing regions with weak regulation and high agrochemical use. Nigeria and India remain hotspots, while Australia and North America illustrate the effectiveness of regulatory frameworks. Health risks from acute and chronic exposure highlight the urgency of intervention. Mitigation requires integrated approaches: farmer education, soil amendments, crop breeding, and robust policies. Collaborative international efforts are vital to safeguard food safety, protect public health, and secure the nutritional role of cereals and legumes for future generations.

Author's contribution

All the authors involved in this paper have contributed to the success of this study.

Conflict of interest

There is no any conflict of interest among the authors in whatever form.

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