The Journal of Anatomical Sciences
Email: journalofanatomicalsciences@gmail.com

J. Anat Sci 17(1) Mar

Submitted: November 19th, 2025
Revised: February 3rd, 2026
Accepted: February 6th, 2026

Recent Trends in Heavy Metal Poisoning and Management: A Concise Review

Saheed O. Afolabi*, Sifau, Sarafa Oloyede, Afolabi Adeosun, Itiolu Ibilola Funsho, Oyebanji Sunday Rotimi, Yahaya Hassanat, Anoka A. Njan

Department of Pharmacology and Therapeutics, Faculty of Basic Clinical Sciences, College of Health Sciences, Ilorin, Nigeria.

***Corresponding Author:** Email: afolabi.so@unilorin.edu.ng. Tel No.: +2348060728734; ORCID number: 0000-0001-9411-9229

ABSTRACT

Heavy metal poisoning is a global challenge, causing a major threat to public health and safety. It captures specific regional and national problems, such as arsenic contamination in India and parts of Asia, and lead contamination in urban soils from road construction and related activities in both developing and developed countries. These metals are linked to several pathologies, including cardiovascular diseases, cancer, etc. This review explores emerging trends in the incidence, routes of exposure, risk assessment, and management of heavy metal toxicity, with particular focus on vulnerable populations and geographic hotspots. New routes of exposure include the addition of mercury to skin-lightening creams, industrial emissions, contaminated nanomaterials, food and supplements contaminated with heavy metals, and inhalation of airborne particles from industrial activities such as rock blasting and waste incineration. These have increased exposure to these toxic metals at very harmful concentrations. Additionally, the influence of environmental factors such as climate change, advances in detection, and novel analytical techniques is being explored. The current review also highlights novel strategies for managing these toxicities in clinical and environmental settings. Strategies include optimized approaches in nanotechnology, e.g., coating nanoparticles with red blood cell membranes and loading them with di-mercaptosuccinic acid; the development of more targeted and effective chelating agents; phytotherapy; and nanotechnology-based detoxification through the microbial community. Overall, this review highlights the importance of scientific innovation, education, and environmental safety policies as tools for reducing the risks posed by exposure to toxic metals and ensuring the sustainable management of heavy metal poisoning.

Keywords: Heavy metals, exposure pathways, mechanisms, chelating therapy, nanotechnology-based therapy

INTRODUCTION

Heavy metals, including mercury (Hg), cadmium (Cd), arsenic (As), chromium (Cr), lead (Pb), etc., are harmful toxicants to man and the environment [1]. Exposure to these metals have a broad range, from the use of lead and cadmium in lipsticks and lip-glosses, to the use of mercury in skin lightening creams commonly used amongst male and females [2] and to the impact of burning, gas-flaring, rock-blasting, etc. [3]. Heavy metal poisoning can be defined as the bioaccumulation of heavy metals in soft tissues in toxic (very high dose) amounts, leading to adverse health effects [4]. While metals such as iron, zinc, copper, chromium, and manganese are required in minute amounts but become toxic at higher doses, others, such as lead, arsenic, mercury, and cadmium, are toxic even at low doses [5]. Exposure to these metallic elements is intensified by anthropogenic (man's) and industrial activities [3]. Their deleterious effects counteract the health relevance of heavy metals; for example, elevated exposure to antimony and/or chromium promotes carcinogenicity, lead poisoning is implicated in cognitive dysfunctions in infants, and mercury poisoning can cause Minamata disease. In contrast, cadmium toxicity leads to itai-itai disorder [6].

Recent research findings have postulated a very strong link between exposure to toxic heavy metals and cardiovascular diseases [7, 8]. Since cardiovascular pathologies rank high amongst the causes of global morbidity and mortality, this raises a major public health concern. Basic clinical and epidemiological data have identified some toxicodynamic mechanisms of these heavy metals, including oxidative stress mediated by the reactive nitrogen species (RNS) and reactive oxygen species (ROS), which can lead to other downstream mechanisms like oxidative stress, induction of inflammation, disruption of lipid metabolism, endothelial dysfunction, etc. [9, 10].

Recent trends in heavy metal poisoning are of growing global concern due to increased contamination from mining, agriculture, industrialization, and waste disposal [11]. These lead to bioaccumulation and diverse threats to optimal well-being, such as cancer, nephrotoxicity, and neurotoxicity[12]. Children and infants are the most vulnerable group, due to their developing immunological and anatomical systems [13, 14]. The emergence of new contaminants and advances in detection and remediation technologies, such as nanotechnology-based sensors and bioremediation methods, underscores the need for ongoing research. Furthermore, understanding the subclinical effects of chronic, low-level exposure is important. This review seeks to define heavy metal poisoning, differentiate essential from toxic metals, identify sources of contamination, explain mechanisms of toxicity, discuss routes of exposure, outline health effects, emphasize the research significance for public health, and identify knowledge gaps and future research directions.

Toxic heavy metals

Lead

Lead (Pb) is a bright silvery metal with a bluish glow in a dry atmosphere. The major routes of lead exposure include domestic sources (e.g., wall paint), water, food, and industrial processes. The industrial lead sources are storage batteries, plumbing pipes, combustion fuel, lead bullets, and pewter pitches. Occasionally, it permeates the soil, flows into rivers, is exposed to plants, and is eventually consumed by humans [15] (Figure 1).

Arsenic

Arsenic is amongst the most abundant elements with an atomic number of 33. Synthetic arsenate and arsenite compounds are toxic forms of arsenic that are commonly ingested through contaminated food and drinking water. Sources of contamination are typically pesticides, wood preservatives, smelting processes for copper and lead, and volcanic eruptions [16].

Mercury

Mercury is a known toxic element with multiple exposure routes, including consumption of certain seafood and ornamental use of certain types of jewelry. The commonest route of mercury intoxication is from consuming organic mercury or methylmercury, which is directly absorbed in seafood. Studies have shown that children and pregnant women are uniquely vulnerable to the hazardous effects of mercury poisoning, especially because it can access the placenta, causing neurological defects in the fetus [17].

Cadmium

Cadmium and its compounds are hydrophilic (water-soluble); therefore, they enter the food chain easily. Human exposure to cadmium occurs through smoking, dietary intake, and industrial activities such as battery production, mining, and smelting. Cadmium accesses the biological system via inhalation by residents of cadmium-polluted localities, while others are mainly through smoking and food. Additionally, high cadmium contents accumulate in the vegetation of wheat, rice, potatoes, etc., when irrigated with cadmium-contaminated water. This contamination results from industrial discharges from fossil fuel combustion, electroplating, alloying, sewage sludge incineration, and the use of fertilizers, particularly those containing phosphate. Women have been reported to have a high rate of intestinal Cadmium absorption when compared with men, and this has been linked to possible iron deficiency during pregnancy and menstruation[18].

Chromium

Chromium is considered a human carcinogen [19]. Chromium has two major stable forms; they are the trivalent Cr (III) and hexavalent Cr (VI) forms. The bioaccumulation of Cr (VI) leads to congenital malformations and genetic mutations, causing mutagenesis. Environmental and industrial exposure to Cr (VI) can lead to several pathologies, e.g., kidney failure, allergy, bronchospasm, and lung cancer. Gastric and duodenal ulcers, anemia, and gonadotoxicity, particularly in males, have also been linked to chromium poisoning [19]. The most prominent means of exposure to chromium in man are via the oral, inhalation, and transdermal routes.

Thallium

Thallium is not a common substance. It's a soft, bluish-white metal in form, malleable, and exists in two oxidation states (I and III). This element is a non-essential metal; in an abnormal physiological state, its concentration is low in humans, but it has high potential for adverse effects. Thallium toxicosis is a common acute disease among toxic metals. The Toxic dose at 50 % (TD_{50}) for thallium ranges from 8-10mg/kg for an adult human. In acute toxicity settings, it causes pathological changes in organs such as the heart (cardiotoxicity), stomach, liver (hepatotoxicity), brain (neurotoxicity), and kidneys (nephrotoxicity). Thallium can contaminate food and water via environmental pollution. Historically, it has been used as a pesticide and rodenticide [20].

Routes of exposure to toxic metals

In the last several decades, Lead (Pb) toxicity and its deleterious health effects have been reported by clinical researchers and toxicologists. The primary route of lead exposure has been identified as environmental pollution (Figure 2). The toxicological profile of lead is attributed to sex, the age at exposure, and host genetic variations. In addition, lead exposure has been recognized as a public health issue by several global organizations [21]. Under normal conditions, metallic lead is stable and largely unreactive in aqueous environments; upon thermalization, lead can be oxidized to various organic and inorganic species. Organic and inorganic lead metabolites have been linked with deleterious human health effects. The chronic presence of lead in water, air, and the atmosphere poses a significant health risk to the biosphere and its associated biodata. Toxicodynamic and risk assessment data on lead indicate a high risk among painters using lead-containing paints and industry workers exposed to burning fuels containing lead [22]. Furthermore, human activities cause environmental spills, including copper-silver and zinc-lead deposits. The addition of Tetraethyl lead (TEL) to gasoline has significantly contributed to environmental pollution. Lead has also been reported to be released from smelters and recycling centers in municipal areas, and young individuals have been exposed to lead through previously used sources of drinking water. However, lifestyle choices such as smoking and the use of lead-containing diet fillings have been reported as other means of human exposure to lead. Additionally, research has shown that the use of beauty products, such as cosmetics, facial creams, and surfactants containing lead-based chemicals, can result in direct lead toxicity through their use [23]. In humans, this exposure to lead poisoning via the use of cosmetics has a major impact, and the harmful consequences are definitely continuous [24]. Thus, chronic lead exposure and accumulation in the body can lead to severe adverse health consequences, particularly among the elderly. Research has shown that lead exposure in humans causes cognitive and behavioral disorders, pulmonary dysfunctions, hepatic and renal abnormalities.

The primary route by which cadmium enters the biological system is through the consumption of contaminated water and food. Active and passive smoke are the primary sources of exposure via inhalation. The adverse effect of cadmium is consequent upon the bioaccumulation in animals and plants for over 25 years. Fermentation by microorganisms is one of the significant approaches to eliminating cadmium from food. The use of phosphate fertilizers containing cadmium and waste incineration are additional exposure routes to cadmium. Scientific data have reported a significant difference in the levels of serum cadmium between non-smokers and smokers of cigarettes. Exposure to cadmium and lead can access the brain and cause neurodegenerative disorders such as Alzheimer's disease. Cadmium also bioaccumulates in specific organs, such as the kidneys; thus, urinary cadmium levels serve as biomarkers for cadmium toxicity in humans [25].

Mercury is one of the heavy metals studied worldwide because of its toxicity and apparent threat to food chains and ecosystems. The chemical composition of mercury determines a lot about its toxicity, i.e., a specific organic compound formed when mercury reacts with microorganisms is methylmercury [26]. Although it is an analog of mercury, it is more toxic than mercury. Sources of mercury have also been attributed to natural disasters, such as volcanoes and forest fires, and to human activities, such as fossil-fuel combustion in power plants.

One of the major global pollutants is mercury, which is a by-product of most modes of transportation [27]. Biological and physiological systems, which include the digestive and nervous systems of the body and organs like lungs and kidneys, are impacted due to toxicity even when exposure is to traces or minute quantities. Mercury was declared as part of the top-prioritized heavy metal contaminants. Aquatic ecosystems are severely affected by mercury, which is further transferred to the food chain, where humans can also be affected.

A metalloid naturally present in the lithosphere is arsenic, which enters the environment through human activities or through separation techniques that remove iron, manganese, and aluminum oxides [28]. The primary sources of arsenic are groundwater. A report by the World Health Organisation revealed that an estimated twenty-one countries have arsenic in their drinking water [29].

The exposure of arsenic is usually preceded by organo-arsenicals, and will change to inorganic forms, causing toxicity in the body [30]. Development of skin lesions, angiosarcoma, urinary tract cancers, etc., is part of the resultant effect of chronic exposure to arsenic in drinking water [31]. Furthermore, the severity of short-term exposure to arsenic can cause systemic adverse effects and mortality [32]. Diarrhea, fatigue, poor appetite, skin sores, muscle cramps, and hair loss are among the symptoms of acute arsenic poisoning; however, these are rare in waterborne arsenic exposure. The exposure of skin to arsenic for a long time may damage and cause changes like discoloration of the skin [33].

Toxicodynamic mechanisms of heavy metals

Several harmful effects are due to mechanisms associated with heavy metals, including protein dysfunction, DNA damage, membrane damage, oxidative stress, enzyme inactivation, and the quenching of in vivo antioxidants [34] (Figure 3). Studies have shown that metal toxicity due to oxidative stress leads to the formation of complexes between biological molecules, such as DNA, proteins, and lipids, and heavy metals, thereby causing cell damage [8, 35]. Consumption of food or water containing heavy metals is acidified and further oxidized, and consequently binds to macromolecules, i.e., enzymes and proteins, to form strong and stable bonds. The thiol groups (SCH3 group of methionine and SH group of cysteine) are the usual moieties that bind to heavy metals. Enzymes such as thioredoxin reductase, thiol transferases, glutathione reductase, and thioredoxin are found in humans and can prevent cadmium from binding to cysteine residues in their active sites [8].

Recent trends in heavy metal poisoning

The contamination, exposure, and health indices of heavy metal poisoning reveal that the current trends are complex and evolving. Although there has been a decline in certain areas due to awareness and regulations, the overall concern persists [32]. This is attributable to increased exposure via the use of cosmetics; aggressive industrialization in specific regions, emerging source of nano-contamination, etc. [24] (Figure 4). Though there has been a downward trend in emissions in advanced countries over the past century, pollution due to heavy metals remains an important issue globally. There is a significant increase in heavy metal poisoning in developing nations [36]. Agriculture, mining, and inadequate management of waste are industrial activities that are sources of heavy metals in the water and soil worldwide [37]. There has been an expansion in research to accommodate less studied heavy metals and metalloids, as against the traditional ones like arsenic, cadmium, lead and mercury, they include antimony, tin, nickel, copper, zinc, manganese, aluminium, selenium and chromium etc. due to the recognition of the possibilities of toxicity by these heavy metals at certain levels [38, 32]. Electronic waste recycling, also known as e-waste recycling, is identified as an emerging source of heavy metal contamination in developing nations, as well as the use of heavy metal-contaminated fertilizers and the leaching of metals from unconventional sources [39]. In addition to e-waste, microplastics are potential disseminators of heavy metals in the environment, and their absorption into the biological systems of organisms is increasing [40]. Different chronic diseases, i.e., renal disease, heart disease, neurological diseases, cancer, diabetes, and respiratory issues, are long-term effects associated with exposure to low-level heavy metals. A growing number of studies focus on the adverse health effects associated with these exposures [41]. The potential long-term consequences of the indirect effects of heavy metals on developmental stages, particularly in children, are being investigated.

Detection and monitoring of heavy metal poisoning

Long-term exposure to heavy metals, even at low levels, can result in neurologic, renal, cardiovascular, and developmental impairment. This is mainly due to polyphasic bioaccumulation. This implies that low consistent exposure, if not detected early, could be as detrimental as exposure at toxic concentrations [34]. Conservative detection methods, such as atomic absorption spectroscopy (AAS) coupled with inductively coupled plasma mass spectrometry (ICP-MS), are accurate but time-consuming and expensive, requiring complex instrumentation. However, optimization with artificial intelligence has greatly improved these techniques [43]. Recent advances in nanotechnology, biosensing, and artificial intelligence have combined to reshape detection and monitoring techniques into highly accessible, sensitive, and real-time methods.

Graphene quantum dots (GQDs) coupled with Machine Learning

Graphene quantum dots (GQDs) are regarded as a more efficient and accurate sensing material with excellent sensitivity because they possess physicochemical properties that improve their aqueous solubility [44]**.** The photoluminescence (PL) feature of GQDs has been used to develop an optical nano sensor for the identification of hazardous heavy metal ions in aqueous solutions [45]. Machine learning models have been incorporated into this system. This is to analyze and quantify ions based on the spectral data with high accuracy in various water bodies or water samples. This integration of AI and nanomaterials has enabled the development of a more robust, real-time monitoring tool that is cost-effective, portable, and environmentally stable.

Crowns ethers decorated silicon photonics for lead detection

Silicon photonics-based detection systems are another cutting-edge development in recent times. A silicon photonics-based detection system is functionalized with crown ether-amine conjugates to detect Pb (II) ions [46]. These crown ethers bind selectively to Pb (II) ions and, when on silicon photonic devices, permit label-free detection through resonance shifts. The developed system exhibited a wide dynamic detection range, from 1 ppb to more than 260000 ppb, with high selectivity against most interfering metal ions, including Ca (II) and Mg (II). This technology looks promising for continuous in situ environmental monitoring of industrial areas and drinking water sources [47].

Molecular communication-based nanomachines for biomedical monitoring

Yaldiz and Akan [48] proposed a nanomachine known as Particle Collector-Transmitter (PaCoT). This apparatus operates on the principles of molecular communication to adsorb heavy metals from blood. Briefly, the principle involves using metallothionein proteins as receptors; heavy metals such as cadmium and mercury, acting as ligands; microscale pumps; and the principle of Brownian motion to transport these metals to release points, such as lymphatic capillaries. PaCoT monitors receptor-binding event duration as a surrogate for metal concentration and initiates active transport upon reaching toxic levels. This could serve as the foundation for wearable detoxification devices in occupational health or during environmental emergencies.

Organic electronic biosensors for portable monitoring

Organic electronic materials are engineered as biosensors, since they are biocompatible, flexible, and produced at low cost. In a review by Kaushal *et al.* [49], the authors analyze the use of organic electronic materials to design all kinds of sensor types, including piezoelectric, optical, and electrochemical. These materials have proven sensitivity for heavy metal detection. Organic transistor-based biosensors that can be incorporated into wearables are particularly promising. These can be paired with smartphones to collect real-time quantified data and cloud-monitoring systems, providing individualized monitoring of exposure to individuals working in high-risk environments [50].

Management and treatment strategies for heavy metal poisoning

Early detection and treatment are critical for limiting irreversible damage and preventing fatality. Management usually includes removing the source of exposure, promoting elimination, inhibiting further intake or absorption, providing supportive therapies to maintain airway, breathing, and circulation, monitoring water and electrolyte balance, and managing other symptomatic manifestations [51]. These management approaches are categorized into three. These include the traditional approach, chelating therapy, and supportive and asymptomatic management.

Traditional or conventional approach

Traditional management strategies focus on identification and removal of the source of exposure and minimizing further absorption of heavy metals through GIT decontaminations, promoting elimination, monitoring systemic toxicity, and supporting affected organs [3]. Gastrointestinal (GIT) decontamination involves common modalities, including orogastric lavage, activated charcoal, and whole-bowel irrigation. Endoscopic retrieval and laparotomy are uncommon procedures used for severe ingestions and body packers [52]. Gastrointestinal decontamination is likely to improve patient outcomes across a range of conditions. However, technical limitations and contraindications can account for their infrequent use [53]. Activated charcoal is generally ineffective for most heavy metals, but may be used if the metal is co-ingested with other absorbable toxins.

Chelating therapy

Chelation therapy is the use of compounds to treat heavy metal poisoning. Chelating agents are commonly used to treat heavy metal poisoning like arsenic, lead, and mercury, which are known to be neurotoxic [54]. Some chelating agents selectively bind to target metals, whilst others chelate numerous metals. Deferoxamine, deferasirox, and deferiprone are chelating agents that are highly selective for iron, although their role in the management of lead, copper, magnesium, and calcium poisoning is little [55]. Penicillamine, trientine, and dimercaprol are used as copper-chelating agents. Dimercaprol is administered intravenously to treat acute or advanced symptoms of Wilson's disease. Additionally, Dimercaprol reduces levels of other heavy metals, such as arsenic and mercury. Lead and other heavy metal chelators include succimer (dimercaptol succinic acid, DMSA), dimercaprol (BAL), and ethylenediaminetetraacetic acid (EDTA). Succimer is given orally and appears to be more successful and more tolerated than the other medications, which need intravenous administration. These drugs are also used to treat arsenic, mercury, and cadmium toxicity [56].

Fig. 1. Some toxic heavy metals and their impact on living organisms [3]

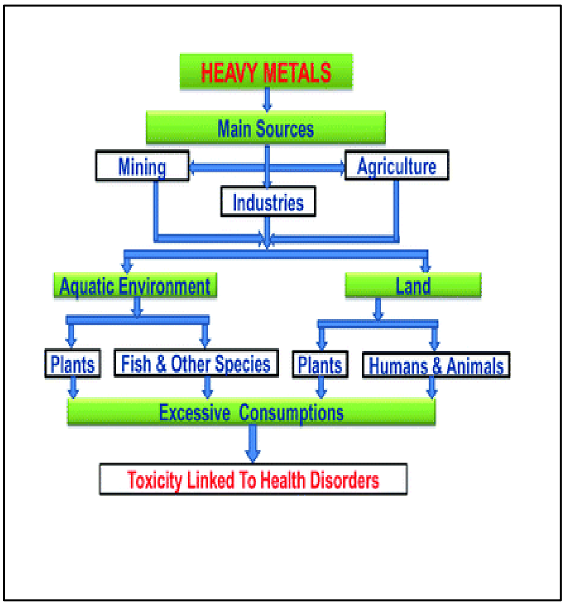

Figure 2. Major routes of exposure to heavy metals [3].

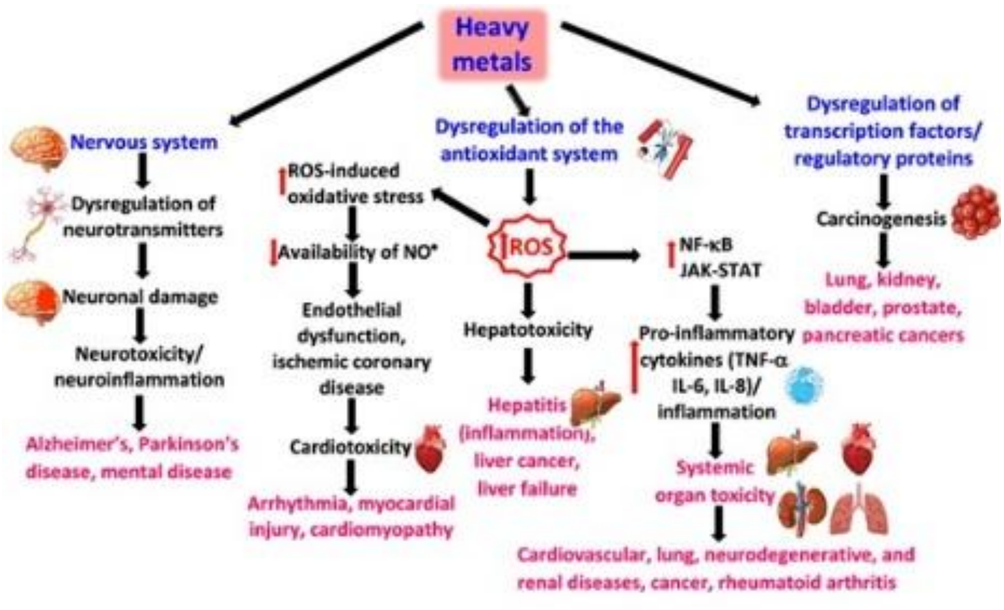

Fig. 3 Toxicodynamic mechanisms of heavy metals [8].

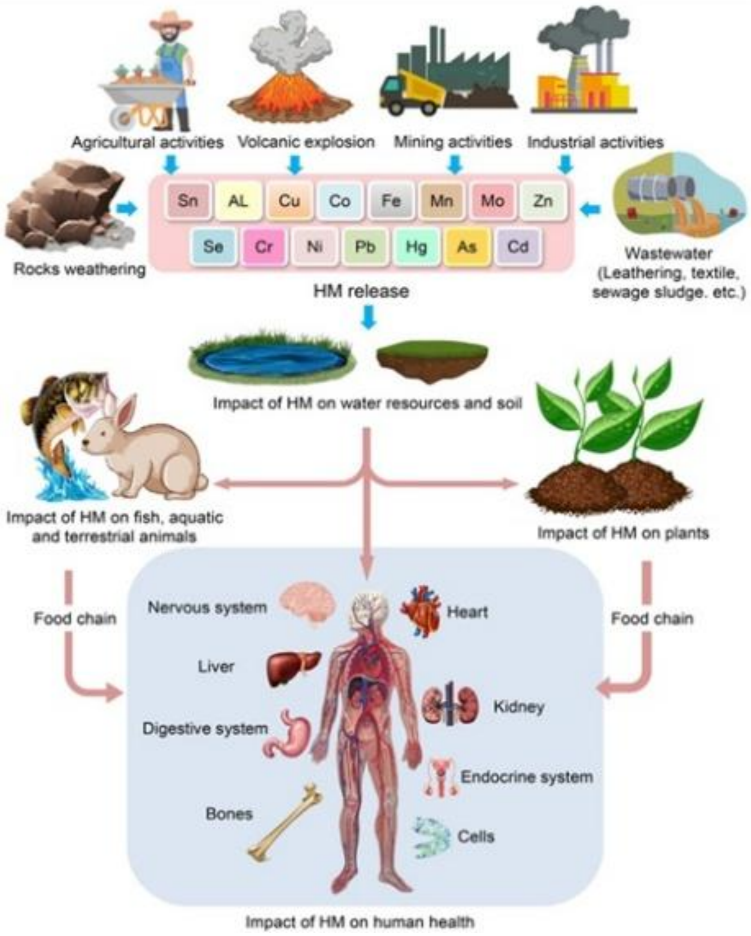

Fig. 4. Overview of recent exposure to heavy metals [42].

Recent advances in treatments and management of heavy metal poisoning

Recent advancements in the treatment of heavy metal poisoning include bioremediation, chelation therapy, and advanced filtration technologies. These developments aim to address the limitations inherent in traditional methodologies, particularly their efficacy at low concentrations and their potential to generate secondary pollutants.

Nanotechnology-based detoxification methods

The employment of nanotechnology for detoxification presents a contemporary and highly promising strategy for the removal or mitigation of heavy metals within biological and environmental contexts. Designed nanomaterials possess unique characteristics, such as high heavy metal adsorption capacity, which enhances effectiveness compared with conventional heavy metal removal techniques [57]. The distinctive attributes of nanomaterials, including substantial surface area, varied surface chemistry, and differing reactivity, have led to their extensive application in the elimination of heavy metals. Various types of nanomaterials have been investigated, including metal and metal-oxide nanoparticles, carbon-based nanomaterials, polymeric nanomaterials, and composite or magnetic nanoparticles [58].

Metal oxide nanoparticles

Metal oxide nanoparticles (MONPs) are among the most potent agents for detoxifying environments contaminated with heavy metals. Common examples include iron oxide, zinc oxide, titanium oxide, etc. The high adsorption capacity of MONPs is attributed to their expansive surface areas and reactive sites, facilitating effective binding with heavy metals [59]. Voltammetry, an electrochemical method, is frequently utilized for the detection of heavy metals due to its benefits of increased surface area and selectivity. The incorporation of nanoparticles into electrode modifications has been shown to significantly enhance analytical performance, yielding higher sensitivities and lower detection limits than conventional methods. Notably, iron oxide-based sensors provide a rapid, cost-effective, and efficient means for detecting lead in environmental contexts [60].

Carbon nanomaterials

Carbon-based nanoparticles for heavy metal detoxification primarily consist of carbon nanotubes (CNTs), graphene, its oxide derivatives, and carbon nanofibers. Significant scholarly attention has been devoted to exploring the application of CNTs in the extraction of toxic and heavy metals from both gaseous and aqueous environments [61]. The adsorption efficacy of CNTs is influenced by the concentration of heavy metals in the aqueous solution and the pH level of the medium. The predominant mechanism for heavy metal removal is adsorption, characterized by chemical reactions between heavy metals and CNTs bearing surface functional groups. Functionalized graphene nanocomposites, known for being a less corrosive adsorbent, possess extensive surface areas and multiple functional groups, thereby enhancing their effectiveness in removing contaminants such as Hg, Cr, Cu, Ni, and Pb.

Polymer-based and biopolymer nanomaterials

Among polymer-based solutions, clay/polymer nanocomposites present an environmentally sustainable approach for the removal of heavy metals from wastewater. The affordability and large surface area of clay contribute to enhanced adsorption via mechanisms such as electrostatic interactions, ion exchange, and chelation. Chitosan remains a prominent biodegradable and reusable material, noted for its environmentally friendly attributes in eliminating hazardous substances from ecological systems. Nonetheless, limitations remain regarding its long-term stability and efficacy in complex wastewater matrices [62].

Other nano-based approaches

Additional techniques rooted in nanotechnology for heavy metal detoxification encompass nano-zeolites, metal-organic frameworks (MOFs), and magnetic nanocomposites, among others. Nano-zeolites and MOFs are both porous materials with diverse structural and functional properties, providing utility in industrial and environmental applications [63]. Both materials share structural similarities, including extensive surface areas and distinctive adsorption capabilities, thereby enhancing their operational effectiveness. Applications of nano-zeolites are prevalent in the petrochemical sector, whereas MOFs are used for gas storage and separation, particularly for hydrogen and methane. In the context of environmental detoxification, nanomaterials play a crucial role in water purification and pollution control; however, their application is limited to specific high-temperature conditions. Magnetic nanoparticles are often coated with fucoidan, which serves as an effective and eco-friendly biomedical detoxifying agent. A notable advantage of these nanoparticles is their ability to withstand high temperatures and maintain stability under extreme pH levels, thereby rendering them particularly suitable for clinical applications [64].

Microbial bioremediation strategies

Microbial methods for heavy metal detoxification explore various mechanisms and efficiencies. Biosorption is a passive process that leverages cellular components to sequester metals, functioning effectively even in non-viable cells, thereby demonstrating cost-effectiveness [65]. Conversely, bioaccumulation necessitates metabolic energy for the active transport of metals into cells, enabling dynamic regulatory responses to fluctuating environmental conditions. Redox transformations detoxify metals by modifying their valence states through enzymatic processes, which are vital for metal cycling [66]. Chelation, facilitated by microbial metabolites such as siderophores, forms stable complexes with metals, thereby reducing their reactivity [67]. Furthermore, precipitation and biomineralization processes convert metals into insoluble or mineralized forms, assisting in long-term sequestration [65]. Each of these methods enhances the efficacy of environmental detoxification efforts.

CONCLUSION

Heavy metal toxicity persists as a major global environmental and public health problem. It is aggravated by contaminated water sources, industrialization, the escalating effects of climate change, and improper waste disposal. Some regions and nations have successfully implemented management measures via regulatory policies. However, these problems continue to affect developing nations and vulnerable demographics, such as pregnant women, children, laborers, and low-income communities. A comprehensive approach is essential to address the increasing challenge posed by heavy metal toxicity effectively. This approach should encompass proactive public health regulations, ethical business conduct, active environmental monitoring, public awareness initiatives, and international cooperation on both regulatory and remedial efforts. To address existing knowledge deficits and maintain environmental integrity, continuous media awareness and investment in advanced technologies and focused research efforts are imperative. The convergence of scientific inquiry, policy formation and social responsibility is vital for the future management of heavy metals.

REFERENCES

1. Pan Z, Gong T, Liang P. Heavy metal exposure and cardiovascular disease. Circ Res. 2024;134(9):1160-1178.
2. Saah SA, Boadi NO, Sakyi PO, Smith EQ. Human health risks of lead, cadmium, and other heavy metals in lipsticks. Heliyon. 2024;10(23).
3. Balali-Mood M, Naseri K, Tahergorabi Z, Khazdair MR, Sadeghi M. Toxic mechanisms of five heavy metals: mercury, lead, chromium, cadmium, and arsenic. Front Pharmacol. 2021; 12:643972.
4. Tchounwou PB, Yedjou CG, Patlolla AK, Sutton DJ. Heavy metal toxicity and the environment. Exp Suppl. 2012; 101:133-164. doi:10.1007/978-3-7643-8340-4_6.
5. Cheema S, Hussain SI, Faheem MS, Jalal AA, Rifai M, Dar A, *et al*. Toxic heavy metal exposure and heart health: a systematic review and meta-analysis of 324,331 patients. BMC Cardiovasc Disord. 2025;25(1):792.
6. Xu W, Jin Y, Zeng G. Heavy metals contamination in water and soil: a review on source, toxicity and remediation methods. Green Chem Lett Rev. 2024;17(1):2404235.
7. Ozarde Y, Purandare D, Deshmukh S, Gadhave R. Heavy metals and cardiovascular health: uncovering links and health challenges. J Trace Elem Med Biol. 2025;127648. doi: 10.1016/j.jtemb.2025.127648.
8. Jomova K, Alomar SY, Nepovimova E. Heavy metals: toxicity and human health effects. Arch Toxicol. 2025; 99:153-209. doi:10.1007/s00204-024-03903-2.
9. Davidova S, Milushev V, Satchanska G. The mechanisms of cadmium toxicity in living organisms. Toxics. 2024;12(12):875.
10. Ohiagu FO, Chikezie PC, Ahaneku CC. Human exposure to heavy metals: toxicity mechanisms and health implications. Mater Sci Eng Int J. 2022;6(2):78-87. doi:10.15406/mseij.2022.06.00183.
11. Das S, Sultana KW, Ndhlala AR, Mondal M, Chandra I. Heavy metal pollution in the environment and its impact on health: exploring green technology for remediation. Environ Health Insights. 2023; 17:11786302231201259. doi:10.1177/117863022312012.
12. Afzal A, Mahreen N. Emerging insights into the impacts of heavy metals exposure on health, reproductive, and productive performance of livestock. Front Pharmacol. 2024; 15:1375137.
13. Feiler MO, Kulick ER, Sinclair K, Spiegel N, Habel S, Castello OG. Toxic metals and pediatric clinical immune dysfunction: a systematic review of the epidemiological evidence. Sci Total Environ. 2024; 927:172303.
14. Zheng K, Zeng Z, Tian Q, Huang J, Zhong Q, Huo X. Epidemiological evidence for the effect of environmental heavy metal exposure on the immune system in children. Sci Total Environ. 2023; 868:161691.
15. Engwa AG, Ferdinand UP, Nwalo NF, Unachukwu NM. Mechanism and health effects of heavy metal toxicity in humans. IntechOpen. 2018. doi:10.5772/intechopen.82511.
16. Fisher MR, Gupta V. Heavy metals [Internet]. 2024. Available from: http://creativecommons.org/licenses/by-nc-nd/4.0/
17. Cherney K. Understanding mercury poisoning [Internet]. Healthline; 2022. Available from: https://www.healthline.com/health/mercury-poisoning-symptoms
18. Khan MR, Sarker AR, Akter T. Groundwater arsenic contamination in rural Bangladesh: risk assessment and mitigation. Int J Hyg Environ Health. 2022; 239:113861. doi: 10.1016/j.ijheh.2021.113861.
19. Sharma N, Sodhi KK, Kumar M, Singh KD. Heavy metal pollution: insights into chromium ecotoxicity and recent advancements in its remediation. Environ Nanotechnol Monit Manag. 2021; 15:100388. doi: 10.1016/j.enmm.2020.100388.
20. Genchi G, Sinicropi MS, Lauria G, Carocci A, Catalano A. The effects of cadmium toxicity. Int J Environ Res Public Health. 2020;17(11):3782.
21. Basri NEA, Saleh TA, Al-Gheethi A. Heavy metals contamination in water and sediment of gold mining areas in Malaysia: a review. Environ Nanotechnol Monit Manag. 2017; 7:112-122.
22. World Health Organization. Global analysis of food safety and contaminants monitoring systems [Internet]. Geneva: World Health Organization; 2022. Available from: https://www.who.int/publications/i/item/9789240065204
23. Thangavel P, Park D, Lee YC. Recent insights into particulate matter (PM2.5)-mediated toxicity in humans: an overview. Int J Environ Res Public Health. 2022; 19:7511.
24. Laoye B, Olagbemide P, Ogunnusi T, Akpor O. Heavy metal contamination: sources, health impacts, and sustainable mitigation strategies with insights from Nigerian case studies. F1000Res. 2025. doi:10.12688/f1000research.160148.1.
25. Briffa J, Sinagra E, Blundell R. Heavy metal pollution in the environment and its toxicological effects on humans. Heliyon. 2020;6(9):e04691. doi: 10.1016/j.heliyon. 2020.e04691.
26. Jyothi NR. Heavy metal sources and their effects on human health. IntechOpen. 2020. doi:10.5772/intechopen.95370.
27. Jyothi NR, Mohamed Farook NA. Heavy metal toxicity in public health. IntechOpen. 2020. doi:10.5772/intechopen.90333.
28. Valskys V, Hassan HR, Wołkowicz S, Satkūnas J, Kibirkštis G, Ignatavičius G. A review on detection techniques, health hazards and human health risk assessment of arsenic pollution in soil and

groundwater. Minerals. 2022; 12:1326. doi:10.3390/min12101326.
29. Jaafarzadeh N, Poormohammadi A, Almasi H, Ghaedrahmat Z, Rahim F, Zahedi A. Arsenic in drinking water and kidney cancer: a systematic review. Rev Environ Health. 2023; 38:255-263. doi:10.1515/reveh-2021-0168.
30. Ganie SY, Javaid D, Hajam YA. Arsenic toxicity: sources, pathophysiology, and mechanism. Toxicol Res (Camb). 2024. doi:10.1093/toxres/tfad111.
31. Passeron T, Krutmann J, Andersen M. Clinical and biological impact of exposure on the skin. J Eur Acad Dermatol Venereol. 2020; 34:4-25. doi:10.1111/jdv.16614.
32. Acharya S. Heavy metal contamination in food: sources, impact, and remedy. In: Food safety and quality in the global south. Singapore: Springer Nature; 2024. p. 233-261.
33. Mishra A, Arora C. Heavy metal poisoning: a brief overview. Int J Acad Med Pharm. 2024;6(4):1031-1033.
34. Cheng YF, Zhao YJ, Chen C, Zhang F. Heavy metals toxicity: mechanism, health effects, and therapeutic interventions. MedComm (2020). 2025;6(9): e70241.
35. Haidar Z, Fatema K, Shoily SS, Sajib AA. Disease-associated metabolic pathways affected by heavy metals and metalloids. Toxicol Rep. 2023; 10:554-570.
36. Ondrasek G, Shepherd J, Rathod S, Dharavath R, Rashid MI, Brtnicky M, *et al*. Metal contamination–a global environmental issue: sources, implications and advances in mitigation. RSC Adv. 2025;15(5):3904-3927.
37. Adnan M, Xiao B, Ali MU, Xiao P, Zhao P, Wang H, *et al*. Heavy metals pollution from smelting activities: a threat to soil and groundwater. Ecotoxicol Environ Saf. 2024; 274:116189.
38. Dey S, Rajak P, Sen K. Bioaccumulation of metals and metalloids in seafood: a comprehensive overview of mobilization, interactive effects in eutrophic environments, and implications for public health risks. J Trace Elem Miner. 2024; 8:100141.
39. Chen XJ, Ma JJ, Yu RL, Hu GR, Yan Y. Bioaccessibility of microplastic-associated heavy metals using an in vitro digestion model and its implications for human health risk assessment. Environ Sci Pollut Res Int. 2022;29(51):76983-76991.
40. Osman AI, Hosny M, Eltaweil AS, Omar S, Elgarahy AM, Farghali M, *et al*. Microplastic sources, formation, toxicity, and remediation: a review. Environ Chem Lett. 2023;21(4):2129-2169.
41. Tahir I, Alkheraije KA. A review of important heavy metals toxicity with special emphasis on nephrotoxicity and its management in cattle. Front Vet Sci. 2023; 10:1149720. doi:10.3389/fvets.2023.1149720.
42. AbdElnabi MK, Elkaliny NE, Elyazied MM, Azab SH, Elkhalifa SA, Elmasry S, *et al*. Toxicity of heavy metals and recent advances in their removal: a review. Toxics. 2023;11(7):580. doi:10.3390/toxics11070580.
43. Yadav N, Maurya BM, Chettri D, Pulwani C, Jajula M, Elangovan A, *et al*. Artificial intelligence in heavy metals detection: methodological and ethical challenges. Hyg Environ Health Adv. 2023; 7:100071.
44. Facure MHM, Schneider R, Lima JBS, Mercante LA, Correa DS. Graphene quantum dots-based nanocomposites applied in electrochemical sensors: a recent survey. Electrochem. 2021;2(3):490-519. doi:10.3390/electrochem2030032.
45. Kadian S, Shukla S, Yadav AK, Arya B, Sethi S, Chaudhary V, *et al*. Recent advancements in graphene quantum dot-based bioimaging and drug delivery systems. MedComm (2020). 2025;6(10):e70320.
46. Chow EH, Bhargava M, Song Y, Buriak JM. Crown ether-decorated silicon photonics for selective Pb2+ detection. arXiv. 2023. Available from: https://arxiv.org/abs/2311.07581
47. Ranno L, Tan YZ, Ong CS, Guo X, Koo KN, Li X, Wang W, Serna S, Liu C, Rusli, *et al*. Crown ether decorated silicon photonics for safeguarding against lead poisoning. Nat Commun. 2024;15(1):3820. doi:10.1038/s41467-024-47938-6.
48. Yaldiz HE, Akan OB. Molecular communication-inspired particle collector-transmitter (PaCoT) for heavy metal removal from human circulatory system. arXiv. 2025;2501.06092.
49. Kaushal JB, Raut P, Kumar S. Organic electronics in biosensing: a promising frontier for medical and environmental applications. Biosensors (Basel). 2023;13(11):976.
50. Wu B, Ga L, Wang Y, Ai J. Recent advances in the application of bionanosensors for the analysis of heavy metals in aquatic environments. Molecules. 2023;29(1):34. doi:10.3390/molecules29010034.
51. Gerhardsson L. Diagnosis and treatment of metal poisoning: general aspects. In: Nordberg GF, Costa M, editors. Handbook on the toxicology of metals. 5th ed. Cambridge (MA): Academic Press; 2022. p. 663-684. doi:10.1016/B978-0-12-823292-7.00017-6.
52. Albertson TE, Owen KP, Sutter ME, Chan AL. Gastrointestinal decontamination in the acutely poisoned patient. Int J Emerg Med. 2011; 4:65. doi:10.1186/1865-1380-4-65.
53. Gosselin S, Hoegberg LCG, Hoffman RS. Gut decontamination in the poisoned patient. Br J Clin Pharmacol. 2025;91(3):595-603. doi:10.1111/bcp.16379.
54. Ornillo C, Harbord N. Fundamentals of toxicology—approach to the poisoned patient. Adv Chronic Kidney Dis. 2020;27(1):5-10.
55. Premawardhena A, Perera C, Wijethilaka MN, Wanasinghe SK, Rajakaruna RHMG, Samarasinghe RANKK, *et al*. Efficacy and safety of deferoxamine, deferasirox, and deferiprone triple iron chelator

combination therapy for transfusion-dependent β-thalassaemia with very high iron overload: a protocol for a randomised controlled clinical trial. BMJ Open. 2024;14(2):e077342. doi:10.1136/bmjopen-2023-077342.

56. Flora SJ, Pachauri V. Chelation in metal intoxication. Int J Environ Res Public Health. 2010;7(7):2745-2788.
57. John M. Advances in nanotechnology: innovative approaches for detoxifying heavy metals. J Heavy Met Tox Dis. 2024; 9:41.
58. Karnwal A, Malik T. Nano-revolution in heavy metal removal: engineered nanomaterials for cleaner water. Front Environ Sci. 2024; 12:1393694. doi:10.3389/fenvs.2024.1393694.
59. Sawan S, Maalouf R, Errachid A, Jaffrezic-Renault N. Metal and metal oxide nanoparticles in the voltammetric detection of heavy metals: a review. TrAC Trends Anal Chem. 2020; 131:116014.
60. Jjagwe J, Olupot PW, Kulabako R, Carrara S. Electrochemical sensors modified with iron oxide nanoparticles/nanocomposites for voltammetric detection of Pb (II) in water: a review. Heliyon. 2024;10: e29743. doi: 10.1016/j.heliyon. 2024.e29743.
61. Nayak T, Pathan A. Environmental remediation and application of carbon-based nanomaterials in the treatment of heavy metal-contaminated water: a review. Mater Today Proc. 2023; 92:1659-1667.
62. Hasan MN, Rahman MH, Akter F. Release of antimony from plastic containers into drinking water in tropical environments. Environ Technol Innov. 2021;24:102012. doi: 10.1016/j.eti.2021.102012.
63. Li R, Chen T, Pan X. Metal–organic-framework-based materials for antimicrobial applications. ACS Nano. 2021;15(3):3808-3848.
64. Kuncser V. Multifunctional magnetic nanocomposites: innovative processing and applications. Nanomaterials (Basel). 2023;13(1):206. doi:10.3390/nano13010206.
65. Priya AK, Gnanasekaran L, Dutta K, Rajendran S, Balakrishnan D, Soto-Moscoso M. Biosorption of heavy metals by microorganisms: evaluation of different underlying mechanisms. Chemosphere. 2022; 307:135957.
66. Jayaram S, Ayyasamy PM, Aishwarya KP, Devi MP, Rajakumar S. Mechanism of microbial detoxification of heavy metals: a review. J Pure Appl Microbiol. 2022;16(3):1562-1572.
67. Ghuge SA, Nikalje GC, Kadam US, Suprasanna P, Hong JC. Comprehensive mechanisms of heavy metal toxicity in plants, detoxification, and remediation. J Hazard Mater. 2023; 450:131039.