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COMPREHENSIVE REVIEW OF REMOVAL METHODS IN FOOD SYSTEMS: FOCUS ON ECO-FRIENDLY STRATEGIES AGAINST HEAVY METALS

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ABSTRACT
Heavy metal contamination in food systems has become significant global threat due to its persistence, bioaccumulation, and severe health risks. This review aims as a comprehensive evaluation of eco-friendly strategies for the removal of toxic heavy metals such as Pb, Cd, Hg, As, and Cr from food system. The study identifies major contamination pathways, environmental exposure, agricultural inputs, and food processing. Emphasis is placed on green technologies, including bio-based adsorbents from agricultural waste, microbial and enzymatic biosorption, plant-derived coagulants, and green nanotechnology. These methods offer promising, sustainable alternatives with high removal efficiency, low toxicity, and compatibility with food safety standards. By synthesizing findings from recent studies, this review underscores the practical applicability of eco-friendly materials and biological agents, aligning with global sustainability efforts and food safety regulations.

Keywords: heavy metals, food safety, green technology, eco-friendly removal

INTRODUCTION
Lately, public health concern is focused on heavy metal contamination in the global food supply as effect of massive industrialization, urbanization, and unsustainable agricultural practices (Scutarașu & Trincă, 2023). Heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), cobalt (Co), and iron (Fe) are non-biodegradable and can accumulate in biological tissues, leading to long-term health risks (Jomova et al., 2025). These metals enter the food system through various pathways, including environmental exposure, agricultural inputs, food processing, and packaging (Milanković *et al*., 2024). Their persistent and toxic properties even at low concentrations make them a threat in food safety (Mukherjee *et al*., 2023). Exposure to heavy metals through food consumption has been related with various health issues such as problem in development of neuron in children, renal and immune system issues as well as increased risk of cancers (Mahmood & Malik, 2014). Pregnant women, infants, and elderly are the most vulnerable population to be affected by these toxic pollutions (Udom *et al*., 2025).

Traditionally, there are various approaches to reduce heavy metal concentration in food have included physical and chemical methods such as washing, peeling, heat treatment, and chemical precipitation (Diyarov *et al*., 2022). However, such methods have limit since they unable to remove heavy metal contaminants that has been absorbed into tissues. Furthermore, chemical treatments may work well for tackling down heavy metals pollution, but their toxic trait making them less suitable for food (Bora *et al*., 2022). Therefore, alternative solutions that are high efficiency as well as environmentally sustainable are urgently needed.

For past decades, the utilization of green technologies for heavy metal removal has been growing massive interest. These approaches include the use of bio-based adsorbents, microbial bio sorption, plant-derived coagulants, edible coatings, and green nanotechnology (Priyadarshanee & Das, 2021; Tripathi *et al*., 2023). Moreover, these methods also have benefit in removing heavy metal they are natural, biodegradable materials that pose minimal risk to food quality and consumer health. Their development is aligned with global sustainability goals and offers the potential for scalable and cost-effective applications in food systems. Hence, this review aims to provide a comprehensive overview of recent advancements in the removal of heavy metals from food matrices, with a special focus on eco-friendly and sustainable strategies.

METHODS

This review is based on a systematic analysis of peer-reviewed articles, scientific journals, and authoritative reports published over the past decade. Data sources include online databases such as ScienceDirect, PubMed, Scopus, and Google Scholar. Keywords used in the search included "heavy metal contamination in food," "removal methods," "green nanotechnology," "biosorption,", "microorganism based adsorbents", and "plant based coagulants." Articles were selected based on relevance, novelty, and their emphasis on green or sustainable approaches to heavy metal removal in food systems.

RESULTS AND DISCUSSION

Examination of Heavy Metal Contamination in Foods

The contamination of food with heavy metals should be put into consideration due to the enduring nature and the tendency to bio accumulative of these elements. Understanding the origin and transmission of these metals is essential for developing effective removal. Their presence in food systems is influenced by both natural and human activities, which makes it crucial for designing effective steps to eliminate them from food system in order to prevent long-term exposure in the human population (Ali *et al.*, 2019; Edelstein & Ben-Hur, 2018). Heavy metals enter the food chain through several pathways such as environmental and agricultural sources, as well as food packaging and processing (Hembrom *et al*., 2020; Zheng *et al.*, 2020).

Environmental Sources

Industrial activities such as mining, smelting, manufacturing, and waste disposal often release heavy metals into the environment (V. Singh et al., 2023). These materials can become pollutants in air, water bodies, and soils, and ended in agricultural lands. The existence of heavy metals in irrigation water will directly affects crops during cultivation. In line with this, polluted soils, especially those located near urban or industrial areas can also facilitate the uptake of metals by plants through root absorption (Atta *et al.*, 2023). Once in the plant system, these metals accumulate in edible tissues and are transferred to human body upon ingestion. Hence, contaminated surface waters and groundwater sources used for irrigation are major factors of heavy metals to transport into the food system.

Metals, for instance arsenic (As), cadmium (Cd), mercury (Hg), and lead (Pb) are commonly found in industrial effluents and untreated wastewater. When used for irrigation, such waters contaminate crops directly or through changes in soil chemistry that assists metal uptake. This exposure is majorly to occur in developing regions where industrial regulations and wastewater treatment systems may be lacking or poorly enforced. Urban runoff and landfill leachate also pose significant risks by introducing heavy metals into surrounding agricultural areas (Parvin & Tareq, 2021). Heavy metal quantities in these regions are affected by seasonal variations and industrial activity, creating complex patterns of exposure that challenge monitoring and mitigation efforts. In areas experiencing rapid urban growth, informal settlements and poorly managed waste disposal practices often exacerbate environmental contamination and complicate efforts to safeguard food quality (Pham *et al.*, 2021).

Agricultural Sources

The utilization of chemical based fertilizers and pesticides is commonly contributed to heavy metal accumulation in food crops. Phosphate fertilizers which often contain Cd as an impurity can leach into the soil and be taken up by plants (Khatun *et al.*, 2022). Similarly, the use of copper, and arsenic, based fungicides and insecticides over times can also result in residual metal buildup (Conrad *et al.*, 2021). Excessive fertilizer application not only introduces direct metal contaminants but also affect the soil pH and microbial activity, which in turn alters the mobility and bioavailability of heavy metals (Vicar *et al.*, 2024). Acidic soils, for instance, increase the solubility of many metal ions, making them more readily absorbed by plant roots (Lu *et al.*, 2020). This creates a feedback loop in which common agricultural practices inadvertently increase the risks of contamination, even when good agronomic practices are observed.

Agricultural drainage is another important pathway through which heavy metals spread to neighboring ecosystems and crops. Fields treated with contaminated inputs may leach metals into nearby water systems, contributing to widespread environmental and food chain contamination. Moreover, the overuse of antibiotics and growth promoters in livestock farming has led to the entry of metals into the food system through animal waste (Wales & Davies, 2015). When used as manure or compost, such waste can contaminate soils with persistent metals, which are then taken up by crops over multiple planting cycles. This problem is enhanced by the fact that monitoring and controlling the quality of organic fertilizers is more difficult than regulating synthetic fertilizers, allowing harmful substances to circulate undetected.

Green Approaches to Heavy Metal Removal in Food Systems

Green and eco-friendly strategies for treating heavy metal contaminates are become major attention due to their sustainability, low toxicity, and compatibility with food systems (Bakhtiari et al., 2024a). These approaches aim to reduce environmental impact while ensuring consumer safety. Several innovative methods have emerged, each offering unique advantages in terms of efficacy, biodegradability, and cost-effectiveness.

Bio-Based Adsorbents

Bio-based adsorbents are effective and suitable approach for removing heavy metals from food systems, primarily through mechanisms such as surface adsorption and ion exchange (Yadav *et al.*, 2021). These adsorbents are derived from natured based materials or agricultural by products, which also enhances their value due to eco-friendly and cost-effective nature (Babu *et al.*, 2022). The growing interest in these materials is also driven by their availability, renewability, and less environmental impact. Unlike synthetic adsorbents, bio-based materials often contain various types of functional groups such as hydroxyl, carboxyl, and amino groups, which can make strong bond with metal ions as shown in Figure 1 below (H. Wang et al., 2020). Their application in food systems is also in line with global efforts to promote green technologies, especially in addressing food safety concerns caused by toxic metal contamination.

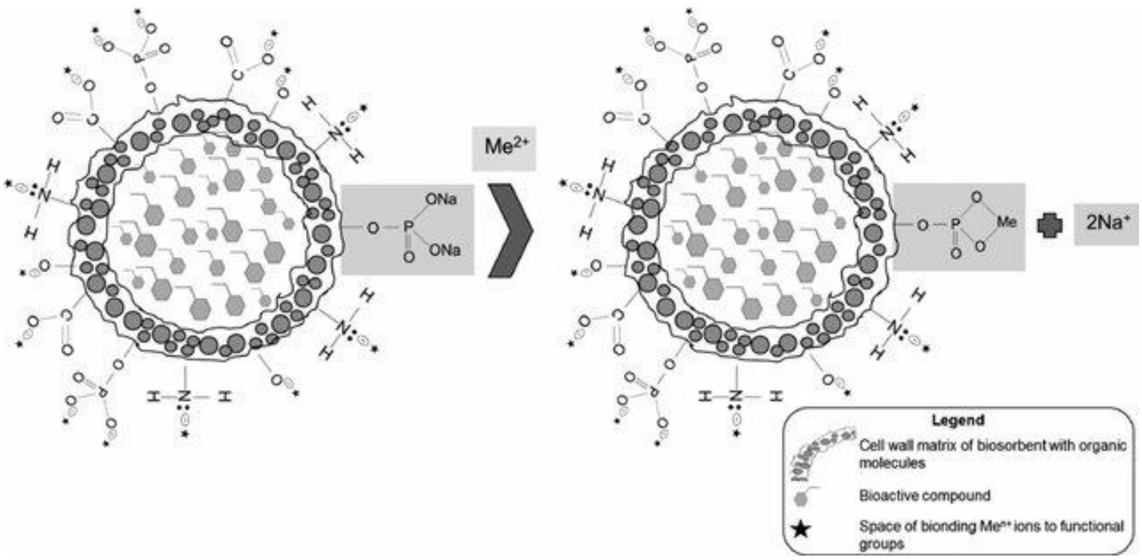

Figure 1 Adsorption of heavy metal ions onto functional groups on the surface of biosorbent (Michalak *et al.*, 2015)

A wide range of agricultural wastes have been identified as effective bio-based adsorbents due to their sponge-like structure and board surface area. Materials such as rice husks, banana peels, coconut shells, and sugarcane bagasse are abundant in many agricultural regions and typically considered waste (Ungureanu *et al.*, 2023). These residues contain lignocellulosic compounds (cellulose, hemicellulose, and lignin) which contribute to their adsorption capacity as exhibited in Figure 2 below (Xu *et al.*, 2025). Additionally, chemical modification or activation such as by modifying with acid or base can also enhance the metal-binding efficiency of these materials by increasing the amount of active sites (Liu *et al.*, 2022).

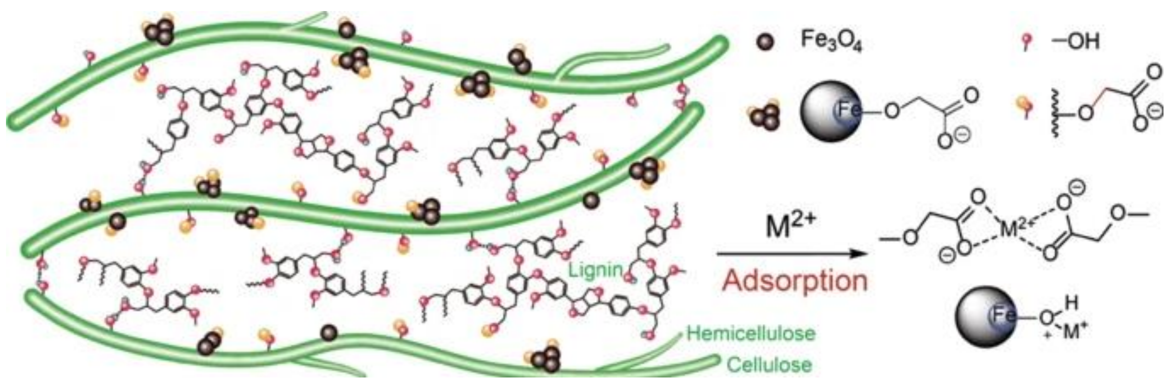

Figure 2 Adsorption of heavy metal ions onto lignocellulosic compounds on the surface of biosorbent (Shen *et al.*, 2019)

The study of removing heavy metals by utilizing banana peels based adsorbent has done by Fabre *et al.* (2020) for treating Hg showed that such material is effective for reducing concentration of such metal in drinking water sample. Similarly, physically activated banana peels, carbon foam (CF) has also applied for abrobing various metals such as Cu, Cd, Pb, and Cr revealed the efficiency of heavy metals removal is up to 98% at 1 h of contact time (Li *et al.*, 2016). Banana peels biochar has also investigated by Duwiejuah *et al.*, (2025) exhibited percentage removal of various heavy metals (Ni and Cr) is up to 99% at 45 min.

In addition, coconut based biosorbent also studied trough shell biochar (Ti-4BC), modified with $NaHCO_3$ and TiO_2, which demonstrated high adsorption capacities for Cd^{2+} (104.2 mg/g), Pb^{2+} (136.8 mg/g), Cr^{3+} (101.2 mg/g), and Cr^{6+} (112.4 mg/g) (Gu *et al.*, 2024). In line with this, Using a molten salt method, biochar derived from rotten sugarcane bagasse (RB-C) was prepared as a low-cost adsorbent, exhibiting a high Pb^{2+} removal capacity of up to 339 mg/g (Bai *et al.*, 2022). Moreover, a study done by Harripersadth et al., (2020) demonstrated that sugarcane bagasse biosorbents effectively removed Pb^{2+} and Cd^{2+} from sample solutions, with sugarcane bagasse achieving maximum adsorption capacities of 31.45 mg/g for Pb^{2+} and 19.49 mg/g for Cd^{2+}, highlighting their potential as low-cost, natural materials for heavy metal remediation.

Microbial and Enzymatic Biosorption

The use of biological organisms as well as enzymes to remediate toxic heavy metals can also be other eco-friendly and efficient step in food safety management (Tarfeen *et al.*, 2022).This approach which is referred to as microbial and enzymatic biosorption, leverages the natural metabolic and biochemical properties of living systems to mitigate the risks posed by heavy metal contamination in food (Huang *et al.*, 2020). Unlike conventional physical or chemical removal techniques, which may introduce secondary pollutants or affect food quality, biological methods offer a sustainable alternative that support green technology principle.

Microorganisms, for instance lactic acid bacteria (LAB) and various species of yeast have demonstrated a strong capacity for immobilization toxic heavy metals (Y. Wang *et al.*, 2024). These microbes are commonly present in fermented foods, including yogurt, kimchi, and tempeh, leading to both practical and accessible of their application as biosorbent in food system. The cell walls of these organisms are composed of complex polymers such as peptidoglycans, teichoic acids, and polysaccharides, which possess functional groups capable of binding metal ions as displayed in Figure 3 below.

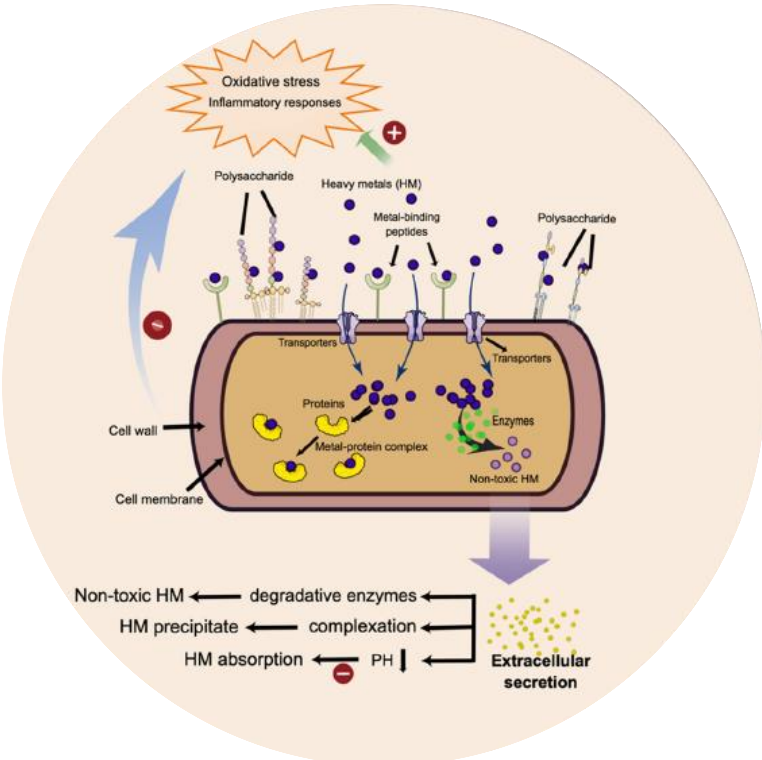

Figure 3 Adsorption of heavy metal ions onto cell wall of microorganism (Chen *et al.*, 2022)

Furthermore, a study that is done by Kirillova *et al.*, (2017) showed that seven strains of *Lactobacillus plantarum* and *L. fermentum* effectively removed Cd^{2+} and lead Pb^{2+} from solutions through a surface-binding mechanism in which highlighting lactic acid bacteria (LAB) as promising biosorbents for heavy metal decontamination in food and beverages. Another work on removing heavy metal through microorganism biosorbent also investigated by Pakdel *et al.*, (2019),found that *Lactobacillus plantarum* subsp. *plantarum* PTCC 1896, exhibited the highest biosorption capacity for Cd^{2+} (122.7 ± 37.3 mg/L) and Pb^{2+} (34.5 ± 2.9 mg/L) in a rapid, pH-dependent process. Another investigation by Massoud *et al.*, (2020) demonstrated that *Lactobacillus acidophilus* acts as an effective natural biosorbent for removing Pb^{2+} and Cd^{2+} from milk, achieving maximum bioremoval efficiencies of 80% and 75%, respectively, at an initial metal concentration of 100 µg/L and a bacterial concentration of 1×10^{12} CFU after 4 days.

In addition, enzymatic treatments represent another promising method of biological remediation of heavy metal pollutants (Saravanan *et al.*, 2021). Enzymes are specialized protein molecules that act as catalysts to accelerate biochemical reactions, including those that transform or treating heavy metals (Robinson, 2015a). For instance, certain oxidoreductases and hydrolases can convert toxic metal ions into safer or nonoluble forms, enabling their removal from food traits (Hazarika *et al.*, 2022; Mgbodile *et al.*, 2022). These enzymes can be extracted from microbial fermentation or from plant and animal tissues, and they are commonly highly specific, work well only on targeted action with minimal side effects. The use of enzymes renders noticeable advantages, such as rapid reaction rates, scalability, and compatibility with existing food processing systems (Chaudhary & Sagar, 2015). Moreover, enzyme-based treatments can be tailored to operate at specific pH and temperature ranges, making them suitable for a variety of food types (Robinson, 2015b).

Plant-Derived Coagulants

Natural plant extracts have also showed a promising and sustainable solution for the removal of heavy metals from aqueous food systems. These extracts, derived from a variety of plant based sources, have demonstrated significant potential in coagulating and eliminating toxic metals through mechanisms such as flocculation, complexation, and adsorption as shown in Figure 4 below.

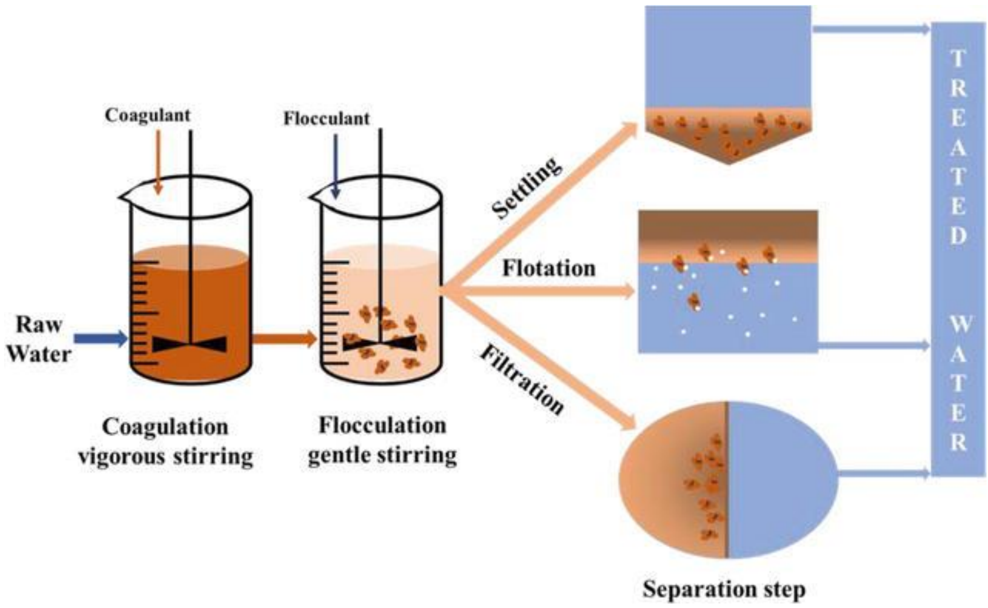

Figure 4 Mechanism of heavy metals removal trough coagulation process **(Lupa *et al.*, 2023)**

High Biodegradability, low toxicity, and as well as widespread availability properties of plant-based agent have made such method to be more appealing (Nguyen *et al.*, 2023). Moreover, plant-derived compounds often exhibit multifunctional properties, enabling them to play role not only in heavy metal removal but also as antioxidants or antimicrobial agents that enhancing food safety and shelf life (Pinto *et al.*, 2023). As the demand for cleaner and greener food technologies grows, plant-based coagulants offer a natural and cost-effective means to reduce the risks associated with heavy metal contamination (Devanathan *et al.*, 2024).

Among the most studied plant materials is *Moringa oleifera* (MO), commonly known as the drumstick tree, in which the seeds of *Moringa* contain water-soluble cationic proteins that exhibit strong flocculating activity (Nouhi *et al.*, 2019). These proteins are positively charged and able to effectively bind to negatively charged heavy metal particles suspended in aqueous solutions. Through this electrostatic interaction, the particles aggregate into larger flocs that can be easily separated by sedimentation or filtration (Barber-Zucker *et al.*, 2020). The use of *Moringa* seed extracts in water purification has been extensively researched, and its application is now being extended to food systems, where it can help reduce metal contamination in beverages, broths, and liquid food ingredients without introducing harmful residues or altering sensory properties. A study done by Shan *et al.*, (2017) on the application of MO seed, a natural coagulant for effective removal of heavy metals revealed complete elimination of Fe, up to 98% removal of Cu and Cd, as well as 78.1% reduction of Pb using a 1% MO seed dosage. In line with this, the investigation of MO seed extract was also done by Tanko *et al.*, (2020) to act as a coagulant for reducing heavy metals from water from system, the study exhibited removal efficiencies of 99.29% for Cd, Cr, and Fe, 96.03% for Cu, 95.56% for Co, 96.84% for Pb, 87.41% for Mg, and 91.35% for Zn. Lastly, the application of MO seed extract as a natural coagulant at dosages of 1–6 g/L, has also effectively removed heavy metals from wastewater with removal efficiencies of 98% for Fe, 95% for Cu, and 72% for Zn as done by Stanikina, (2023).

Green Nanotechnology

Green nanotechnology has become one of transformative approach in the innovation of sustainable solutions for heavy metal removal from food systems (Gong *et al.*, 2021). In contrast to conventional nanotechnology, which often relies on toxic chemicals and energy demanding processes, green nanotechnology emphasizes the use of environmentally friendly, non-toxic, and renewable resources in the synthesis of nanomaterials (Huston *et al.*, 2021). These materials, due to their high surface area and adjustable surface properties, exhibit remarkable capabilities in adsorbing, capturing, and neutralizing toxic metal ions from aqueous and food-based environments (Firdaus *et al.*, 2021).

Among the various applications of green nanotechnology, one particularly promising area is the development of plant-based nanosorbents, which leverage natural biomaterials for the eco-friendly synthesis of nanoparticles. These nanosorbents, derived from a wide range of plant extracts, agricultural by-products, fruit and vegetable wastes as well as other biomass sources (Anawar & Strezov, 2019; Mohammadinejad *et al.*, 2015; Osman *et al.*, 2024). The mechanisms by which these plant-based nanosorbents remove heavy metals typically involve a combination of adsorption, ion exchange, complexation, chemical precipitation, reduction, and electrostatic interactions between the functional groups present on the nanoparticle surface and the metal ions (Figure 5) (S. Singh *et al.*, 2021).

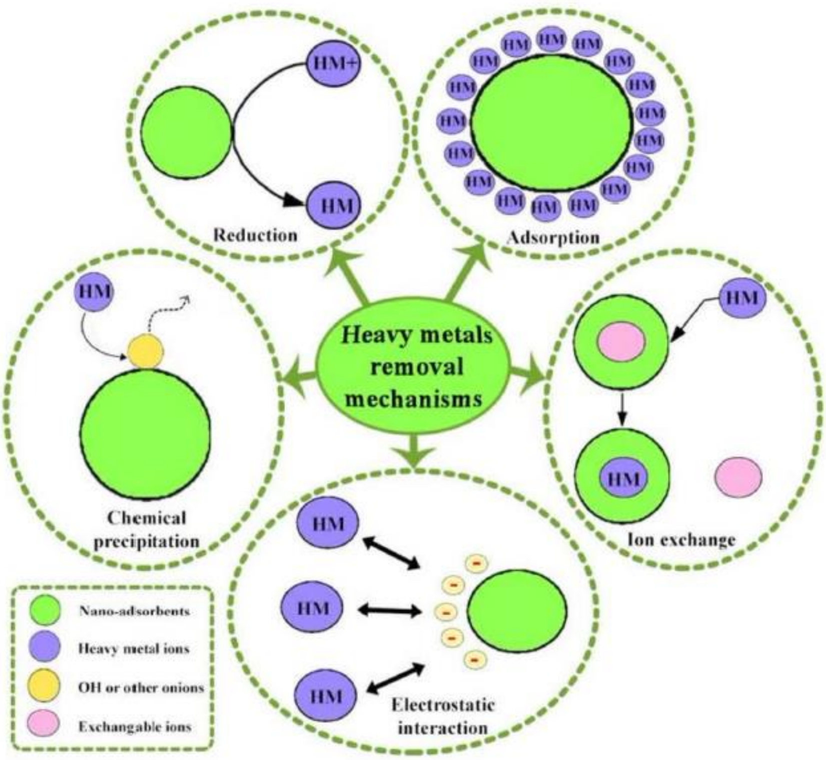

Figure 5 Processes involved in the elimination of heavy metals through nanosorbent system (Bakhtiari et al., 2024b)

For instance, amorphous Fe_3O_4 based hybrid nanosorbent (Fe_3O_4-BHN) has been synthesized using leaf extract from *Datura stramonium* as a green raw material demonstrated effective removal capabilities for Cd and Zn up to 91.88% for Cd and 89.21% for Zn (Chandra Joshi *et al.*, 2021). Similarly, a novel nanobiosorbent was also developed from *Pinus kesiya* cone biomass for the removal Cr, revealed maximum adsorption of heavy metal is up to 73.96 mg/g (Abhishek *et al.*, 2018). Moreover, another studied done by Kanwal *et al.*, (2023) on the synthesis nanosorbent from orange rind as green raw materials which was treated with metal oxide showed effective removal for heavy metals. The raw materials used included organic and nickel-based components, which underwent chemical treatments to form composite nanosorbents. The investigation achieved maximum removal efficiencies of 91% for Cd and 92% for Cr. Furthermore, a research on the use of nanosorbents derived from aquatic weeds, *Eichhornia crassipes* and *Lemna minor*, as effective materials for removing heavy metals has also conducted by Balasubramanian *et* *al., (2020)*. The raw materials, processed from aquatic biomass, undergone chemical and physical treatment to enhance their surface properties showed adsorption capacities of 79.04 mg/g for Cr and 85.09 mg/g for Ni leading them to act as a promising and eco-friendly nanosorbent for the efficient removal of hazardous heavy metals.

CONCLUSION

The persistent and toxic nature of heavy metals in food systems necessitates immediate and sustainable remediation efforts. Conventional methods, while partially effective, often fail to eliminate absorbed contaminants and may introduce additional risks. This review highlights the growing promise of eco-friendly technologies ssuch as bio-based adsorbents, microbial biosorption, plant-derived coagulants, and green nanomaterials which combine high removal efficiency with environmental compatibility. Furthermore, green nanotechnology offers a frontier for scalable, high-performance applications. Collectively, these strategies not only mitigate health risks but also contribute to circular economy and sustainable development goals.

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