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Heavy metal contamination as a major environmental and public health concern - A Review

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Abstract: *Heavy metal contamination remains a major global environmental and public health issue because of the persistence, bioaccumulation, and toxicity of metals including lead, mercury, cadmium, arsenic, and chromium. This study combines bibliometric and qualitative reviews to evaluate research trends and health hazards associated with heavy metal pollution. Data retrieved from the Scopus database (2014–2025) produced 18,930 documents, refined to 7,768 English-language research articles after excluding conference papers, reviews, and errata. VOSviewer, MapPlot, and OriginPro were used to analyze publication trends, research productivity, citation impact, and keyword networks. Contributions came from 174 countries, with 22 meeting the threshold of at least 50 publications and 5,000 citations. China and the United States recorded the highest outputs and citation impacts, while Nigeria contributed about 205 publications with over 5,000 citations, reflecting growing but limited African participation. Among 552 publication outlets, 12 major journals met productivity thresholds and accumulated more than 50,000 citations. Keyword analysis identified 41,618 terms, with 918 significant keywords grouped into seven thematic clusters that guided the qualitative review. The synthesis showed that heavy metals cause toxicity through oxidative stress, enzyme inhibition, mitochondrial dysfunction, genotoxicity, endocrine disruption, and imbalance of essential metal homeostasis, resulting in neurological, renal, hepatic, cardiovascular, reproductive, immune, and carcinogenic disorders. A Nigerian case study highlighted persistent exposure risks and regulatory challenges. Overall, the study provides an integrated evidence base to support environmental monitoring, risk assessment, policy formulation, and sustainable mitigation of heavy metal pollution.*

Keywords*:* *Heavy metals, toxicity, carcinogenicity, nephrotoxicity, environmental pollution, genotoxicity*

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1.0 Introduction

Heavy metals are naturally occurring elements with high atomic weight and toxicity, many of which persist and bioaccumulate in environmental systems. While some metals such as iron, zinc, and copper are essential for biological functions, others including lead, mercury, cadmium, and arsenic pose serious environmental and health risks even at low concentrations due to their toxicity and persistence (Ali et al., 2019; Balali-Mood et al., 2021).Rapid industrialization, mining, intensive agriculture, electronic-waste recycling, and urbanization have significantly increased heavy metal concentrations in soil, water, and air, thereby altering natural biogeochemical cycles (Yin et al., 2021).

Unlike many organic pollutants, heavy metals are non-biodegradable and accumulate in food chains through crops, fish, and contaminated water sources (Khan et al., 2020). Their toxic effects are mainly associated with oxidative stress, enzyme inhibition, and disruption of cellular processes (Huang et al., 2024), leading to kidney damage, neurodevelopmental disorders, cardiovascular diseases, endocrine disruption, immunosuppression, and cancers (Singh et al., 2022). The severity of toxicity depends on the type of metal, exposure route, duration, and health condition of exposed individuals (Balali-Mood et al., 2021). Consequently, understanding contamination sources, exposure pathways, and health implications remains essential for environmental protection and public health management.

Although numerous studies have investigated heavy metal occurrence and toxicological effects, integrated assessments combining bibliometric evaluation with qualitative synthesis remain limited, particularly for developing countries. Therefore, this study presents a combined bibliometric and qualitative review of global research on heavy metal contamination using Scopus data from 2014–2025. The study analyzes global research productivity, leading countries, authors, and publication sources, while keyword co-occurrence analysis was used to develop a conceptual framework for the qualitative review. Recent studies were further examined to evaluate contamination sources, exposure pathways, toxicity mechanisms, and associated clinical effects. A Nigerian case study was included to highlight regional environmental challenges and regulatory concerns. This study provides an integrated perspective on research trends, health impacts, and mitigation strategies necessary for sustainable environmental management.

, and concluding remarks are presented.

2.0 Materials and Method

The bibliometric review was conducted using the Scopus database, recognized as one of the most reliable and comprehensive scientific databases, with broader journal coverage than the Web of Science (WoS). This wider coverage enabled more extensive retrieval of relevant publications. The search query ("heavy metal" OR "contamination" OR "clinical manifestation") AND ("health hazards") was used to identify related studies published between 2014 and November 2025. An initial search retrieved 18,930 documents. The results were refined to include only peer-reviewed research articles published in English, while conference papers, review articles, errata, and other document types were excluded. After refinement, 7,768 articles were retained for bibliometric analysis. VOSviewer, MapPlot, and OriginPro software were employed for visualization, mapping, and statistical analysis. A conceptual framework based on keyword clustering was subsequently developed to guide the qualitative review.

3.0 Results and Bibliometric Analysis

3.1 Country Trends in Heavy Metal Research

A total of 174 countries contributed to research on heavy metals. However, applying a threshold of at least 50 publications and 5,000 citations reduced the dataset to 22 countries for detailed analysis. These countries are presented in the global distribution map (Fig. 1) and comparative visualization (Fig. 2). Figure 1 provides clearer geographical representation for regions that are difficult to distinguish in network maps, such as Hong Kong, which appears merged with China.

China recorded the highest number of publications and citations, followed by the United States, reflecting strong global scientific interest in heavy metal contamination and associated health hazards. The increasing research output highlights the growing importance of heavy metal studies in promoting cleaner and more sustainable environmental systems. Nigeria contributed approximately 205 publications with more than 5,000 citations, indicating increasing regional research participation. Nevertheless, research output from many African countries remains comparatively low despite significant exposure risks.

3.2 Sources of Publications on Heavy Metals

Identifying major publication sources is important for guiding researchers toward suitable journals for disseminating their findings. Source analysis was conducted using VOSviewer by applying a minimum threshold of five publications per source and at least 5,000 citations.

Out of 552 identified publication sources, only 12 met the inclusion criteria (Fig. 3). *Science of The Total Environment* recorded the highest research output and citation impact, accumulating approximately 50,000 citations over the past decade. This was followed by *Chemosphere*, which published about 500 articles and received nearly 3,000 citations during the same period. These journals remain major publication outlets for achieving visibility and scholarly impact in heavy metal research.

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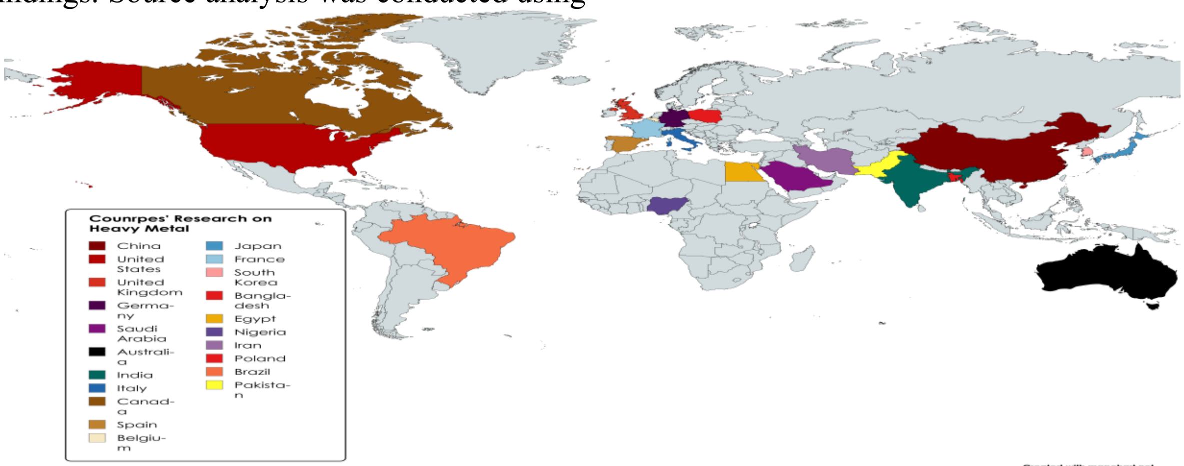


Fig. 1. Global distribution of countries with significant research output on heavy metal contamination.

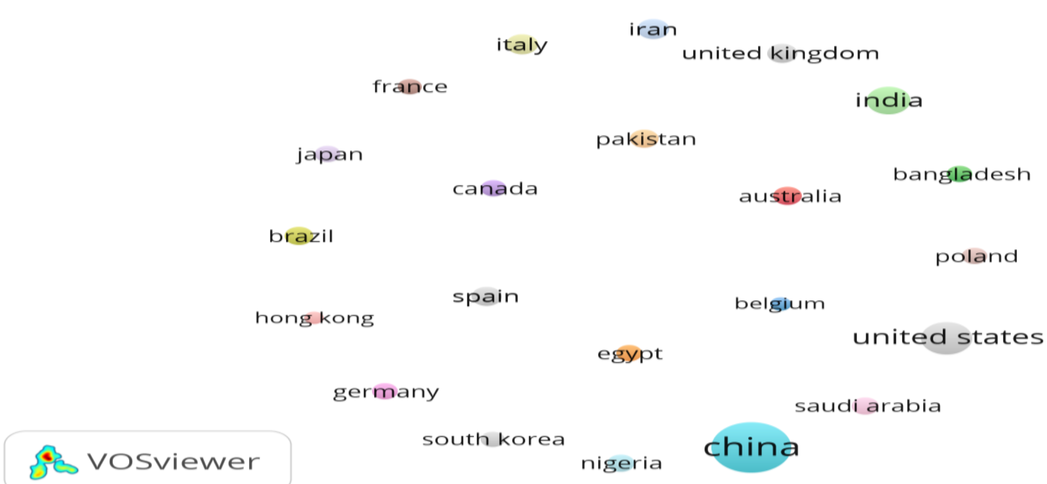


Fig. 2. Network visualization of prolific countries in heavy metal research generated using VOSviewer.

Identification of prolific authors is important for understanding collaboration networks and research leadership within the field. This is necessary for the establishment of collaborative networks and also the mentorship. Author analysis was conducted by setting a minimum threshold of 10 publications and at least 1,000 citations.

Out of 28,971 authors identified in the Scopus dataset, 25 met the established thresholds (Fig. 4). Jörg Rinklebe emerged as the most prolific author, exhibiting the highest number of publications and citations in heavy metal and environmental science research. Zhang Lei has the next highest number of articles in relation to the heavy metal studies but with just about 1300 citations. Figure 4 further indicates that some authors with fewer publications achieved high citation counts, reflecting the substantial scientific impact of their contributions.

3.3 Keywords analysis and conceptual framework

The co-occurrence analysis with all the keywords as the unit analysis was conducted to track the keywords related to the heavy metal by setting the minimum number of occurrences to 50 keywords. About 41618 keywords were identifiedyout of which 941 meet the threshold.

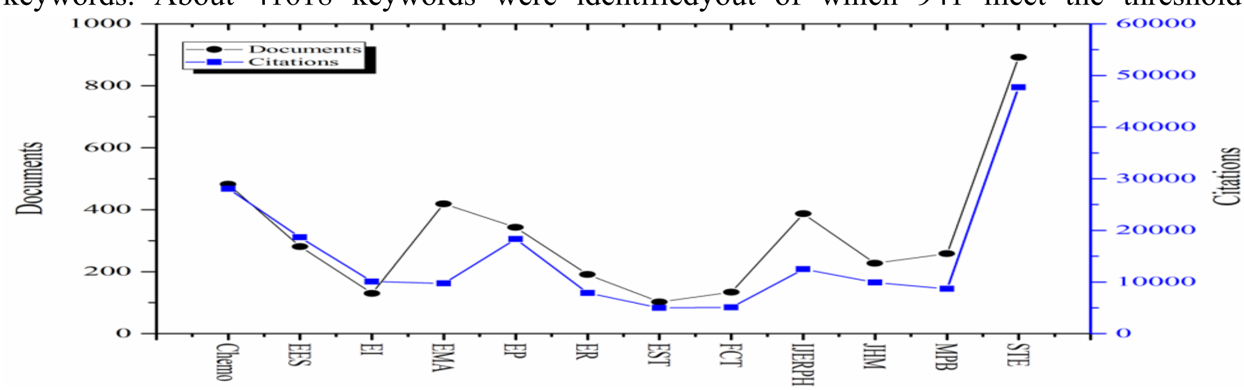
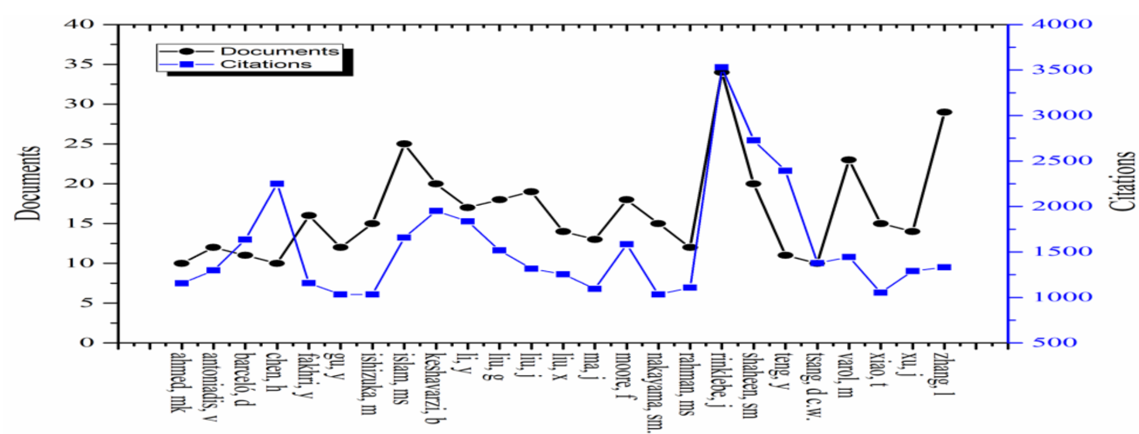


Fig. 3. Major publication sources in heavy metal research.



- **Fig. 4. Network visualization of prolific researchers in heavy metal studies.**

The cleaning was further done on the 941 keywords by removing the words like articles, proximity journal and name of countries like China, Iran, Turkey among others. After the cleaning, we eventually have 918 items. The mapping of the keywords is shown in Fig. 5.z ealth hazards, heavy metals, risk assessments and environmental effects are prominent in the Fig. 5. There are generally seven clusters indicated with different colours such as red, green, blue among others (Fig. 6).The cluster is used to generate the concepture frameework under which the systematic and qualitative review will be done under various headings in relation to heavy metals.

4.0 Discussion Based on the Conceptual Framework

4.1 Heavy metals

Heavy metals have been defined using different criteria depending on physicochemical parameters such as density, atomic weight, and toxicity.

Järup (2003) defined heavy metals as metals with densities greater than 5 g cm^{-3}.

Metals such as lead, cadmium, mercury, and arsenic are among the most toxic heavy metals affecting human health.

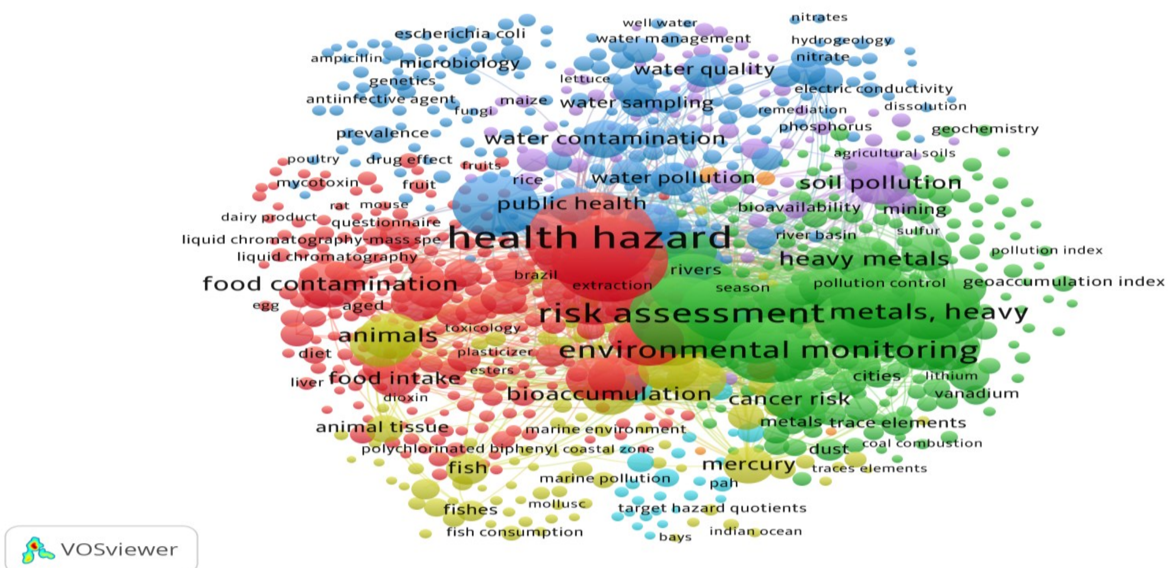
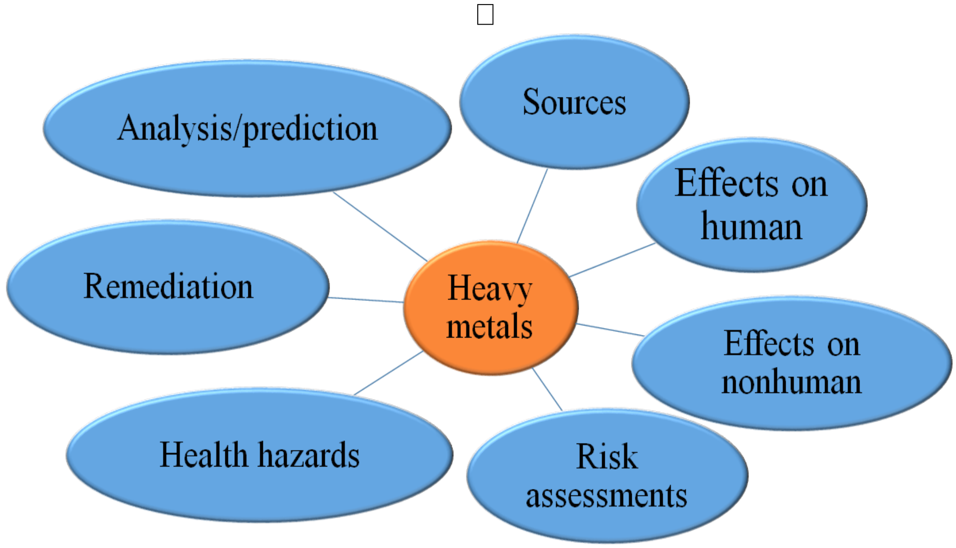


Fig. 5. Keyword co-occurrence network for heavy metal research.



- **Fig. 6. Conceptual framework derived from keyword clustering analysis.**

Duffus (2002) argued that the term "heavy metal" lacks strict scientific meaning because toxicity is not directly correlated with density. Not all heavy metals are harmful; several play essential biological roles when present in trace concentrations, particularly transition elements within the fourth period of the periodic table (Emsley, 2011).

Elements such as vanadium, manganese, selenium, nickel, and arsenic participate in enzymatic reactions, hormone regulation, and cellular metabolism. However, concentrations exceeding physiological thresholds result in toxicity and adverse health effects.

Significant research attention has been devoted to assessing heavy metals across environmental compartments including air, water, and soil due to their toxicity and carcinogenic potential.

Hence, heavy metals can be broadly classified into two which are essential and nonessential as presented in Fig. 7. The importance of heavy metals determination is also supported by the number of studies across different countries that have been done on heavy metals. This subsection provides a qualitative discussion of heavy metals based on the conceptual framework illustrated in Fig. 6.

4.2 Sources of Heavy Metal Contamination

Heavy metals enter the environment through both natural processes and anthropogenic activities. Understanding contamination sources is essential for developing effective monitoring and mitigation strategies. Although geological processes such as volcanic eruptions, weathering of rocks, and forest fires contribute to natural heavy metal deposition, human activities are the predominant source of hazardous contamination today (Zhang *et al.*, 2021).

.4.2.1 Industrial Discharges

The principal anthropogenic sources contributing to heavy metal pollution are discussed below. Industries such as mining, smelting, metallurgy, leather tanning, electroplating, and textile manufacturing release large volumes of heavy metals into surrounding water bodies and soil. For example, effluents from battery production, metal plating, and paint manufacturing often contain significant concentrations of lead, cadmium, and chromium (Wu *et al.*, 2022). These releases contribute significantly to long-term environmental accumulation and ecological toxicity.

Different sources of heavy metals have been identified and are summarized in Fig. 8 (Kim *et al.*, 2019). Heavy metals of major toxicological concern include lead (Pb), mercury (Hg), cadmium (Cd), arsenic (As), and chromium (Cr), among others. These metals vary in their sources, mechanism of action, and clinical effects (Jyothi *et al.*, 2020). A summary of major contamination sources is presented in Fig. 8.

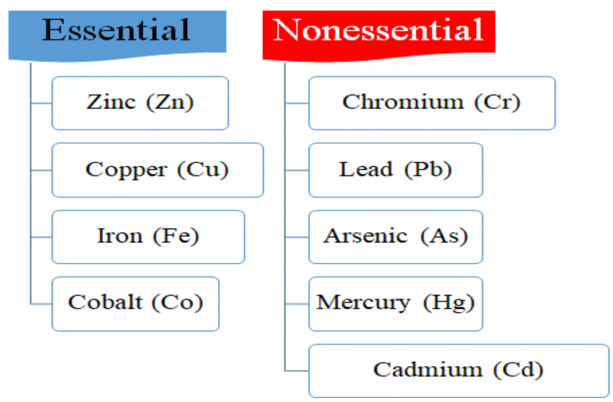


Fig. 7: Classification of heavy metals

4.2.2 Agricultural Inputs

Continuous agricultural application promotes gradual soil accumulation and subsequent food-chain transfer. For example, the use of phosphate fertilizers, pesticides, and herbicides contributes significantly to heavy metal contamination in agricultural soils. These inputs may contain arsenic, lead, mercury, and cadmium, which can leach into groundwater or be taken up by crops, thereby entering the food chain (Khan *et al.*, 2020).

4.2.3 Waste Disposal and Landfills

Improper management of municipal solid waste, electronic waste (e-waste), and industrial residues represents a major pathway for heavy metal release into environmental systems. Leachates from landfills often carry heavy metals such as mercury, arsenic, and lead into nearby ecosystems (Ahmed *et al*., 2020; Beinabaj *et al*., 2023; Montreemuk *et al*. 2025).

4.2.4 Mining Activities

Mining and ore refining generate large amounts of tailings and runoff that are rich in heavy metals. These pollutants can contaminate rivers, groundwater, and agricultural land in nearby communities, posing severe health risks (Yin *et al*., 2020). Mining effluent has been considered as one of the major pollutants because even long after the mining activities have stopped, the emitted metals throughout these effluents continue to persist in the environment (Vendrell-Puigmitja *et al*., 2020).

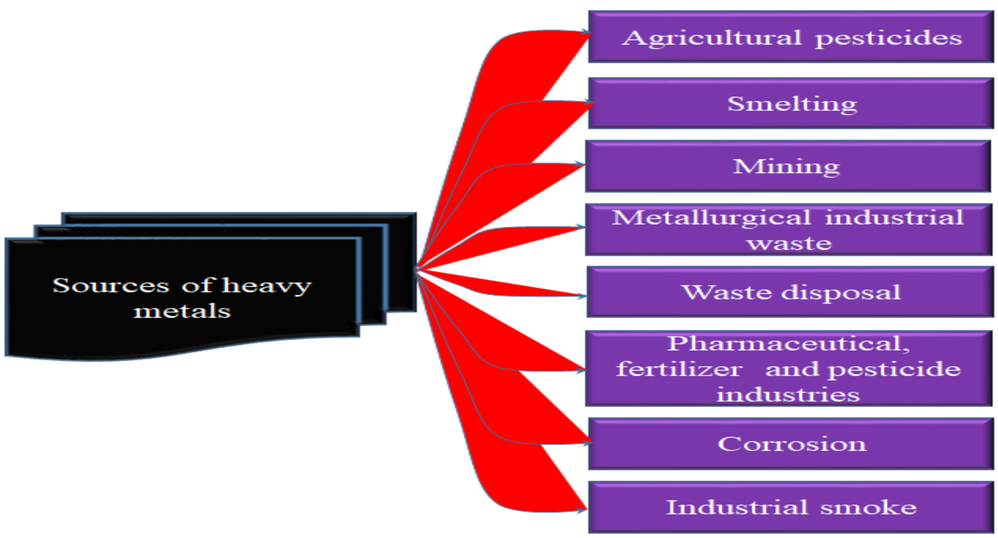


Fig. 8: Sources of Heavy Metals

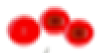
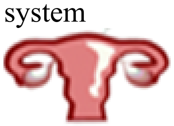
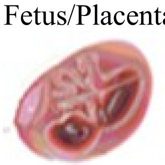
4.2.5 Urbanization and Traffic Emissions

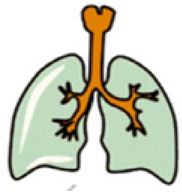
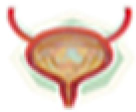
Vehicular emissions and road dust are significant urban sources of heavy metals, particularly lead, zinc, cadmium, and copper derived from fuel combustion and vehicular component wear. The use of leaded gasoline (still prevalent in some countries) and wear and tear of vehicle components contribute to environmental deposition (Lee *et al*., 2023; Shin *et al*., 2024), particularly lead, zinc, cadmium, and copper derived from fuel combustion and vehicular component wear. Table 2 illustrates the organ-specific health effects associated with exposure to selected heavy metals.

Table 1: Sources and effects of some heavy metals

Metal	Primary Sources	Toxic Effects
Lead (Pb)	Batteries, paints, gasoline, pipes	Neurotoxicity, anemia, kidney damage
Mercury (Hg)	Mining, coal combustion, seafood	Neurotoxicity, renal dysfunction
Cadmium (Cd)	Batteries, fertilizers, plastics	Bone demineralization, kidney damage
Arsenic (As)	Pesticides, mining, groundwater	Skin lesions, cancers, diabetes
Chromium (Cr VI)	Electroplating, leather tanning	Carcinogenicity, liver damage

Table 2: Human body and heavy metals (Moukadiri *et al*., 2024)

Human part	**Heavy metals**			
	Lead	**Mercury**	**Cadmium**	Arsenic
Brain 	Mental retardation, brain damage, psychosis, brain injury, etc.	Brain damage, poor performance on tests of mental function	NA	NA
Blood cell 	Toxicity, erythrocytes, immaturity, etc.	Microtubule destruction, mitochondrial damages, lipid peroxidation, genotoxicity...	Erythrocytes, lymphcytes damages in bone marrow	Anemia
Nerve system 	Neurodegenerative diseases, neurotoxic damages, etc.	Neurodegenerative disorder (Parkinson and Alzheimer), changes in nerve responses, Minamata disease...	NA	Peripheral neuropathy
Digestive system 	Stomach cancer...	Gastrointestinal system damage, vomiting and diarrhea...	NA	NA
Kidney 	Kidney damage, dysfunction, nephrotoxicity, cancer, etc.	Kidney damage, impairment of kidney function	Cancer, dysfunction, nephrotoxicity	Kidney damage
Reproductive system 	Infertility, changes in ovaries function, sperm damage, etc.	Abnormal menstrual cycle, reduced fertility	Infertility	Female reproduction failure
Liver 	Liver damages	NA	NA	Same as Lead case
Fetus/Placenta 	Spontaneous abortion, decreased birth weight, malformations. Premature births, etc	Developing fetus damage, neuronal system damage	Decreased birth weight and Premature births,	Increased rate of abortion, preterm birth, neonatal mortality, decreased birth weight

Lung 	NA	Respiratory failure, lung irritation, impairment of pulmonary function, chest pain and dyspea...	Cancer, sever damages	Lung damages
Bladder 	Cancer...	NA	Same as Lead case	Bladder damages
Cartilage 	Arthritis..	NA	Osteoarthris, cartilage degeneration, articular cartilage, cryotoxicity	NA
Bone 	NA	NA	Bone mineralization, oesteoporosis, disturbances in calcium metabolism, osteomalation	NA
Skin 	NA	NA	NA	Dermatological diseases

***NA-Not affected**

4.3 Risk Assessment and Regulatory Limits

Risk assessment of heavy metals evaluates the likelihood of adverse health outcomes based on exposure dose, duration, toxicity, and population susceptibility. Organizations such as the WHO, EPA and EFSA have established permissible limits for metals in drinking water, food and occupational settings. For instance, the WHO limit for lead in drinking water is 10 µg/L. These limits serve as international benchmarks for environmental monitoring and public health protection. Table 3 presents selected WHO guideline values for heavy metals in drinking water (Dwivedi *et al*., 2021). However, recent studies suggest that even levels below current standards may still pose significant health risks (Preonty *et al*., 2025). Table 3 gives the regulatory limits of some heavy metals as set by WHO.

4.4 Health hazards of heavy metals

The health hazards associated with heavy metal exposure arise from complex biochemical interactions that disrupt physiological systems at cellular and molecular levels.

Table 3: WHO regulatory limits for some heavy metals (Dwivedi *et al.,* 2021)

Heavy metals	Max. acceptable conc. (WHO)
Lead (Pb)	0.01 g
Mercury (Hg)	0.001 mg/ L
Cadmium (Cd)	0.003 mg/L
Arsenic (As)	0.01 mg/L
Chromium (Cr VI)	50 mg/L
Zinc (Zn)	5 mg/L

4.4.1 Toxicokinetics and Exposure Pathways

Toxicokinetics describes how toxic substances are absorbed, distributed, metabolized, and excreted (ADME) within biological systems.

Toxicokinetics describes how toxic substances are absorbed, distributed, metabolized, and excreted (ADME) within biological systems. The toxicity of heavy metals depends on their chemical form, route of entry, bioavailability and biological half-life (Gonzalez-Villalva *et al*., 2025).

Routes of Exposure

Humans are exposed to heavy metals through several pathways:

i. **Ingestion:** Contaminated food and drinking water are the most common sources, especially for arsenic, lead, and cadmium. Shellfish, rice, leafy vegetables, and groundwater are frequent contributors (Khan *et al*., 2013; Tang et al. 2022)).
ii. **Inhalation:** Industrial emissions, vehicular exhaust, and occupational dust exposure result in inhalation of airborne heavy metal particulates such as lead, mercury vapor, and cadmium oxide (Singh & Devi, 2023).
iii. **Dermal Contact:** Although skin absorption is typically low, dermal contact with contaminated soil or water can contribute to chronic low-level exposure, especially in children and workers in mining or e-waste handling (Chen *et al*., 2024; Opoku *et al*. 2024).

Bioaccumulation and Biomagnification

Heavy metals can bioaccumulate in tissues such as the liver, kidneys, and bones. They can also biomagnify through trophic levels, meaning higher concentrations are found in organisms higher up the food chain, including humans (Patra *et al*., 2024).

Absorption and Distribution

Absorption varies based on metal type and age of the individual. For instance, children absorb up to 50% of ingested lead compared while for adults (Dwivedi et al., 2021). Once absorbed, metals are distributed via blood to target organs like the brain (lead, mercury), liver (arsenic), or kidneys (cadmium).

Elimination

Excretion routes include urine (e.g., cadmium), feces (e.g., arsenic), sweat, and, to a lesser extent, hair and nails. However, the long biological half-lives of many metals (e.g., cadmium: 10–30 years) make them difficult to eliminate without chelation therapy (Huang *et al*., 2021).

4.4.2 Mechanisms of Toxicity

Heavy metals induce toxicity through multiple overlapping molecular and cellular mechanisms. These mechanisms explain their diverse signs and symptoms and extent of damages to various organs.

Oxidative Stress

Many heavy metals promote the generation of reactive oxygen species (ROS), which damage proteins, lipids, and DNA. For instance, cadmium and arsenic inhibit antioxidant enzymes like glutathione peroxidase, leading to oxidative stress-induced apoptosis (Chen *et al*., 2024).

Enzyme Inhibition

Metals like lead and mercury bind to sulfhydryl groups of proteins, inhibiting key enzymatic processes involved in energy metabolism, neurotransmission, and DNA repair (Zhao *et al*., 2022; Liao *et al*., 2024).

4.4.3 Mitochondrial Dysfunction

Heavy metals disrupt mitochondrial integrity, impairing ATP production and triggering cell death pathways. Mercury and arsenic are known to impair mitochondrial oxidative phosphorylation (Jiang *et al*., 2020).

4.4.4 Disruption of Calcium and Zinc Homeostasis

Lead competes with calcium ions in biological systems, affecting signal transduction and neuronal function. Similarly, cadmium displaces zinc in zinc-finger proteins, compromising transcriptional regulation and immune response (Ahamed *et al*., 2008; Luo *et al*., 2012).

4.4.5 Genotoxicity and Carcinogenesis

Hexavalent chromium (Cr VI) and arsenic are potent genotoxins. They form DNA adducts, induce chromosomal aberrations, and interfere with DNA repair pathways, thereby contributing to carcinogenesis (IARC, 2022).

4.4.6 Endocrine Disruption

Some heavy metals mimic or block hormone signaling. For example, cadmium has estrogenic effects and may disrupt reproductive development and function (Khan *et al*., 2020)

4.4.7. Health Effects by Organ System

The toxic effects of heavy metals vary depending on the type of metal, dose, exposure duration, and individual susceptibility (Arbabi *et al*., 2015). Most heavy metals exert systemic effects, impacting multiple organs and biological systems.

4.4.8 Neurotoxicity

Neurotoxicity refers to structural or functional damage to the nervous system caused by exposure to toxic substances.

This is the damage on the nervous system caused by heavy metals. The nervous system, particularly in children, is highly vulnerable to heavy metal toxicity. Metals such as lead (Pb), mercury (Hg), and arsenic (As) are potent neurotoxins. Lead crosses the blood-brain barrier and interferes with neurotransmitter release, synapse formation, and myelination. Chronic exposure is linked to reduced IQ, attention deficits, behavioral issues, and developmental delays in children (Moukadiri *et al.*, 2024). In its methylmercury form (MeHg), mercury disrupts neuronal migration, inhibits microtubule formation, and induces apoptosis. Prenatal exposure is associated with motor dysfunction, cerebral palsy, and language impairments (Wang *et al*., 2023). Arsenic on its part, alters neuronal signaling and epigenetic regulation, contributing to cognitive dysfunction and increased risk of neurodegenerative diseases such as Alzheimer's and Parkinson's (Antinori *et al*., 2024).

4.4.9 Nephrotoxicity (Kidney Damage)

The kidneys are primary sites of heavy metal accumulation and toxicity due to their role in filtration and excretion. Cadmium and lead are the most nephrotoxic heavy metals due to their accumulation in the kidneys over time. Cadmium exerts its nephrotoxicity through oxidative stress, mitochondrial dysfunction, and inflammation, which compromise glomerular filtration and tubular integrity (Jiang *et al*., 2020; Liang *et al*., 2023; Jomova *et al*. 2025). Lead and mercury cause renal tubular necrosis and glomerular injury). Long-term exposure leads to irreversible kidney dysfunction (Mishra *et al*., 2022). Mercury exposure is associated with autoimmune glomerulonephritis (Bjørklund *et al*., 2020; Liu *et al*., 2025).

4.4.10 Hepatotoxicity (Liver Damage)

The liver, as the primary detoxification organ, is susceptible to heavy metal-induced oxidative stress (Gupta *et al*., 2022). The liver metabolizes and detoxifies xenobiotics, making it a target for heavy metal toxicity. Arsenic and cadmium **i**nduce lipid peroxidation, hepatocyte apoptosis, and mitochondrial injury while chromium (Cr VI) promotes hepatic oxidative damage and cytotoxicity through free radical generation and inflammation (Julius *et al*., 2025). Persistent exposure may ultimately result in chronic liver dysfunction and increased risk of hepatic disease.

4.4.11 Cardiovascular Toxicity

Heavy metal exposure has also been associated with cardiovascular disorders, including hypertension, endothelial dysfunction, and increased risk of atherosclerosis.

Heavy metals have been implicated in cardiovascular diseases (CVDs) such as hypertension, atherosclerosis, and cardiomyopathy. Heavy metals like cadmium and arsenic contribute to cardiovascular diseases (CVDs) by inducing endothelial dysfunction, increasing oxidative stress, and elevating blood pressure (Lin *et al*., 2020). Chronic exposure has been associated with atherosclerosis, myocardial infarction, and hypertension (Ozarde *et al*., 2025).

4.4.12 Immunotoxicity

Heavy metals impair both innate and adaptive immune responses, increasing susceptibility to infections and autoimmune diseases. Mercury and Lead for instance, disrupt cytokine signaling and lymphocyte function. Mercury can promote autoimmune conditions by altering antigen presentation (Harshitha *et al*., 2024) while cadmium inhibits macrophage phagocytic activity and suppresses T-cell proliferation (Aremu *et al*., 2021).

4.4.13 Reproductive and Developmental Toxicity

Heavy metals affect reproductive health by disrupting hormonal signaling, gametogenesis, and fetal development. Lead and Cadmium interfere with spermatogenesis and testosterone production in males, in females, they impair folliculogenesis and estrogen production (Khan *et al*., 2020). Mercury and Arsenic cross the placental barrier, leading to spontaneous abortion, stillbirths, low birth weight, and developmental abnormalities in infants (Wang *et al*., 2023).

4.4.14 Carcinogenicity

The International Agency for Research on Cancer (IARC) has classified several heavy metals as carcinogens. For example, Arsenic a group 1 element is linked to skin, lung, liver, and bladder cancers through mechanisms involving DNA methylation, chromosomal aberrations, and oxidative DNA damage (IARC, 2022); Cadmium (Group 1) is associated with prostate, kidney, and lung cancers (Patra *et al*., 2024) and Chromium VI which is also a group 1 element is a known cause of lung cancer in occupational settings through genotoxic and epigenetic mechanisms (Balali-Mood *et al*., 2021).

4.4.15 Genotoxicity

Heavy metals cause mutations and chromosomal damage. They induce genotoxicity via DNA strand breaks, chromosomal aberrations, and interference with DNA repair enzymes. For instance, cadmium and mercury damage nuclear DNA in somatic and germ cells, increasing cancer risk and heritable mutations (Das *et al*., 2023; Nguyen & Huynh, 2022).

4.4.16 Dermal Toxicity

Although often overlooked, skin is also a target organ of heavy metals. Arsenic and chromium exposure for example, have been linked to various skin disorders (Rival, 2024). Arsenic, in particular, causes hyperkeratosis, melanosis, and skin cancer through prolonged exposure, often via contaminated water (Sinha and Prasad 2020). Chromium causes allergic contact dermatitis by promoting immune hypersensitivity reactions (Hedberg 2020).

4.5 Predictive Models

Conventional methods for heavy metal analysis are often time-consuming and may not provide rapid monitoring of contamination levels. Consequently, recent studies have explored the application of artificial intelligence and machine learning (ML) models for predicting heavy metal concentrations. Although keyword analysis in this study indicates that ML applications in heavy metal research remain limited, these approaches offer accurate and real-time prediction capabilities that can support environmental monitoring and pollution management.

4.6 Remediation Strategies

Several physical, chemical, and biological approaches are used to remediate heavy metal-contaminated environments. Phytoremediation using plants such as vetiver grass and water hyacinth provides a sustainable and cost-effective option for metal removal. In addition, nanotechnology-based adsorbents, membrane filtration systems, biochar, and fungal remediation have shown significant potential for improving remediation efficiency while reducing environmental impacts (Wang et al., 2021).

5.0 Heavy Metal Consequences in Nigeria and Future Research Trends

Nigeria has recorded increasing research activity on heavy metals, with more than 200 publications and over 5,000 citations within the last decade. Despite this progress, cases of heavy metal poisoning remain prevalent. In August 2024, the World Health Organization (WHO) reported traces of heavy metals in the bloodstreams of children aged 4–13 years following investigations into unexplained illnesses in Sokoto State linked to 196 suspected cases and seven deaths, with similar incidents reported in Zamfara State (WHO, 2024). These contaminations are largely associated with mining and industrial activities that pollute water and soil.

Although several studies have been conducted in Nigeria, significant gaps remain in monitoring and controlling illegal mining activities and contaminated industrial effluents. Emerging technologies such as artificial intelligence, Internet of Things (IoT) systems, and hybrid AI/ML models could support real-time environmental monitoring and early detection of contamination. Nanotechnology also offers opportunities for improved treatment of industrial effluents before environmental discharge. However, concerns regarding residual metal-based nanoparticles highlight the need for safer, non-metallic alternatives. These challenges present important directions for future research aimed at improving environmental safety and public health protection in Nigeria.

6. 0 Conclusion

Heavy metal contamination remains a major environmental and public health concern worldwide, affecting diverse geographical, industrial, and socioeconomic settings. This study examined the sources, environmental pathways, toxicity mechanisms, exposure routes, health effects, and regulatory issues associated with heavy metal pollution. Toxic metals such as lead, mercury, cadmium, arsenic, and chromium are persistent, bioaccumulative, and highly toxic, allowing them to accumulate in environmental and biological systems. Human exposure occurs through contaminated water, food, air, and occupational activities, with children and pregnant women being particularly vulnerable. Heavy metal toxicity affects multiple organ systems, including neurological, renal, hepatic, cardiovascular, reproductive, and immune functions. The findings emphasize the importance of continuous environmental monitoring, strengthened regulatory enforcement, and sustainable mitigation measures. Effective occupational and environmental management practices are therefore necessary to reduce heavy metal release, limit exposure risks, and ensure long-term environmental and public health protection.

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Not Applicable

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