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Review Article

Smart and Sustainable Packaging Approaches for Reducing Heavy Metal Contamination in Foods: A Comprehensive Review

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ABSTRACT

Heavy metal contamination of food via lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), and chromium (Cr), represents a persistent global public health crisis, with food packaging materials themselves serving as a documented contamination source through diffusion, leaching, and chemical interaction migration mechanisms. This review systematically examines emerging smart and sustainable packaging technologies designed to prevent, detect, and remediate heavy metal contamination. Active packaging strategies (chelating agents, metal-scavenging biopolymer films, adsorbent systems, antioxidant-releasing materials) are evaluated alongside intelligent packaging technologies (colorimetric sensors, nanomaterial biosensors, IoT/RFID real-time monitoring). The role of nanotechnology in amplifying active and sensing performance is critically assessed, with attention to nanotoxicity concerns and evolving regulatory frameworks. Sustainable alternatives such as polylactic acid (PLA), starch, cellulose, chitosan, proteins, and PHAs are evaluated for combined food safety and environmental benefits supported by life cycle assessment. Applications across dairy, seafood, fruits and vegetables, beverages, and processed foods are discussed with reference to experimental findings and commercial case studies.

KEYWORDS

• Heavy Metal • Scalability • Cost • Sensor Selectivity • Regulatory Harmonisation • Ai Food Safety Solutions.

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INTRODUCTION

The contamination of food with heavy metals is one of the most serious concerns in the field of food safety and has been the subject of constant scientific, regulatory and public scrutiny for more than 20 years. Chemically stable, resistant to degradation, and bioaccumulating hundreds of fold at each trophic level, toxic heavy metals end up at the top of the food chain in human tissues. Chronic low-level dietary exposures have been consistently linked to nephrotoxicity, neurotoxicity, carcinogenicity and developmental disorders in just about every food category, including cereals, vegetables, fruit, dairy, fish, and seafood.

There are 5 main metals to consider. There is no safe limit for lead (Pb). Cereal crop uptake of Cadmium (Cd) from soils fertilised with phosphate. Methylmercury is a good bioaccumulator in aquatic food chains. Hexavalent chromium Cr (VI), a Group 1 carcinogen (IARC), is produced in industrial processes, and may leach into food from contaminated water, soils and food contact materials.

1. Sources of Heavy Metal Contamination

Contamination routes are throughout the farm to fork supply chain. Heavy metals from atmospheric deposition from industry, as well as metallic agrochemicals, sewage sludge and contaminated irrigation water enter the agricultural soils, and the root uptake depends on the amount of metals in the soil, its pH and plant physiology. Industrial pollution occurs directly by effluents discharged to water and by emissions to the atmosphere from the smelting, and battery production processes. The milling, grinding and cooking process of food processing equipment made of metallic alloys will lead to the addition of Pb and Cr into the food with acid pH.[1,2,11]

The subpar food packaging is an underrated source of contamination. Conventional polymers (PET, PP, PS, PVC, PA) contain metallic light stabilisers, heat stabilisers and flame retardants that are able to migrate under normal storage conditions between the polymer and food. The literature describes five types of migrations that have been identified: contact migration, gas-phase migration, penetration migration, set-off migration, and condensation migration, and each requires specific mitigation.

2. Health Risks of Heavy Metal Exposure

The toxicity is due to displacement of necessary metal cofactors from enzymatic active sites, ROS-induced oxidative stress and disruption of cellular signalling cascades. The effects of lead on cognition are irreversible at any level of detection in the blood and the effects of methylmercury on the nervous systems of foetuses are also irreversible. Cadmium is known to deposit in the renal cortex, and lead to progressive tubular dysfunction (as seen in the Itai-Itai disease in Japan). Arsenic, cadmium, and Cr(VI) are IARC Group 1 carcinogens and lead is IARC Group 2A, believed to cause lung, bladder, kidney and liver cancers.

3. The Imperative for Smart and Sustainable Packaging

The concentrations of these contaminants in food have been significantly lowered by EU Regulation 2023/915, where the maximum levels are now set at: Pb $\leq$ 0.10 mg/kg (most foods); Cd $\leq$ 0.05 mg/kg (cereals); Hg $\leq$ 0.01 mg/kg (fish); and As $\leq$ 0.1 mg/kg (rice), creating new compliance pressures for food producers. When conventional plastic packaging fragments, it adds metallic additives to soils, which are part of soils' contamination cycles that re-enter the food chain. Biodegradable biopolymers remove these metallic additives and offer true end-of-life degradation pathways while smart sensor technologies remove traditional laboratory-based analytical tools and provide real-time in-package monitoring along with IoT and RFID technologies.

HEAVY METAL LEACHING FROM FOOD PACKAGING

1. Mechanisms of Migration

Contact migration is predominant and occurs through the path of Fickian diffusion: heavy metal ions diffuse from polymer matrix to food, the diffusivity is dependent on the free volume of the polymer, the size of the migrant ions, and temperature. The process of leaching refers to the dissolution of metal species from the surface of packaging caused by the presence of acidic, aqueous or alcoholic food components, the acidic food simulants always leaching the highest number of metals from recycled paper and metallic can surfaces. Factors such as redox reactions, ligand exchange, complexation change the immobile metal in the packaging into a mobile form. The multiplication of the effect is synergistic between temperature and pH; as both the diffusion coefficient is increased by higher temperature, and the solubility of the metal compounds is increased by low pH.

Plastic polymers are required to be thermally stable, UV resistant and coloured and are therefore loaded with organometallic additives and inorganic metal salts. Pb and Cd compounds are still used in PVC in legacy materials as heat stabilisers, while Cr-based pigments are still contained in other legacy materials. The internal protective coatings of aluminium cans are also known to migrate to the food, in the form of Cr, and some cans containing metal are susceptible to corrosive attack by acidic foods, which can lead to the release of Sn, Fe and Pb. Set-off and solvent-residue migration pathways are created by printing inks (Pb chromate, Cd sulfide pigments) and adhesives in multi-layer laminates.[3,8,13]

Table 1: Heavy Metals of Primary Food Safety Concern: Sources, Migration, Health Effects, and EU Limits

Metal	Primary Packaging Source	Migration Pathway	Key Health Effects	EU Limit (Reg. 2023/915)
Lead (Pb)	PVC stabilisers; metallic can solder; Pb chromate printing ink	Diffusion from polymer; leaching from can seams; set-off from printed layers	Irreversible neurotoxicity (all doses); anaemia; developmental disorders; IARC Group 2A	0.10 mg/kg (most foods); no safe threshold
Cadmium (Cd)	PVC stabilisers; recycled board; Cd sulfide printing ink	Diffusion; leaching in acidic matrices; contaminated recycled fibre migration	Nephrotoxicity (Itai-Itai); IARC Group 1 (lung, kidney, bladder cancers)	0.05 mg/kg cereals; 0.10 mg/kg leafy vegetables
Mercury (Hg)	Metallic pigments; industrial contamination via recycled board	Leaching; gas-phase migration at elevated temperature	Methylmercury: placental transfer; developmental neurological deficits; IARC Group 1	0.01 mg/kg fish and fishery products
Arsenic (As)	Recycled paper/board; contaminated recycled glass fillers	Leaching; penetration migration	Inorganic As: skin, lung, bladder carcinoma; adverse birth outcomes; IARC Group 1	0.10 mg/kg rice; 0.01 mg/kg drinking water
Chromium (Cr)	Protective can coatings; stainless steel equipment; Cr oxide inks	Leaching from corroded metallic surfaces; chemical interaction	Cr(VI): lung carcinogen IARC Group 1; skin sensitisation; oxidative DNA damage	General food contact materials legislation

*Sources:[*1,2,3,11,13]

3. SMART PACKAGING TECHNOLOGIES

1. Active Packaging

Active packaging can act on purpose with the food and food environment to improve safety beyond passive packaging for heavy metal control in the following ways: scavenging metal ions, controlled release of antioxidants, physical adsorption and selective chelation. The four ways in which active packaging can act purposefully to improve its role in food safety beyond passive packaging include: scavenging metal ions, controlled release of antioxidants, physical adsorption and selective chelation.

Metal Scavengers, Chelating Agents. An EDTA-functionalised packaging film and coating is able to bind the metals Pb^{2+}, Cd^{2+}, Hg^{2+}, and Cr^{3+}, forming multi-dentate coordination complexes, which result in high reduction of the bioavailable concentration of the metal at the packaging food interface. The natural alternatives (e.g., phytic acid, tannic acid, polyphenolic plant extracts) take advantage of the hydroxyl and carbonyl groups to coordinate the metals, but are not chemically synthetic and therefore are not hazardous in food applications.[6,15,16]

Antioxidant-Releasing Films. The release of metal catalysed ROS from Fenton and Haber-Weiss reactions is prevented by the incorporation of tocopherols, ascorbic acid, curcumin, thymol and carvacrol in biopolymer matrices, which can be controlled by encapsulation, crosslinking and multilayer architecture. These dual action systems not only inhibit lipid oxidation, they also scavenge the oxidative effects of any remaining metal exposure.[7,14,17]

ADSorbent Systems and Chitosan Films are produced in a novel method that is patented. Activated carbon liners offer a passive in package heavy metal scavenging and have specific surface area ranging from 500 to 3000 m2/g. The metal-scavenging properties of Chitosan (which contains many NH2 and OH groups yielding inner-sphere coordinating sites for the metals Pb^{2+}, Cd^{2+}, Hg^{2}+ and Cu^{2}+) combine with biodegradable packaging material and antimicrobial barrier properties into a single bio-based material. The incorporation of metal oxide nanoparticles to chitosan further enhances the adsorption ability and gives chitosan "sensing" ability.[15,18]

2. Intelligent Packaging

Colorimetric Sensors. The metal responsive dyes, chelating chromophores and the nanoparticle-based probes react with threshold concentrations of Pb^{2+}, Hg^{2+} and Cd^{2+} to yield visible colour changes in the solution without any instrument or power source. These systems offer scalable solutions for communicating contamination status without an instrument and accessible by consumers.

Nanomaterial-Based Biosensors. The gold nanoparticles, silver nanoparticles, metal oxide nanoparticles, graphene, carbon nanotubes and carbon quantum dots offer the signal amplification that allow the detection of the presence of Pb, Cd and Hg in complex food matrices with very low detection limits. The single-stranded DNA and RNA aptamer-based platforms have dissociation constants ranging from nanoliter to picoliter for both the metal ions Pb^{2+} and Hg^{2+}, which is more selective than small molecule probe dissociation constants. Fluorescence biosensors based on FRET principles are fast, inexpensive and are capable of simultaneous multi-metals detection.[4,5,6]

Integration of IoT and RFID. Smart packaging with IoT involves installing sensors within the package, transmitting data in real-time wirelessly to the cloud for processing/aggregation, and then applying algorithms to create actionable alerts in advance of consumers regarding contamination. This will be replacing the retrospective approach to laboratory monitoring conducted periodically with the prospective approach at the in-pack level, at individual product level, eliminating waste and enhancing timeliness in food safety management.

3. Nanotechnology-Based Packaging

With surface groups such as carboxyl, hydroxyl, and epoxide groups with its high surface areal density, graphene oxide exhibits outstanding adsorption capacity for the ions of Pb^{2+}, Cd^{2+}, $Hg2^{+}$ and As, which is several orders of magnitude higher than that of bulk adsorbents, and it also offers gas barrier performance and structural integrity. The hydroxyl-rich surfaces allow for the functionalisation with metal ions, while the excellent mechanical reinforcement properties make the cellulose nanocrystals (CNCs) and nanofibres (CNFs) useful for applications in which they provide reinforcement. The excellent mechanical reinforcement properties, together with the hydroxyl-rich surface, which can be functionalised with metal ions, make the cellulose nanocrystals (CNCs) and nanofibres (CNFs) useful for applications in which they provide reinforcement.

Nanotoxicity and Regulatory Concerns. The migration of nanoparticles from packaging materials into food may result in the unintended exposure of the consumers to engineered nanomaterials whose gastrointestinal and systemic effects over the long-term are poorly understood, an ironic counterpoint to systems where heavy metal contamination is reduced. The regulatory landscape for nanomaterials in food contact materials is dynamic and is currently in a state of development across the EU, USA, Japan and China and the development of standardised migration testing, toxicological characterisation and engagement with the regulators should run alongside the development of performance optimisation.

SUSTAINABLE PACKAGING APPROACHES

1. Biodegradable Biopolymers

Starch based films exhibit sufficient oxygen barrier properties, however these films need to be filled with nanofillers to enhance their water resistance. PLA is expected to take over biodegradable polymer production capacity in the mid-2020s and has mechanical properties similar to PET, processability on common machines. Cellulose-based formats have a high degree of hydrogen bonding and a crystalline structure, providing outstanding mechanical strength and gas barrier. Soy protein-based films have oxygen permeability 260-670 times lower than the conventional PE films, which eliminates the need to use metal-containing barrier coatings. The bacterial fermentation-based PHA biodegradability is combined with the ability to be mechanically tuned by changing the copolymer composition of the PHAs.[7,10,14]

2. Bioactive Natural Materials

Polyphenolic extracts (green tea, rosemary, grape pomace, curcumin), encapsulated essential oils (thyme, oregano, clove, cinnamon) and algal biopolymers (carrageenan, agar, alginate) have two roles: to be active against microbial growth and against oxidative deterioration, and to pose no risk of heavy metal contamination when there is any inadvertent migration to food. The citrus, mango and pomegranate processing waste comprises of fruit peel, which is an example of waste products from the production of water, sugar, juice or fiber from fruits and vegetables, and can be used as a packaging material by following the principles of circular bioeconomy.[7,10,19]

Unlike conventional plastics that fragment and release stabiliser-derived metals into soil and back into the food chain, compostable packaging certified to EN 13432 or ASTM D6400 into which the packaging is converted into compost, water and CO_2 without leaving behind any persistent plastic residues or heavy metal contaminants. Active biocomposite packaging can be proven to significantly lower global warming potential and ecotoxicity when compared with conventional plastics by LCA. This 2023 UN SDG Progress Report explicitly mentions that biodegradable films can help to achieve SDG 12 and SDG 13 for embedding sustainable packaging into global sustainable development governance.

5. Packaging materials used for heavy metal adsorption and removal

Bioadsorbents such as chitosan, biochar, clay minerals (montmorillonite and halloysite nanotubes) and agricultural waste (rice husks, sugarcane bagasse, fruit peels) bind heavy metal ions via adsorption, ion exchange, complexation and electrostatic interaction at the packaging food interface. The selectivity of functionalised chelating polymer films for the metal ions, such as Pb^{2+}, Hg^{2+} and Cd^{2+}, with presence of iminodiacetate pendant ligand, thiol pendant ligand, dithiocarbamate pendant ligand and Schiff base pendant ligand over the essential mineral ions, Ca^{2+} and Mg^{2+}, has been obtained. Selectivity of the functionalised chelating polymer films for the metal ions such as Pb^{2+}, Hg^{2+} and Cd^{2+} over essential mineral ions Ca^{2+} and Mg^{2+} has been achieved.

For most systems, there are four physicochemical mechanisms: (i) adsorption (physical and chemisorption); (ii) ion exchange (stoichiometric cation displacement); (iii) complexation (inner-sphere chelate formation); and (iv) electrostatic interaction (coulombic attraction at charged surfaces). For high-performance systems, optimization of the relative contributions of each mechanism is necessary for rational design, which necessitates targeted material functionalization in order to achieve this optimization.

APPLICATIONS ACROSS FOOD SYSTEMS

Table 2: Smart and Sustainable Packaging Applications Across Major Food Categories

Food Category	Packaging Technology Applied	Target Metal(s)	Documented Performance	Adoption Status
Dairy products	Chitosan active coatings on container interiors; PLA biodegradable dairy containers	Pb, Cd, Cr	Significant reduction in detectable metal ion concentrations; PLA eliminates metallic additive risk	Experimental; commercial PLA dairy containers in EU markets
Seafood & fish	Electrolytically tinned steel cans with polymer-sealed seams; algal biopolymer and chitosan coatings on fresh fish	Pb, Sn, Cd, Hg	Elimination of Pb migration; Sn below regulatory threshold; extended microbiological shelf life	Mainstream in regulated markets; active coatings at pilot scale
Fruits & vegetables	Cellulose nanofibre composite wraps; PLA clamshells; starch-based biodegradable trays	Pb, Cd, As	Reduced O_2 permeability and moisture loss; metal additive-free environment; EU market uptake	Commercial penetration in European fresh produce sector
Beverages	IoT electrochemical biosensors in multi-layer carton formats; RFID colorimetric Pb^{2+}/Hg^{2+} indicator labels	Pb, Cd, Sb, Cr, Ni	Good agreement with reference ICP-MS; continuous cold-chain surveillance; consumer-accessible point-of-sale status	Commercial pilot studies; RFID labels in prototype beverage applications
Processed & packaged foods	EDTA-functionalised barrier layers; antioxidant-releasing biopolymer coatings; biodegradable multi-layer laminates	Pb, Cd, Cr, Co	Simultaneous reduction in migration and lipid oxidation; reduced LCA ecotoxicity versus conventional laminates	Experimental; commercial adoption accelerating under regulatory pressure

*Sources: *[1, 3, 4, 9, 10, 12,14,15]

CHALLENGES AND FUTURE DIRECTIONS

Scalability and cost are still major challenges; the majority of biosensor and active packaging systems that have been presented in the research scale are based on materials and processes that are not suitable for high throughput industrial manufacturing. Organic acids, proteins, lipids and mineral ion interferers are all factors that can affect sensor performance in complex food matrices; aptamer and molecularly imprinted polymer platforms possess the greatest selectivity potential, but need to be extensively validated using authentic matrices.[23] The jurisdictional fragmentation of current regulatory frameworks for nanomaterials in the food contact materials sector is a major hurdle to commercial investment in food contact materials trading, especially in the context of a globally traded product. The situation of current fragmented jurisdictional regulatory frameworks is an urgent need to harmonise regulatory approaches for nanomaterials presently in food contact materials. The concern of biodegradability performance in high humidity distribution condition in tropical region can be best addressed by hybrid strategies using biopolymer nanocellulose with crosslinking treatments. Perhaps most significantly, the marriage of AI and IoT smart packaging, by using machine learning algorithms to analyse streams of information from sensors, can predict contamination events before thresholds are reached, determine contamination source signatures, and optimise supply chain routing to reduce consumer exposure.

CONCLUSION

Together, smart and sustainable packaging technologies tackle all phases of the heavy metal contamination risk: Active packaging scavenges and chelates metal ions in contact with the food product; Intelligent packaging detects and communicates contamination in real time; Nanotechnology enhances the activity and sensing; and Biodegradable biopolymer eliminates the contamination risks inherent in conventional packaging products, while reducing the environmental burden associated with the use of metallic additives. The evidence analysed herein demonstrates that chitosan nanocomposites, graphene oxide nanoadsorbents, aptamer biosensors and IoT-based real-time monitoring platforms are currently the most efficient technologies in the control of heavy metal contamination. Sustainability and food safety goals align and complement each other, as seen in the current meaningful commercial uptake of PLA, starch composites and protein-based films in fresh produce and dairy. The progressive tightening of regulatory boundaries established by EU Regulation 2023/915, in combination with the integration of sustainable packaging in the UN SDG 12 and SDG 13, contribute to creating an environment conducive to the accelerated adoption. Consumer demand, regulatory requirement, environmental sustainability, and technology all come together and make the smart sustainable packaging a more than just a step forward, it is a platform for the next generation of food safety assurance.

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