

Heavy Metal Contamination From Anthropogenic Waste Sources: Environmental Fate, Aquatic Toxicity, And Human Health Implications

Irine Jerald¹, Monica Muniendra Babu¹, Shirin Fargana Bava¹, Dhivya Bharathi Venkata Krishnan¹ and Ebine Joel Sam Christy¹

¹ Department of Biotechnology, Rajalakshmi Engineering College, Thandalam, Chennai-602105, India

Corresponding Author: irinebrinyhepzibha.j@rajalakshmi.edu.in

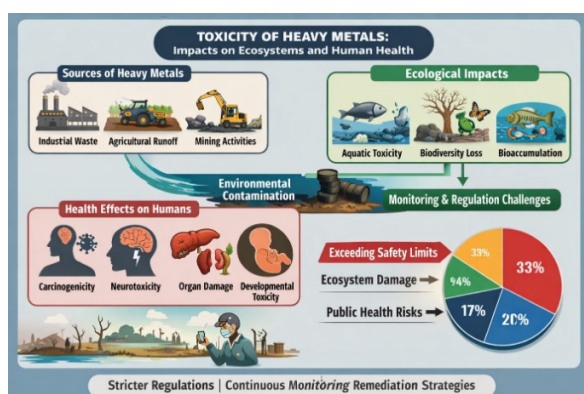
ABSTRACT:

Heavy metals are ubiquitous environmental pollutants that arise from diverse waste sources, and have detrimental effects on ecosystems, human health, and aquatic life. This comprehensive review synthesizes current knowledge regarding the impacts of heavy metals originating from various waste sources. This review begins by elucidating the sources and pathways through which heavy metals infiltrate the environment, encompassing industrial emissions, agricultural runoff, urban waste, mining activities, and atmospheric deposition. It explores the dynamic interactions between heavy metals and abiotic environments, including soil, water, and sediments, shedding light on the mechanisms underlying their persistence and bioavailability. A pivotal focus of this review is the profound consequences of heavy metal contamination on aquatic ecosystems. It evaluates the ecological repercussions of heavy metal exposure on diverse aquatic organisms, ranging from algae and invertebrates to fish and amphibians. The cascading effects on food webs, biodiversity, and ecosystem services are elucidated, highlighting the need for rigorous monitoring and mitigation strategies. Moreover, this review delves into the complex interplay between heavy metals and human health. It assesses the pathways of human exposure, encompassing consumption of contaminated seafood, drinking water, and inhalation of particulate matter. This review scrutinizes health hazards, including carcinogenicity, neurotoxicity, and developmental toxicity, emphasizing vulnerable populations and long-term health implications.

Keywords: Heavy Metal Pollution, Aquatic Life, Ecosystem, Human Health

Graphical Abstract:

How to cite this article: Jerald I, Babu MM, Bava SF, Krishnan DBV, Christy EJS. Heavy Metal Contamination From Anthropogenic Waste Sources: Environmental Fate, Aquatic Toxicity, And Human Health Implications. *Int J Drug Deliv Technol.* 2026;16(6s): 589-609; DOI: 10.25258/ijddt.16.6s.85



1. Introduction:

In an era marked by rapid industrialization and urbanization, the increasing generation of waste materials has emerged as a formidable challenge to environmental sustainability and human well-being. Among the multifaceted pollutants that emanate from these waste streams, heavy metals have attracted considerable attention due to their persistent presence and profound impacts on both terrestrial and aquatic ecosystems. These nondegradable substances, which

originate from diverse waste sources such as industrial effluents, agricultural runoff, electronic waste, and landfill leachates, have become agents of ecological disruption and potential threats to human health.

Heavy metal contamination encompasses a complex network of biogeochemical cycles, necessitating a detailed characterization of its diverse lithogenic and anthropogenic origins, environmental transport mechanisms, and subsequent ecological ramifications. It seeks to illuminate the multifaceted interactions between heavy metals and the intricate ecosystems they infiltrate, from the macrocosms of aquatic ecosystems to the microcosms within human bodies. Through an amalgamation of research findings, case studies, and analytical insights, this review paper aims to provide a holistic understanding of the far-reaching repercussions of heavy metal contamination on both human and aquatic life. In the following pages, the investigation of the intricate tapestry of heavy metal contamination, beginning with an exploration of the various waste sources that contribute to dissemination of heavy metal contamination are discussed. From

Heavy Metal Contamination From Anthropogenic Waste Sources: Environmental Fate, Aquatic Toxicity, And Human Health Implications

industrial processes that discharge heavy metals into water bodies to the indiscriminate disposal of electronic waste laden with toxic elements, through the diverse channels by which heavy metals find their way into our environment were embarked. The impacts of heavy metals on aquatic ecosystems, including their deleterious effects on fish, will be elucidated. This review examines the intricate relationships between heavy metal exposure and alterations in aquatic biodiversity, food chain dynamics, and water quality. Additionally, this review will delve into the bioaccumulation phenomena that amplify the toxic effects of heavy metals up to trophic levels, affecting not only aquatic organisms but also humans who rely on these ecosystems for sustenance. Transitioning from the aquatic realm to the human dimension, explore the alarming consequences of heavy metal exposure on human health were explored.

From the insidious ingestion of contaminated food and water to the inhalation of airborne heavy metal particulates, humans are exposed to these toxic elements through various pathways. The mechanisms through which heavy metals disrupt vital physiological processes, leading to a spectrum of health issues ranging from subtle subclinical effects to debilitating diseases were examined. Cadmium (Cd), commonly detected at concentrations around 0.01 mg/L in industrial effluents, is widely used in steel and plastic manufacturing, nickel-cadmium batteries, electroplating, pigments, coatings, and electronic components. Classified as a human carcinogen, cadmium exposure is associated with severe health consequences, including respiratory disorders, renal dysfunction, kidney stone formation, skeletal damage, anemia, and disruption of calcium metabolism. Chronic exposure may also contribute to lung and urinary bladder cancers, chronic obstructive pulmonary disease (COPD), and congenital abnormalities. Therefore, strict industrial monitoring and safe handling practices are essential to minimize cadmium-related health risks (Gibb *et al.*, 2000).

Chromium (Cr), often reported at concentrations near 0.05 mg/L in industrial discharges, is extensively used in metal plating, leather tanning, pigment production, glass manufacturing, and metallurgical processes. Hexavalent chromium [Cr(VI)] is particularly hazardous due to its high mobility and carcinogenic potential. Exposure can result in respiratory complications, gastrointestinal distress, hepatic and renal damage, pulmonary fibrosis, and genotoxic effects. Long-term exposure has been linked to lung,

stomach, prostate, and kidney cancers, highlighting the need for stringent control measures in occupational and environmental settings (Miretzky and Fernandez, 2009). Lead (Pb) and zinc (Zn) are also prevalent in industrial and environmental sources. Lead, detected at approximately 6.0×10^{-3} mg/L, originates from paints, batteries, fuel additives, mining, and combustion activities. It is a potent neurotoxin that affects the nervous, cardiovascular, and reproductive systems, particularly impairing cognitive development in children (Malaviya and Singh, 2012). Zinc, present at around 0.80 mg/L in certain industrial effluents, is widely used in alloy production, galvanization, and rubber industries. Although an essential trace element, excessive zinc exposure may cause gastrointestinal disturbances, anemia, neurological symptoms, and metabolic imbalances (Joshi, 2011).

This comprehensive review aims to shed light on the interconnectedness of heavy metal contamination from diverse waste sources and its cascading impacts on both aquatic ecosystems and human health. By synthesizing a vast body of knowledge to raise awareness about the urgency of addressing this global concern and provide valuable insights that can inform policies, practices, and research endeavors aimed at mitigating the adverse effects of heavy metals on our planet and its inhabitants.

2. Sources of Heavy Metal Waste and Their Impact on the Environment and Human Health:

2.1 E-Waste:

E-waste, or electronic waste, refers to discarded electronic devices that have reached the end of their useful life. These devices contain hazardous materials and valuable resources that require proper management and disposal to minimize environmental and public health risks.

In 2016, India generated approximately 1.85 million tonnes of electronic waste, accounting for about 12% of the global e-waste output. India has become the fifth largest contributor to electronic waste worldwide (Table 1). The predominant source of e-waste comprises computer devices, making up nearly 70% of the total, while the telecom sector, medical equipment, and electric appliances contribute 12%, 8%, and 7%, respectively, to the yearly e-waste production. The majority of e-waste generation is distributed among the government, public sector entities, and private sector companies, accounting for approximately 75%, whereas individual households contribute only 16%. Among cities, Mumbai leads in terms of electronic

Heavy Metal Contamination From Anthropogenic Waste Sources: Environmental Fate, Aquatic Toxicity, And Human Health Implications

waste production, followed by New Delhi, Bangalore, and Chennai (Bagwan, 2023).

Table 1. Some of the hazardous substances present as e-waste constituents (Alabi *et al.*, 2021)

Pollutant	Sources
Halogenated compounds	
PVC (polyvinyl chloride)	Insulating material for cables.
PBDE (polybrominated diphenyl ethers)	Flame-resistant additives for plastics, such as thermoplastic
PBB (polybrominated biphenyls)	components and cable insulation.
TBBA (tetrabromo-bisphenol-A)	TBBA (The most commonly employed fire-resistant additive in printed circuit boards and enclosures)
Chlorofluorocarbon (CFC)	Cooling unit, Insulation foam.
PCB (polychlorinated biphenyls)	Condensers, Transformers.
Heavy metals and other metals	
Arsenic	In light-emitting diodes, there are minute amounts of gallium arsenide.
Barium	Materials used for gettering in cathode ray tubes (CRT).
Beryllium	Enclosures housing silicon-controlled rectifiers and X-ray lenses in power supply units.
Cadmium	Rechargeable nickel-cadmium batteries, phosphorescent coating (found on CRT screens), printing inks and toners, and photocopier machines (specifically, the printer drums).
Chromium VI	Floppy-disks, Data tapes,
Lead	Batteries, PWB, CRT screens.
Lithium	Batteries
Mercury	Fluorescent tubes used for illuminating LCD backlights, found in certain alkaline batteries,

	and incorporated into mercury-wetted switches.
Nickel	Rechargeable nickel-cadmium or nickel-metal hydride batteries, and the electron emitter in a cathode ray tube (CRT).
Rare Earth elements	Fluorescent layer (CRT-screen), Yttrium, Europium.
Selenium	Photocopiers of an earlier generation (specifically, their photo drums).
Zinc sulphide	The inner components of CRT displays, blended with rare earth elements.
Others	
Toner Dust	Cartridges containing toner for laser printers and copiers.
Radio-active substances	
Americium	Healthcare devices, fire alarms, and the responsive sensor component within smoke detectors.

Heavy metals present in electronic waste, including mercury, lithium, lead, and barium, gradually permeate deeper into the soil, ultimately reaching groundwater. Once heavy metals enter groundwater, they eventually flow into rivers, ponds, and lakes. These pathways lead to water acidification and ground water contamination, posing harm to wildlife, vegetation, and communities located several kilometers away from recycling sites. As a result, accessing safe drinking water has also become increasingly compromised in affected regions (Jain *et al.*, 2023).

2.1.1 Impact of E-Waste on Human Health:

According to a report by The Associated Chambers of Commerce and Industry of India (ASSOCHAM), nearly 80% of individuals employed in handling e-waste experience respiratory issues such as breathlessness, irritation, coughing, and suffocation due to inadequate safety measures (Table 2). Workers, including children in informal recycling sectors, frequently face high exposure to toxic fumes without adequate personal protective equipment (PPE), such as protective facemasks or gloves. Common informal recycling practices involve open burning of items such as tube lights, motherboards, and toner cartridges,

Heavy Metal Contamination From Anthropogenic Waste Sources: Environmental Fate, Aquatic Toxicity, And Human Health Implications

which release substances such as lead, mercury, and cadmium into the atmosphere (Bagwan, 2023). Electronic waste contains a significant amount of hazardous metals, polyaromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), and various other contaminants such as phthalates found in polyvinyl chloride (Wong *et al.*, 2007).

Table 2. Diseases caused by e-waste in humans (Jain *et al.*, 2023).

Hazardous Components	Sources	Implications of Hazardous Substances in Electronic Waste	References
Arsenic	LEDs, Semiconductors, diodes, solar cells, microwaves.	Extended contact can affect both the nervous system and skin, potentially increasing the risk of developing lung cancer over an extended period.	El-Ghiaty and El-Kadi 2021, Kumaratilaka <i>et al.</i> , 2018
Asbestos	Insulators in heating equipment.	Serious negative consequences encompass respiratory issues, persistent coughing, lung harm, and even the onset of cancer.	Debnath <i>et al.</i> , 2021

Barium	Electron tubes, Fillers for plastics and rubbers,.	The cardiac muscle may experience an impact.	Vidyadhar, 2016
BFR	Circuit boards, Chips, Different Casing.	Damage to the reproductive and immune systems is a potential outcome, alongside the risk of hormone imbalances and disruptions in the endocrine system.	Julander <i>et al.</i> , 2014
Cd	Batteries, PCB, alloys and solders.	Joints and the spinal column are notably susceptible, leading to severe discomfort, weakening of the bones, and harm to the kidneys.	Vidyadhar, 2016
CFC	Refrigerants, Aerosol propellants, and Cleaning solvents.	The possibility of developing skin cancer and potential genetic	Salhofer, 2017

Heavy Metal Contamination From Anthropogenic Waste Sources: Environmental Fate, Aquatic Toxicity, And Human Health Implications

		damage is a concern.					
Cr	Pigments, Dyes.	Possible side effects encompasses conditions like asthma, bronchitis, lung cancer, and potential harm to the liver and kidneys.	97% of collected E-waste recycled for useful applications, 2022				symptoms like queasiness, throwing up, confusion, and muscle weakness, among various other effects.
Dioxins	Metal smelting, different type of cables and Printed wiring board (PWB).	Increased cancer risk	Jain <i>et al.</i> , 2023				It exerts harmful effects on the central nervous system, kidneys, and immune system, and can also impact fetal development. Additionally, it carries the potential to damage the brain, liver, and lead to skin problems.
Pb	Thermistors, Thermocouples, and Thermoelectric elements	The kidneys, reproductive system, and nervous system could all face potential impacts, which may lead to disorders related to the blood and brain.	Liao <i>et al.</i> , 2004	Hg	Switches, Batteries, Copper machines, Flat screen monitors.		Oh <i>et al.</i> , 2003
Li	Photographic equipment, and Batteries of mobiles.	Prolonged exposure to lithium vapors may result in	Liao <i>et al.</i> , 2004	PAH	Printed circuit boards (PCB), Wiring.		Jain <i>et al.</i> , 2023

Heavy Metal Contamination From Anthropogenic Waste Sources: Environmental Fate, Aquatic Toxicity, And Human Health Implications

		s, vomiting, diarrhea, and confusion . Extended use may lead to conditions like cataracts, kidney and liver impairment, jaundice, and other related symptoms.	
PVC	Insulation coating, Cables.	It has the potential to result in harm to the respiratory and immune systems.	Stapleton <i>et al.</i> , 2008
PCB	Softening agents, Capacitors, Transformers.	The immunological, reproductive, neurological, and endocrine systems can all be susceptible to harm. The continuous pollution of PCBs poses an environmental concern.	Stapleton <i>et al.</i> , 2008

2.1.2 Impact of E-Waste on the Environment:

Electronic waste, or e-waste, does not breakdown naturally and accumulates in environmental compartments, including soil, air, water, and aquatic creatures. Although e-waste might constitute only about 2% of total solid waste by volume, it can contribute to as much as 70% of the hazardous waste deposited in landfills (S. M. Ali & Selva, 2022). Mining operations have already led to higher concentrations of rare earth elements (REEs) in surface waters due to the growing demand for electronic and electrical equipment (EEE) production (Freitas *et al.*, 2020). The aquatic ecosystem faces considerable potential risk because external stacks of e-waste components are frequently soaked or inundated by rainfall, generating runoff that flows from storage areas into local water channels. Both water and sediment analyses revealed that contaminants linked to e-waste underscore the necessity of evaluating the ecological hazards posed by the numerous pollutants discharged during e-waste handling. Although water bodies are already impacted by pollutants originating from other sources, it is evident that contaminants present in e-waste also heavily influence these water bodies (Figure 1) (Huang *et al.*, 2014).

High levels of heavy metals such as lead, cadmium, copper, and zinc, along with organic pollutants such as PCDD/Fs and PBDEs, surpass natural levels by a significant margin. This contamination implies that aquatic organisms residing in the affected water systems face substantial exposure to these perilous, slowly degrading, and bioaccumulative pollutants. (Huang *et al.*, 2014). Electronic waste comprises both minor and metallic constituents. Minor elements function as dopants in electronic devices. Silicon-based chips incorporate minor elements such as phosphorus (P), indium (In), antimony (Sb), arsenic (As), and gallium (Ga) within their structures. Moreover, these minor elements are utilized in the manufacturing of semiconductors such as indium phosphide or gallium arsenide (Alabi *et al.*, 2021). Additional metal elements found within electronic waste include beryllium (Be), cobalt (Co), barium (Ba), selenium (Se), zinc (Zn), yttrium (Y), europium (Eu), gold (Au), platinum, iron (Fe), aluminum (Al), tin, germanium, tantalum, vanadium, ruthenium, tantalum, rhodium, americium, palladium, manganese, silver, bismuth, niobium, silica, lithium, tritium, terbium, etc. (Tanaka 2004).

Heavy Metal Contamination From Anthropogenic Waste Sources: Environmental Fate, Aquatic Toxicity, And Human Health Implications

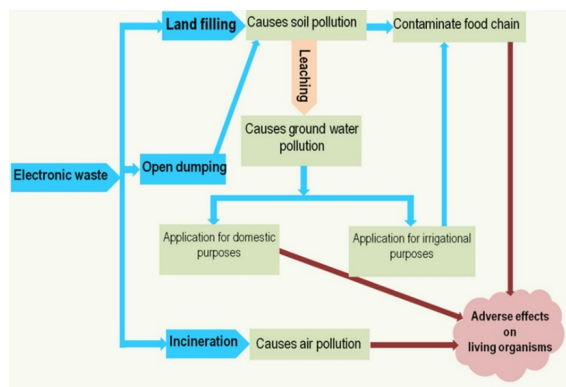


Figure 1. Impact of E-Waste on the environment and its ecology (Ankit *et al.*, 2021)

2.2 Industrial waste:

Kar *et al.*, (2021) showed that the possible origins of heavy metal toxicity include mining, tailing disposal, smelting operations, industrial discharge, runoff from agricultural activities, workplace contact, paints and preserved wood products. Numerous industries have played a role in this issue, with the most common pollutants being cadmium (Cd), zinc (Zn), lead (Pb), chromium (Cr), nickel (Ni), copper (Cu), vanadium (V), platinum (Pt), silver (Ag), tin (Sn), and titanium (Ti). Heavy metals are typically characterized by a density exceeding 5 g/cm³, are widely recognized for their toxicity and potential to act as carcinogens. Exposure to cadmium (Cd) has been associated with increased cancer risk, bone demineralization, and renal dysfunction (WHO, 2010). They are frequently generated by industries such as electroplating, electrolytic deposition, conversion coating, anodizing-cleaning, milling, and etching processes.

According to Tchounwou *et al.* (2012), mining activities release heavy metals like lead (Pb), zinc (Zn), and cadmium (Cd) into the environment, causing significant contamination and potential health risks. The use of pesticides and fertilizers containing elements like cadmium (Cd) and lead (Pb) is one way that agricultural activities contribute to heavy metal contamination (Alloway, 2012). Lead (Pb) is known for its high toxicity and possible cancer-causing effects; in children, it especially affects the development of the nervous system (ATSDR, 2021).

2.3 Leather Industry:

In India, it is estimated that between 2000 and 3000 tons of chromium are discharged into the environment annually by tanneries (CPCB, 2009). Due to inadequate effluent treatment, the tanning industry in India is a major source of chromium pollution, with significant amounts of the metal released into the environment (Garbo *et al.*, 2018). Significant pollution

problems arise from the release of treated effluents from many Indian industries, including tanneries, which frequently do not adhere to established environmental standards (Shukla & Singhal, 1984). The Environment (Protection) Rules, 1986 established strict effluent standards, but non-compliance is still a major problem that contributes to environmental pollution (MoEFCC, 2016). For instance, effluents from tanneries in Tamil Nadu's Vellore district are released into open spaces and water bodies without sufficient treatment, making them a major source of chromium pollution (Rangasamy, S.R *et al.*, 2015). The city of Kanpur, which is home to a significant number of tanneries, has released untreated or inadequately treated effluents, which has severely contaminated surrounding water bodies with chromium (Sharma *et al.*, 2012).

Chromium is commercially employed in various occupational sectors and industries, including leather tanning, metal finishing, pigment and dye production, wood preservation, corrosion prevention, and cleaning solutions for glassware. In the leather industry, chromium (Cr) is frequently found among heavy metals due to the extensive use of chromium sulfate $[\text{Cr}(\text{H}_2\text{O})_5(\text{OH})\text{SO}_4]$ salts. The mutagenic characteristics of chromium depend on several factors, including its oxidation state, availability for biological uptake, adsorption by organisms, mobility of ligands, and stability in the environment. Both the United States Environmental Protection Agency (USEPA) and the International Agency for Research on Cancer (IARC) have classified chromium (VI) as a human carcinogen (Junaid *et al.*, 2017). Cr(VI), a potent oxidizing agent that may generate chromate and dichromate ions in the environment, has been identified as a serious occupational carcinogen. Hexavalent chromium $[\text{Cr}(\text{VI})]$ enters cells through surface transport channels due to its structural similarity to sulfate ions, where it is reduced to trivalent chromium $[\text{Cr}(\text{III})]$, which causes genotoxic consequences in the cell (Nagpure *et al.*, 2014).

2.3.1 Impact on Human Health:

Chandrasekaran V *et al.* (2014) proposed that leather tanning involves chemically preserving raw hides through the use of substances such as chromium salts. India hosts more than 2000 tanneries, and the leather industry, known for its labor-intensive nature, offers employment to approximately 2.5 million individuals, primarily from marginalized communities. This situation places a significant portion of the population at risk of exposure to hazardous chemicals. The

Heavy Metal Contamination From Anthropogenic Waste Sources: Environmental Fate, Aquatic Toxicity, And Human Health Implications

financial burden stemming from the healthcare costs associated with the health issues of tannery workers could become substantial for society. A cross-sectional study conducted in Kanpur, India, revealed a heightened occurrence of health issues, specifically hand dermatitis, asthma, and lower back problems, among workers.

2.4 Textile Industry:

According to H. Ali and Khan (2017), "Textile industries are major sources of heavy metal pollution, frequently releasing metal ions into the environment through their effluents, including chromium (VI), cadmium (II), lead (II), and zinc (II). In the process of producing textiles, sizing is the application of different chemicals to improve the performance and strength of yarns, including starch, waxes, carboxymethyl cellulose (CMC), polyvinyl alcohol (PVA), and wetting agents (Khan *et al.*, 2022). The hazardous components found in textile sizing agents pose serious health and environmental risks, so proper management and disposal are necessary to ensure safety (Figure 2). Chemicals used in the manufacturing of textiles, such as those found in sizing agents, have the potential to cause mutagenic effects, harm the central nervous system, and cause cancer. For these reasons, it is crucial to manage chemicals properly. (Velusamy *et al.*, 2021).

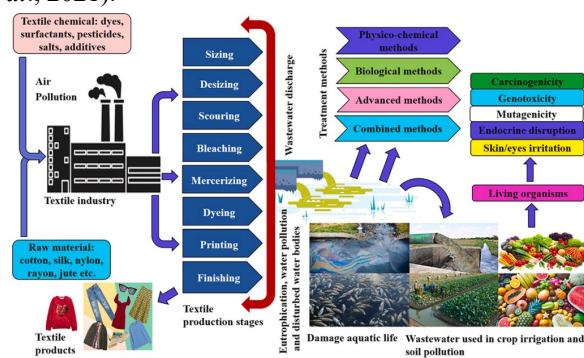


Figure 2. Impact of Textile Industrial Waste on the environment and human health (Kishor *et al.*, 2021)

2.4.1 Impact on Human Health:

Kaur *et al.* (2021) proposed the toxicity and carcinogenic potential of nickel, particularly focusing on the generation and role of reactive oxygen species. In the textile effluent samples, the nickel concentrations ranged from 0.11 mg/l to 0.22 mg/l. Iron toxicity is associated with joint disease (arthropathy), arrhythmia, heart failure, increased atherosclerosis risk, and a greater likelihood of liver, breast, gastrointestinal, and hematologic cancers. The recorded values for iron in untreated textile effluent

samples ranged from 0.39 mg/l to 0.90 mg/l, with the highest concentration found in the treated textile samples at 0.90 mg/l. Zinc concentrations in these samples ranged from 0.11 mg/l to 0.51 mg/l, and it is worth noting that zinc is an essential element for human health. Cadmium, a highly toxic and carcinogenic metal, is detected at a concentration of 0.01 mg/l in both textile effluent and samples. Cadmium can accumulate in various organs, negatively affecting the liver, kidney, lung, bones, placenta, brain, and central nervous system.

2.5 Paint & Polymer Industry:

The global paint industry has garnered significant attention from environmental regulators due to the discharge of both hazardous and nonhazardous wastes into the environment. This industry is a source of various pollutants that continuously contaminate crucial environmental elements such as soil, water, and air. (Jolly *et al.*, 2013). Waste water generated from paint manufacturing contains high concentrations of organic compounds, such as solvents, pigments, and surfactants, as well as heavy metals, such as lead, chromium, and cadmium, are frequently found in the wastewater from paint industries. According to studies, the Chemical Oxygen Demand (COD) of paint industry wastewater can range from 2000 to 4000 mg/L, which is substantially higher than the COD levels of typical domestic wastewater, which are between 200 and 500 mg/L (K *et al.*, 2021).

Paint waste has the potential to seriously contaminate soil. For instance, studies have revealed higher than average concentrations of heavy metals in the soils surrounding paint factories, with lead concentrations reaching up to 1500 mg/kg, significantly above the background levels of 10–50 mg/kg. Pollutant concentrations in water bodies receiving paint industry effluents are frequently high. According to one study, lead and chromium concentrations in river water close to paint factories were five to ten times higher than those considered safe (Al-Tohamy *et al.*, 2022).

Untreated paint waste released into the environment has the potential to seriously harm the environment. Research has shown instances of fish kills and a decline in biodiversity in water bodies where paint industry effluents have been present. Toxic substances from paint waste can also pose a risk to human health. Communities residing near paint manufacturing facilities have noted increased rates of skin disorders, respiratory ailments, and other pollution-related illnesses.

2.6 Paper & Pulp Industry:

Heavy Metal Contamination From Anthropogenic Waste Sources: Environmental Fate, Aquatic Toxicity, And Human Health Implications

The pulp and paper industry stands out as one of the most environmentally damaging industries worldwide, due to its high-water consumption and pollutant discharge. In both Europe and Asia, the global demand for paper reached approximately 250 metric tons in 2015, with projections estimating it to surpass 350 metric tons by 2030. Additionally, there has been a consistent annual increase in global paper trade, ranging from 1.5% to 4% across various paper categories. This surge in production inevitably leads to a corresponding increase in waste generation (Gaur *et al.*, 2020).

Gavrilescu *et al.* (2012) stated that the waste generated by the pulp and paper industry can be categorized into waste resulting from washing, bleaching, and pulping processes, as well as primary and secondary sludge. This waste has the potential to contaminate air, water, and soil (Figure 3). The waste produced by this industry consists of intricate inorganic and organic compounds. Its primary impact is on aquatic ecosystems, as discharged wastewater is known to contain mutagenic, clastogenic, carcinogenic, and endocrine-disrupting substances.

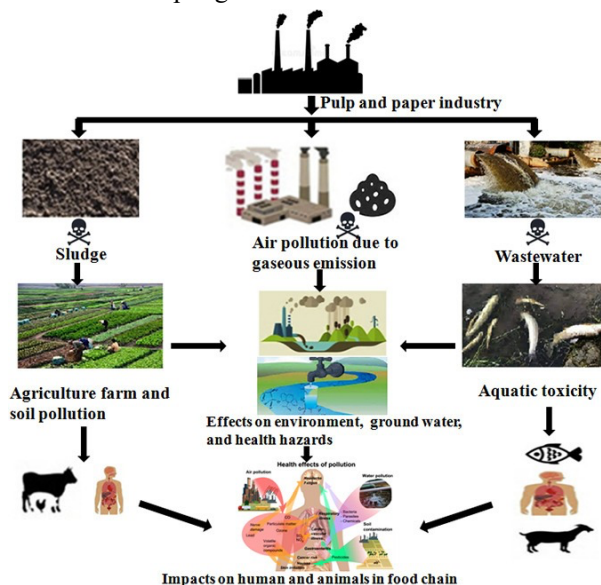


Figure 3. Impact of waste generated from Paper and Pulp Industries on Environment (A. K. Singh *et al.*, 2022)

2.6.1 Impact on the Environment and Aquatics:

Heavy metals, including manganese (Mn), chromium (Cr), iron (Fe), and cadmium (Cd), and nonmetallic elements, such as sodium, calcium, magnesium, sulfate, and chlorine-based substances, are discharged from paper mills during processes such as pulping, pulp bleaching, and washing. The toxicity of these heavy metals is influenced by the presence of inorganic nonmetallic elements and the rigidity of the paper

industry's effluent, among other factors (Tripathy *et al.*, 2021).

The waste from the pulp and paperboard industry contains various environmentally harmful compounds, with a significant portion being released into the environment through wastewater discharge. This poses a substantial concern for the pollution of surface water bodies. When left untreated, both solid and liquid waste can seriously degrade water quality. The long-term impacts of the pulp and paperboard industry on the environment have been documented, including instances of water pollution leading to ecotoxicity and slow gill recovery in Caddis larvae (Mandeep *et al.*, 2019). Additionally, studies have shown that compounds such as resin acids and retene found in the effluent can exhibit genotoxicity to sea bass, while abietic acid and retene can inhibit liver ethoxyresorufin-O-deethylase activity (Aprianti *et al.*, 2018).

In addition to various pollutants in paper mill wastewater, there are also a significant presence of endocrine-disrupting compounds (EDCs) that interfere with the endocrine system, potentially causing adverse effects on living organisms (Holmes *et al.*, 2017). Reports have identified toxic elements and compounds such as nickel, copper, chromium, lead, trichlorophenol, trichloroguaiacol, tetrachloroguaiacol, dichlorophenol, dichloroguaiacol, and pentachlorophenol in pulp and paper wastewater. These chemical pollutants can have detrimental effects on animal survival and disrupt animal functions at the molecular, cellular, individual, and population levels. The environmental consequences of waste generated by pulp and paper manufacturing include aquatic toxicity and impacts on the food chain (A. K. Singh & Chandra, 2019).

2.7 Oil and Mining Industry:

Heavy metals in effluents resulting from the oil industry are attributed to exploration activities, oil spills at terminals, tanker accidents, offshore drilling, and land-based industrial, urban, recreational, and agricultural sources, as discussed in TSose (2017). These non-biodegradable substances include metals such as Cu, Pb, Zn, Cd, Fe, Mn, and Ni. These substances contaminate water and soil, resulting in severe risks to ecosystems by disrupting environmental quality and to humans by hazardous emissions. These metals are present in limited quantities in the Arabian Gulf, a sea environment, in toxic forms and are absorbed by carbon chains, making them even more toxic to living organisms. Heavy metals associated

Heavy Metal Contamination From Anthropogenic Waste Sources: Environmental Fate, Aquatic Toxicity, And Human Health Implications

with oil result in long-term soil and water pollution, limiting the process of bioremediation. The exposure of aquatic organisms to heavy metals such as Pb and Zn near the refineries poses health hazards, which might result in long-term health problems. This is exemplified by the profile of Pb and Zn in the sediments near the refineries (Freije, 2014). The heavy metal contamination of soil samples from the surroundings of a chlor-alkali slag residue storage facility in Qiqihar, NE China, for eight heavy metals: As, Cd, Cr, Cu, Hg, Ni, Pb, and Zn. The results showed high levels of mercury contamination in the soil samples, with a maximum of 112.19 mg/kg, and high concentrations of As, Cu, and Pb due to industrial waste. The source apportionment using the PMF model showed that oil refinery wastewater and parent material, vinyl chloride/PVC industrial waste, and parent material were the major source contributions. The results of the ecological risk assessment showed extremely high levels of risk due to Hg contamination in the soil (Wu *et al.*, 2022).

Fashola *et al.* (2016) asserted that gold mining comprises both open-pit and deep shaft methods, frequently entailing the extraction of other heavy metals such as lead (Pb), silver (Ag), and copper (Cu). The choice of mining process depends on the location and dictates the amount of waste generated. To separate gold (Au) from mineral-bearing rock, mercury is combined with the extracted ores from ground or stream beds, forming an amalgam. When the amalgam is heated, elemental mercury vaporizes into a toxic plume, posing severe occupational and environmental health risks leaving the gold behind. This mercury amalgamation technique, which has been used for centuries, is still employed today in artisanal and small-scale gold mining (ASGM). In modern extraction processes, gold is first dissolved using cyanide, and then the dissolved gold is recovered from the cyanide solution either through cementation with zinc or by adsorption onto activated carbon.

2.7.1 Arsenic:

Nriagu *et al.* (2007) posited that arsenic is present in gold-bearing rock in various compounds, such as arsenopyrite [FeSAs], realgar [As₂S₂], and orpiment [As₂S₃]. The most toxic forms of arsenic are As(III) and arsenate As(V), and these forms are commonly encountered in mine tailings. Arsenic exposure can lead to a range of severe health consequences, including peripheral vascular disease, as well as the development of cancer in the lungs, skin, kidneys, and bladder. Additionally, it can cause significant

disruptions to the cardiovascular and central nervous systems, potentially resulting in fatal outcomes. Other observed effects of arsenic toxicity include bone marrow depression, hemolysis (destruction of red blood cells), hepatomegaly (enlargement of the liver), melanosis (darkening of the skin), polyneuropathy (damage to multiple nerves), and encephalopathy (brain dysfunction).

2.7.2 Cadmium:

In the tailings of gold mines, cadmium is found at levels ranging from 6.4 to 11.7 mg/kg. It is present in gold-bearing orebodies as a trace element within sphalerite, and its concentration is linked to the amount of sphalerite in the ore body. Cadmium exposure can lead to bronchial and pulmonary irritation, the formation of kidney stones, liver damage, and various systemic disorders affecting the nervous and immune systems, blood, bones, and potentially cause Itai-Itai disease (Satarug *et al.*, 2011).

2.7.3 Chromium:

Chromium is widely distributed in natural environments and is present in minerals such as chromite [(Fe, Mg, Al) Cr₂O₄], which is found in soils and rocks. In unpolluted soil, chromium concentrations typically range from 2 to 60 mg/kg, but in gold mine tailings, a higher concentration of 486 mg/kg has been recorded (Dhal *et al.*, 2013). Chromium(III) species tend to be less soluble and relatively immobile due to their adsorption to clays and oxide minerals at pH values below 5. Conversely, their solubility is limited above pH 5, primarily as Cr(OH)₃ (S). Hexavalent chromium (Cr(VI)) is the most oxidized form and is potentially hazardous because of its high solubility and mobility, enabling it to penetrate biological membranes and contaminate soil and water (Sultan *et al.*, 2003). Exposure to chromium can result in skin rashes, stomach ulcers, respiratory issues, a weakened immune system, kidney and liver damage, genetic material alterations, lung cancer, and even fatalities. Chromium also interferes with enzyme activity, causes DNA damage, disrupts gene expression, and induces mutations (Bagchi, 2002).

2.7.4 Lead:

The typical average concentration of lead (Pb) in surface soils worldwide is approximately 32 mg/kg, which falls within a range of 10–67 mg/kg. However, in gold mine tailings, significantly higher concentrations have been documented, varying between 80 mg/kg and 510 mg/kg. In gold ore, lead is commonly present in the form of galena (PbS), particularly when the ore has a high sulfide

Heavy Metal Contamination From Anthropogenic Waste Sources: Environmental Fate, Aquatic Toxicity, And Human Health Implications

concentration (Ogola *et al.*, 2002). Exposure to lead can result in various health issues, including blood-related disorders such as colic, constipation, and anemia; elevated blood pressure; reduced hemoglobin production; disorders of the kidney, joints, reproductive system, and cardiovascular system; and long-term damage to both the central and peripheral nervous systems. Additionally, it can lead to a decrease in IQ, a low sperm count, and hearing loss (Shahid *et al.*, 2012).

2.7.5 Zinc:

Zinc is also found in gold ore deposits, typically in the form of sphalerite (ZnS), often occurring alongside galena. In the Earth's crust, the natural average level of zinc is approximately 70 mg/kg (dry weight), with a range of 10 to 300 mg/kg. However, in gold mine tailings, zinc concentrations can vary between 8.9 and 65.7 mg/kg (Bempah and Ewusi 2016). Exposure to zinc can lead to various health effects, including tachycardia, vascular shock, dyspeptic nausea, headaches, and nasal cavity and lung cancer. Other symptoms may include asthma, vomiting, diarrhea, hypoglycemia, pancreatitis, damage to the hepatic parenchyma (liver tissue), and impaired growth and reproduction (Rattan *et al.*, 2005).

2.8 Agricultural Waste:

Heavy metal contamination of the environment arises from various sources, including human activities and natural processes. Anthropogenic factors, primarily driven by the rapid growth of the human population, industrialization, and agricultural expansion, play a substantial role in this contamination. The key contributors to heavy metal pollution include mining operations, the use of fertilizers, herbicides, and pesticides in agriculture, and the irrigation of farmland with untreated sewage and industrial effluents (Rattan *et al.*, 2005).

Mercury is a heavy metal that can enter the environment through human activities. These activities encompass a wide range of industries, such as chlorine and caustic soda production, paper and pulp preservation, agricultural practices, and pharmaceutical manufacturing.

Cadmium, another concerning heavy metal, is commonly present in geological materials such as mineral fertilizers, coal, soils, and rocks. To address heavy metal pollution in water, researchers have explored the use of various materials. These include agricultural waste products such as walnut shells, coffee grounds, rice husk ash, and sawdust, as well as industrial waste materials such as red sludge, fly ash

from power plants, and steel slag, all of which serve as effective adsorbents for removing heavy metal ions from water (Miretzky & Fernandez, 2009).

Additionally, local and naturally occurring materials, such as biomass, feedstocks, and industrial and agricultural waste, have shown promise in removing heavy metals from complex water systems. In summary, while natural processes also contribute to heavy metal contamination, human activities such as industrial operations, mining, the use of industrial water for crop irrigation, and the intensification of industrialization and agricultural practices significantly amplify the issue of heavy metal pollution in the environment.

Agricultural waste comprises organic materials such as spent grains, straw, molasses, bagasse, husks (from maize, wheat, and rice), peels (from avocado and banana), shells (from groundnuts, coconuts, and walnuts), crop stalks (from cotton), and other similar components. Alternatively, these waste materials have the potential to be harnessed as sources of renewable energy or used as raw materials for producing value-added products. According to the Food and Agriculture Organization's 2013 report, the global annual production of agro-industrial waste from nonedible plants during crop processing amounts to 250 million tons, while India alone generates over 350 million tons of agro-industrial waste each year (Gaur *et al.*, 2020).

3. Effects of Heavy Metals on Aquatic Life:

Heavy metals entering fish tissues may have the potential to accumulate in various body regions, and prolonged exposure may result in concentrations reaching toxic levels (Emenike *et al.*, 2021). Fish accumulate elevated amounts of heavy metals within their tissues through absorption across gill surfaces, and via ingestion through the walls of their kidneys, livers, and gastrointestinal tracts, surpassing the levels found in the surrounding environment (Rajeshkumar & Li, 2018). Metal uptake in aquatic organisms may occur through passive diffusion or active transport mechanism. Variations in metal accumulation among species may result from differences in assimilation efficiency, metabolic detoxification capacity, and excretion rates (Ayodele *et al.*, 2023). The penetration of heavy metals into fish organs primarily occurs through adsorption and absorption mechanisms. The pace at which accumulation transpires is influenced by the rates of uptake and removal (Annabi *et al.*, 2013). Heavy metals infiltrate the aquatic food chain primarily through two pathways: direct ingestion via water and food intake through the digestive tract, as well as

Heavy Metal Contamination From Anthropogenic Waste Sources: Environmental Fate, Aquatic Toxicity, And Human Health Implications

nondietary routes involving passage across permeable membranes such as muscles and gills. (Ribeiro *et al.*, 2005)

3.1 Accumulation of Heavy Metal in Fish:

Metal accumulation in specific fish organs can induce structural damage and impair physiological function. According to the literature, the accumulation of metals in fish and their subsequent dispersion within organs varies significantly among different species. Moreover, numerous elements can affect the absorption of metals, such as gender, age, sex, body size, reproductive stage, swimming habits, eating patterns, and geographic position (Bawuro *et al.*, 2018). The accumulation of metals in the liver could be attributed to its metabolic function, which encompasses the biochemical processes vital for an organism's survival. Additionally, increased concentrations of Zn and Cu in the liver are tied to inherent protein-binding mechanisms such as metallothionein (Görür *et al.*, 2012). The quantities of heavy metals differed notably among the different types of fish and their body parts. The flesh contained the least amount of these metals overall. The liver was the primary site for Zn, Cu, and Pb accumulation, while the gills had a relatively high concentration of Cd. The presence of metals varies among fish species (Bawuro *et al.*, 2018). The gill and liver exhibited the greatest levels of most metals, with the gonad containing intermediate concentrations and the muscle having the lowest amounts. Substantial variations were observed across the tissues. Metal concentrations in certain tissues (such as muscle and gill) differ significantly based on region and feeding behavior (Pan *et al.*, 2022).

The sequence of chromium levels in various organs was as follows: gill > skin > muscle tissues (lowest concentration). The chromium concentration in the gills ranged from 3.11 to 45.23 $\mu\text{g g}^{-1}$ wet weight (w.w.), whereas in fish muscle tissue, it varied from 0.86 to 12.34 $\mu\text{g g}^{-1}$ w.w. (Yılmaz *et al.*, 2017). The lead that accumulated in the investigated samples displayed a distribution that was specific to each organ. Elevated concentrations were observed in the blood, followed by the kidney, gill, liver, and brain. In comparison, the amounts found in the ovary and muscle tissues were relatively lower (Tulasi *et al.*, 1992). The toxic effects of chromium (Cr) exposure on the striped catfish (*Pangasianodon hypophthalmus*), implying that the sources are from industries and anthropogenic activities, such as those from effluents commonly found in polluted water bodies. The study showed that exposure of the fish to chromium at

concentrations of 0, 5, 10, and 20 mg/L for 30 days results in structural abnormalities in the erythrocyte cells, such as micronuclei and nuclear buds; the gill filaments, such as epithelial lifting and hyperplasia; the liver, such as vacuolation and necrosis; and the kidney, such as glomerular shrinkage and renal tubular degeneration, as well as genetic damage, such as increased frequency of micronuclei, nuclear abnormalities, and DNA strand breaks using the comet test. The study clearly showed that chromium acts as a potent environmental pollutant that results in oxidative stress, cytotoxicity, genotoxicity, and organ damage in the exposed fish (Suchana *et al.*, 2020).

3.2 Physiological Effect:

Several trace metals, such as manganese, iron, cobalt, copper, chromium, and zinc, are recognized as essential minerals that positively impact the physiology and metabolism of fish. Many heavy metals possess strong carcinogenic properties, and furthermore, they have the potential to cause severe health issues such as liver ailments, cardiovascular challenges, kidney malfunctions, and, in extreme instances, even fatality. Heavy metal contamination substantially alters the hematological parameters, enzymatic activity and biochemical characteristics of fish, leading to various anomalies in both cellular and nuclear blood components. Various studies have documented genetic harm resulting from the toxic effects of heavy metals. Heavy metal contamination significantly impedes the reproductive capabilities of fish (Taslina *et al.*, 2022). Various pollutants in paper mill wastewater include endocrine-disrupting compounds (EDCs) that interfere with the endocrine system, potentially causing adverse effects on living organisms Kar *et al.* (2021). Reports have identified toxic elements and compounds such as nickel, copper, chromium, lead, trichlorophenol, trichloroguaiacol, tetrachloroguaiacol, dichlorophenol, dichloroguaiacol, and pentachlorophenol in pulp and paper wastewater. These chemical pollutants can have detrimental effects on animal survival and disrupt animal functions at the molecular, cellular, individual, and population levels (Aprianti *et al.*, 2018).

3.3 Behaviourial Effect:

Behavioral endpoints are increasingly recognized as sensitive indicators in toxicity assessments for fish, as it is acknowledged as a useful tool in ecotoxicology. When evaluating the effects of toxic stress caused by different environmental contaminants, locomotor activity has continuously been shown to be an extremely sensitive metric (Rao *et al.*, 2006). Heavy Metals can impact the mobility of fish through various

Heavy Metal Contamination From Anthropogenic Waste Sources: Environmental Fate, Aquatic Toxicity, And Human Health Implications

mechanisms: (1) inducing movement either toward (attraction) or away from (avoidance) a polluted region; (2) modifying sensory perception, thereby diminishing reactions to typical olfactory signals linked to activities such as feeding, selecting mates, or navigating (all of which encompass locomotion); (3) leading to changes in overall locomotor activity, evident as decreased or increased activity levels; (4) modifying specific locomotor aspects such as the frequency of turns or angular orientation; and (5) diminishing a fish's swimming performance or its ability to endure swimming against a current (Atchison *et al.*, 1987). When the freshwater fish *Channa punctatus* was subjected to a sublethal concentration of cadmium in the experiment, it exhibited notable differences in its behavioral patterns, such as agitation, leaping, unpredictable swimming, inhaling air from the water surface, balance disruption, sluggishness, gill cover movement, and surface gulping, loss of equilibrium and reduced opercular movement. Additionally, physical alterations such as skin discoloration and the presence of pigmented patches were observed (N. Singh & Saxena, 2020).

The freshwater-breathing fish *Clarias batrachus* (Linn), which was exposed to a sublethal concentration of zinc sulfate in the experiment, displayed abnormal behavioral patterns, such as rapid movement, increased opercular activity, frequent exposure to gulp air, and erratic swimming characterized by jerky movements, hyperactivity, convulsions, and a tendency to escape from the aquarium. These behaviors showed an initial increase followed by a subsequent decrease (Sabullah *et al.*, 2015). Observed physiological alterations included reduction in body pigmentation, accompanied by excessive mucus secretion that coagulated throughout the body. This was followed by a loss of equilibrium, causing the fish to slowly ascend in a vertical direction. Subsequently, the fish became increasingly lethargic and completely lost their sense of balance. Ultimately, they settled at the bottom of the aquarium with their bellies facing upward before succumbing (Joshi 2011). In a (2002) study conducted by Tanimoto and Kizaki, the authors investigated how a proteasome inhibitor impacted the Ras/ERK signaling pathway. Their research revealed that the inhibitor led to the suppression of Fas ligand expression, ultimately resulting in a reduction in the production of molecules associated with both apoptosis and necrosis.

4. Implications for Human Health by Contaminated Fish Consumption:

Fish represent a major source of dietary protein globally; however, the consumption of fish contaminated with heavy metals can lead to bioaccumulation of toxic elements in the human body. Therefore, systematic monitoring and assessment of heavy metal concentrations in edible fish tissues are essential to ensure food safety (Singh and Saxena 2020). Elevated concentrations of heavy metals may negate the nutritional benefits associated with fish consumption. The adverse health effects associated with chronic heavy metal exposure are well documented. These effects include renal dysfunction, hepatic injury, cardiovascular disorders, neurotoxicity, and in severe cases, mortality (Bawuro *et al.*, 2018). These metals are toxic, do not breakdown naturally, build up in living organisms, and have cancer-causing properties. This combination of characteristics amplifies their impact (Ahmadijokani *et al.*, 2022).

Heavy metal ions are toxic, have the potential to induce cancer, and can accumulate within living organisms. Even at low concentrations, chronic exposure may damage multiple organ systems, including the nervous, hepatic, renal, respiratory, dermatological, and reproductive systems (Aziz *et al.*, 2023). Dietary exposure to heavy metals may result in their deposition in bones and adipose tissues, potentially leading to mineral imbalances, immunosuppression, and metabolic dysfunction. Heavy metals such as cadmium and lead, along with other similar elements, have been linked to instances of restricted fetal growth during pregnancy (Rai *et al.*, 2019).

Several historical incidents have highlighted the consequences of heavy metal contamination in food systems. Various countries, such as Japan, Iraq, and the United States, have faced situations where large numbers of individuals became ill or lost their lives due to such incidents. Among these occurrences, Minamata disease stands out as the most widely recognized. This outbreak, which involved methylmercury poisoning, initially surfaced in 1956 near Minamata Bay in Kumamoto Prefecture, Japan, and a subsequent outbreak occurred in 1965 along the Agano River in Niigata Prefecture, Japan (Ikeda *et al.*, 2003).

Table 3: International Regulatory Limits for Selected Heavy Metals

	WHO Drinking Water Limit (mg/L)	USEP A MCL (mg/L)	FAO/WHO Fish Limit (mg/kg)	CPC B Surface Water
Heavy Metal				

Heavy Metal Contamination From Anthropogenic Waste Sources: Environmental Fate, Aquatic Toxicity, And Human Health Implications

				Limit (mg/L)
Cadmium (Cd)	0.003	0.005	0.05	0.01
Lead (Pb)	0.01	0.015 (Action Level)	0.3	0.05
Chromium (Total Cr)	0.05	0.1	0.5	0.05
Hexavalent Chromium (Cr VI)	0.05 (guideline)	0.1 (total Cr)	—	0.05
Mercury (Hg)	0.006	0.002	0.5 (methylmercury)	0.01
Arsenic (As)	0.01	0.01	0.1	0.05
Nickel (Ni)	0.07	0.1	0.5	0.02
Zinc (Zn)	3.0 (aesthetic)	5.0 (secondary)	40	5.0
Copper (Cu)	2.0	1.3 (Action Level)	30	3.0

Although regulatory standards for heavy metals have been established, many investigations report that concentrations in industrial discharges and aquatic environments often surpass the prescribed limits (Table 3). This issue is especially prevalent in developing countries, where regulatory enforcement and monitoring systems may be insufficient. Therefore, sustained environmental surveillance, stronger implementation of compliance measures, and the adoption of updated, risk-based regulatory policies are crucial to minimize long-term ecological damage and protect public health.

5. Conclusion:

Heavy metal contamination arising from anthropogenic waste streams represents one of the most persistent and complex environmental challenges of the modern industrial era. The synthesis of evidence presented in this review clearly demonstrates that diverse waste sources including electronic waste,

industrial effluents, leather tanning, textile processing, paint and polymer manufacturing, pulp and paper production, and mining activities contribute significantly to the continuous release of toxic metals into terrestrial and aquatic ecosystems. Unlike many organic pollutants, heavy metals are non-biodegradable and exhibit long environmental residence times, enabling them to accumulate in soil, sediments, and water bodies and subsequently enter biological systems through various exposure pathways. The environmental fate of heavy metals is governed by complex physicochemical processes such as adsorption, precipitation, complexation, and redox transformations, which influence their mobility and bioavailability. Once introduced into aquatic ecosystems, these metals can disrupt ecological balance by affecting primary producers, invertebrates, and higher trophic organisms. Bioaccumulation and biomagnification further intensify their ecological impact, allowing toxic metals to concentrate progressively along food chains. Such processes not only threaten aquatic biodiversity but also compromise ecosystem services such as water purification, fisheries productivity, and nutrient cycling. From a human health perspective, the consequences of chronic heavy metal exposure are particularly alarming. Exposure routes—including ingestion of contaminated water and food, dermal contact, and inhalation of particulate matter—facilitate the accumulation of metals such as cadmium, chromium, lead, and mercury within vital organs. Numerous toxicological studies have established strong associations between heavy metal exposure and a wide spectrum of health disorders, including neurological impairment, renal dysfunction, respiratory diseases, developmental abnormalities, and carcinogenesis. Vulnerable populations such as industrial workers, informal waste recyclers, and communities residing near industrial clusters face disproportionately higher exposure risks, emphasizing the urgent need for improved occupational safety and environmental protection measures.

Despite the establishment of regulatory frameworks and effluent discharge standards in many countries, inadequate enforcement, rapid industrial expansion, and improper waste management practices continue to exacerbate heavy metal pollution, particularly in developing regions. This review highlights that conventional wastewater treatment technologies alone are often insufficient to address the complexity of heavy metal contamination. Therefore, integrated strategies combining advanced remediation

Heavy Metal Contamination From Anthropogenic Waste Sources: Environmental Fate, Aquatic Toxicity, And Human Health Implications

technologies, sustainable waste management practices, and strict regulatory monitoring are essential to mitigate environmental risks. Future research should focus on developing cost-effective and environmentally sustainable remediation approaches, including biosorption, nanomaterial-based adsorbents, phytoremediation, and microbial biotransformation processes. Additionally, interdisciplinary approaches integrating environmental monitoring, toxicological assessment, and predictive modeling will be crucial for understanding long-term ecological impacts and guiding evidence-based policy decisions. Strengthening international collaboration and promoting circular economy principles particularly in sectors such as electronic waste recycling—can also play a critical role in reducing heavy metal release at the source. In conclusion, addressing heavy metal contamination requires a comprehensive and multidisciplinary framework that integrates scientific innovation, environmental governance, and sustainable industrial practices. Only through coordinated global efforts can the escalating risks posed by heavy metal pollution be effectively managed, thereby safeguarding ecosystem integrity and protecting human health for future generations.

Author contribution

Irine Briny Hepzibha. J: Conceptualization, Data Curation, Methodology, Writing- Original draft, Visualization. **Monica Muniendra Babu:** Writing – review & editing, Validation, Supervision, Conceptualization. **Shirin Fargana Bava:** Writing – review, Visualization, Investigation. **Dhivya Bharathi Venkata Krishnan:** Writing – review, Data curation and **Ebine Joel Sam Christy:** Writing – review, Data curation.

Funding:

No funding was received for this manuscript.

Data availability:

The data are available upon request

Reference:

- 1) Agency for Toxic Substances and Disease Registry (ATSDR). (2021). *Toxicological profile for lead*. U.S. Department of Health and Human Services. <https://www.atsdr.cdc.gov/toxprofiles/tp.asp?id=96&tid=22>
- 2) Ahmadijokani, F., Molavi, H., Peyghambari, A., Shojaei, A., Rezakazemi, M., Aminabhavi, T. M., & Arjmand, M. (2022). Efficient removal of heavy metal ions from aqueous media by unmodified and modified nanodiamonds. *Journal of Environmental Management*, 316, 115214. <https://doi.org/10.1016/j.jenvman.2022.115214>
- 3) Alabi, O. A., Adeoluwa, Y. M., Huo, X., Xu, X., & Bakare, A. A. (2021). Environmental contamination and public health effects of electronic waste: an overview. *Journal of Environmental Health Science and Engineering*, 19(1), 1209–1227. <https://doi.org/10.1007/s40201-021-00654-5>
- 4) Ali, H., & Khan, E. (2017). What are heavy metals? Long-standing controversy over the scientific use of the term ‘heavy metals’ – proposal of a comprehensive definition. *Toxicological & Environmental Chemistry Reviews*, 100(1), 6–19. <https://doi.org/10.1080/02772248.2017.1413652>
- 5) Ali, S. M., & Selva, S. (2022). E-Waste management of electronics and its impact on environment and health. *International Journal of Applied Research*, 8(6), 77–81. <https://doi.org/10.22271/allresearch.2022.v8.i6b.9821>
- 6) Alloway, B. J. (2012). Sources of heavy metals and metalloids in soils. In *Environmental pollution* (pp. 11–50). https://doi.org/10.1007/978-94-007-4470-7_2
- 7) Al-Tohamy, R., Ali, S. S., Li, F., Okasha, K. M., Mahmoud, Y. A., Elsamahy, T., Jiao, H., Fu, Y., & Sun, J. (2022). A critical review on the treatment of dye-containing wastewater: Ecotoxicological and health concerns of textile dyes and possible remediation approaches for environmental safety. *Ecotoxicology and Environmental Safety*, 231, 113160. <https://doi.org/10.1016/j.ecoenv.2021.113160>
- 8) Ankit, Saha, L., Kumar, V., Tiwari, J., Sweta, Rawat, S., Singh, J., & Bauddh, K. (2021). Electronic waste and their leachates impact on human health and environment: Global ecological threat and management. *Environmental Technology & Innovation*, 24, 102049. <https://doi.org/10.1016/j.eti.2021.102049>
- 9) Annabi, A., Said, K., & Messoudi, I. (2013). Cadmium: bioaccumulation, histopathology

Heavy Metal Contamination From Anthropogenic Waste Sources: Environmental Fate, Aquatic Toxicity, And Human Health Implications

- and detoxifying mechanisms in fish. *American Journal of Research Communication*, 4-4, 60–79. http://www.usa-journals.com/wp-content/uploads/2013/03/Annabi_Vol14_1.pdf
- 10) Aprianti, T., Miskah, S., Selpiana, Komala, R., & Hatina, S. (2018). Heavy metal ions adsorption from pulp and paper industry wastewater using zeolite/activated carbon-ceramic composite adsorbent. *AIP Conference Proceedings*. <https://doi.org/10.1063/1.5054531>
 - 11) Atchison, G. J., Henry, M. G., & Sandheinrich, M. B. (1987). Effects of metals on fish behavior: a review. *Environmental Biology of Fishes*, 18(1), 11–25. <https://doi.org/10.1007/bf00002324>
 - 12) Ayodele, O. S., Adelodun, A. A., & Oluwagbohunmi, A. (2023). Trace metal concentration in common fishes from the Lagos lagoon, Southwestern Nigeria. *Regional Studies in Marine Science*, 60, 102844. <https://doi.org/10.1016/j.rsma.2023.102844>
 - 13) Aziz, K. H. H., Mustafa, F. S., Omer, K. M., Hama, S., Hamarawf, R. F., & Rahman, K. O. (2023). Heavy metal pollution in the aquatic environment: efficient and low-cost removal approaches to eliminate their toxicity: a review. *RSC Advances*, 13(26), 17595–17610. <https://doi.org/10.1039/d3ra00723e>
 - 14) Bagchi, D. (2002). Cytotoxicity and oxidative mechanisms of different forms of chromium. *Toxicology*, 180(1), 5–22. [https://doi.org/10.1016/s0300-483x\(02\)00378-5](https://doi.org/10.1016/s0300-483x(02)00378-5)
 - 15) Bagwan, W. A. (2023). Electronic waste (E-waste) generation and management scenario of India, and ARIMA forecasting of E-waste processing capacity of Maharashtra state till 2030. *Waste Management Bulletin*, 1(4), 41–51. <https://doi.org/10.1016/j.wmb.2023.08.002>
 - 16) Bawuro, A. A., Voegborlo, R. B., & Adimado, A. A. (2018). Bioaccumulation of heavy metals in some tissues of fish in Lake Geriyo, Adamawa State, Nigeria. *Journal of Environmental and Public Health*, 2018, 1–7. <https://doi.org/10.1155/2018/1854892>
 - 17) Bempah, C. K., & Ewusi, A. (2016). Heavy metals contamination and human health risk assessment around Obuasi gold mine in Ghana. *Environmental Monitoring and Assessment*, 188(5), 261. <https://doi.org/10.1007/s10661-016-5241-3>
 - 18) Central Pollution Control Board (CPCB), India. (2009). *Status of groundwater quality in India - Part II*. http://cpcb.nic.in/upload/NewItems/NewItem_149_GroundWaterQuality-09.pdf
 - 19) Chandrasekaran V, Dilara K, & Padmavathi R. (2014). Pulmonary functions in tannery workers--a cross sectional study. *Indian Journal of Physiology and Pharmacology*, 58(3), 206–210.
 - 20) Chen, H. (2007). Exposure and Health Risk of Gallium, Indium, and Arsenic from Semiconductor Manufacturing Industry Workers. *Bulletin of Environmental Contamination and Toxicology*, 78(2), 123–127. <https://doi.org/10.1007/s00128-007-9079-9>
 - 21) Debnath, B., Saha, I., Mukherjee, T., Mitra, S., Das, A., & Das, A. (2021). Sorbents from waste materials: A circular economic approach. In *Elsevier eBooks* (pp. 285–322). <https://doi.org/10.1016/b978-0-12-820042-1.00028-6>
 - 22) Dhal, B., Thatoi, H., Das, N., & Pandey, B. (2013). Chemical and microbial remediation of hexavalent chromium from contaminated soil and mining/metallurgical solid waste: A review. *Journal of Hazardous Materials*, 250–251, 272–291. <https://doi.org/10.1016/j.jhazmat.2013.01.048>
 - 23) El-Ghiaty, M. A., & El-Kadi, A. O. (2021). Arsenic: Various species with different effects on cytochrome P450 regulation in humans. *PubMed*, 20, 1184–1242. <https://doi.org/10.17179/excli2021-3890>
 - 24) Emenike, E. C., Iwuzor, K. O., & Anidiobi, S. U. (2021). Heavy metal pollution in aquaculture: sources, impacts and mitigation techniques. *Biological Trace Element Research*, 200(10), 4476–4492. <https://doi.org/10.1007/s12011-021-03037-x>
 - 25) Fashola, M., Ngole-Jeme, V., & Babalola, O. (2016). Heavy Metal Pollution from Gold Mines: Environmental Effects and Bacterial

Heavy Metal Contamination From Anthropogenic Waste Sources: Environmental Fate, Aquatic Toxicity, And Human Health Implications

- Strategies for Resistance. *International Journal of Environmental Research and Public Health*, 13(11), 1047. <https://doi.org/10.3390/ijerph13111047>
- 26) Freije, A. M. (2014). Heavy metal, trace element and petroleum hydrocarbon pollution in the Arabian Gulf: Review. *Journal of the Association of Arab Universities for Basic and Applied Sciences*, 17(1), 90–100. <https://doi.org/10.1016/j.jaubas.2014.02.001>
- 27) Freitas, R., Cardoso, C. E., Costa, S., Morais, T., Moleiro, P., Lima, A. F., Soares, M., Figueiredo, S., Águeda, T. L., Rocha, P., Amador, G., Soares, A. M., & Pereira, E. (2020). New insights on the impacts of e-waste towards marine bivalves: The case of the rare earth element Dysprosium. *Environmental Pollution*, 260, 113859. <https://doi.org/10.1016/j.envpol.2019.113859>
- 28) Garai, P., Banerjee, P., Mondal, P.K., Ch, N., & Saha, R. (2021). Effect of Heavy Metals on Fishes: Toxicity and Bioaccumulation. *Journal of Clinical Toxicology*, 1-10.
- 29) Garbo, F., Pivato, A., Manachini, B., Moretto, C. G., & Lavagnolo, M. C. (2018). Assessment of the ecotoxicity of phytotreatment substrate soil as landfill cover material for in-situ leachate management. *Journal of Environmental Management*, 231, 289–296. <https://doi.org/10.1016/j.jenvman.2018.10.014>
- 30) Gaur, V. K., Sharma, P., Sirohi, R., Awasthi, M. K., Dussap, C., & Pandey, A. (2020). Assessing the impact of industrial waste on environment and mitigation strategies: A comprehensive review. *Journal of Hazardous Materials*, 398, 123019. <https://doi.org/10.1016/j.jhazmat.2020.123019>
- 31) Gavrilescu, D., Puitel, A. C., Dutuc, G., & Craciun, G. (2012). Environmental Impact of Pulp and Paper Mills. *Environmental Engineering and Management Journal*, 11(1), 81–85. <https://doi.org/10.30638/eemj.2012.012>
- 32) Gibb, H. J., Lees, P. S., Pinsky, P. F., & Rooney, B. C. (2000). Lung cancer among workers in chromium chemical production. *American journal of industrial medicine*, 38(2), 115–126. [https://doi.org/10.1002/1097-0274\(200008\)38:2<115::aid-ajim1>3.0.co;2-y](https://doi.org/10.1002/1097-0274(200008)38:2<115::aid-ajim1>3.0.co;2-y)
- 33) Görür, F. K., Keser, R., Akçay, N., & Dizman, S. (2012). Radioactivity and heavy metal concentrations of some commercial fish species consumed in the Black Sea Region of Turkey. *Chemosphere*, 87(4), 356–361. <https://doi.org/10.1016/j.chemosphere.2011.12.022>
- 34) Halimoon, N., & Yin, R. G. S. (2010). Removal of Heavy Metals from Textile Wastewater using Zeolite. *Universiti Putra Malaysia Institutional Repository (Universiti Putra Malaysia)*. <https://doi.org/10.14456/ea.2010.51>
- 35) Holmes, B. E., Smeester, L., Fry, R. C., & Weinberg, H. S. (2017). Identification of endocrine active disinfection by-products (DBPs) that bind to the androgen receptor. *Chemosphere*, 187, 114–122. <https://doi.org/10.1016/j.chemosphere.2017.08.105>
- 36) Huang, J., Nkrumah, P. N., Anim, D. O., & Mensah, E. (2013). E-Waste disposal effects on the aquatic environment: Accra, Ghana. *Reviews of Environmental Contamination and Toxicology*, 229, 19–34. https://doi.org/10.1007/978-3-319-03777-6_2
- 37) Ikeda, M., Ezaki, T., Tsukahara, T., Moriguchi, J., Furuki, K., Fukui, Y., Ukai, H., Okamoto, S., & Sakurai, H. (2003). Threshold levels of urinary cadmium in relation to increases in urinary β 2-microglobulin among general Japanese populations. *Toxicology Letters*, 137(3), 135–141. [https://doi.org/10.1016/s0378-4274\(02\)00389-2](https://doi.org/10.1016/s0378-4274(02)00389-2)
- 38) Jain, M., Kumar, D., Chaudhary, J., Kumar, S., Sharma, S., & Verma, A. S. (2023). Review on E-waste management and its impact on the environment and society. *Waste Management Bulletin*, 1(3), 34–44. <https://doi.org/10.1016/j.wmb.2023.06.004>
- 39) Jolly, Y., Hossain, A., Sattar, A., & Islam, A. (2013). Impact of heavy metals on water and soil environment of a paint industry. *Journal of Bangladesh Chemical Society*, 25(2), 159–

Heavy Metal Contamination From Anthropogenic Waste Sources: Environmental Fate, Aquatic Toxicity, And Human Health Implications

165.
<https://doi.org/10.3329/jbcs.v25i2.15068>
- 40) Joshi, P. (2011). Impact of zinc sulphate on behavioural responses in the freshwater fish *Clarias batrachus* (Linn.). *International Journal of Environmental Sciences*, 1, 76–82.
- 41) Julander, A., Lundgren, L., Skare, L., Grandér, M., Palm, B., Vahter, M., & Lidén, C. (2014). Formal recycling of e-waste leads to increased exposure to toxic metals: An occupational exposure study from Sweden. *Environment International*, 73, 243–251. <https://doi.org/10.1016/j.envint.2014.07.006>
- 42) Junaid, M., Hashmi, M. Z., Tang, Y., Malik, R. N., & Pei, D. (2017). Potential health risk of heavy metals in the leather manufacturing industries in Sialkot, Pakistan. *Scientific Reports*, 7(1), 8848. <https://doi.org/10.1038/s41598-017-09075-7>
- 43) K, S. N., Manu, B., & Azhoni, A. (2021). Sustainable treatment of paint industry wastewater: Current techniques and challenges. *Journal of Environmental Management*, 296, 113105. <https://doi.org/10.1016/j.jenvman.2021.113105>
- 44) Kar, S., Sangem, P., Anusha, N., & Senthilkumaran, B. (2020). Endocrine disruptors in teleosts: Evaluating environmental risks and biomarkers. *Aquaculture and Fisheries*, 6(1), 1–26. <https://doi.org/10.1016/j.aaf.2020.07.013>
- 45) Kaur, J., Bhatti, S. S., Bhat, S. A., Nagpal, A. K., Kaur, V., & Katnoria, J. K. (2021). Evaluating potential ecological risks of heavy metals of textile effluents and soil samples in vicinity of textile industries. *Soil Systems*, 5(4), 63. <https://doi.org/10.3390/soilsystems5040063>
- 46) Khan, W. U., Ahmed, S., Dhoble, Y., & Madhav, S. (2022). A critical review of hazardous waste generation from textile industries and associated ecological impacts. *Journal of the Indian Chemical Society*, 100(1), 100829. <https://doi.org/10.1016/j.jics.2022.100829>
- 47) Kishor, R., Purchase, D., Saratale, G. D., Saratale, R. G., Ferreira, L. F. R., Bilal, M., Chandra, R., & Bharagava, R. N. (2021). Ecotoxicological and health concerns of persistent coloring pollutants of textile industry wastewater and treatment approaches for environmental safety. *Journal of Environmental Chemical Engineering*, 9(2), 105012. <https://doi.org/10.1016/j.jece.2020.105012>
- 48) Kumarathilaka, P., Seneweera, S., Meharg, A., & Bundschuh, J. (2018). Arsenic speciation dynamics in paddy rice soil-water environment: sources, physico-chemical, and biological factors - A review. *Water Research*, 140, 403–414. <https://doi.org/10.1016/j.watres.2018.04.034>
- 49) Liao, Y.-., Yu, H.-., Ho, C.-., Wu, M.-., Yang, C.-., Chen, J.-., & Chang, C.-. (2004). Biological monitoring of exposures to aluminium, gallium, indium, arsenic, and antimony in optoelectronic industry workers. *Journal of Occupational and Environmental Medicine*, 46(9), 931–936. <https://doi.org/10.1097/01.jom.0000137718.93558.b8>
- 50) Malaviya, P., & Singh, A. (2012). Phytoremediation Strategies for Remediation of Uranium-Contaminated Environments: A review. *Critical Reviews in Environmental Science and Technology*, 42(24), 2575–2647. <https://doi.org/10.1080/10643389.2011.592761>
- 51) Mandeep, Gupta, G. K., Liu, H., & Shukla, P. (2019). Pulp and paper industry-based pollutants, their health hazards and environmental risks. *Current Opinion in Environmental Science & Health*, 12, 48–56. <https://doi.org/10.1016/j.coesh.2019.09.010>
- 52) Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India. (2016). *Environment (Protection) Rules, 1986 - Schedule VI*. <http://envfor.nic.in/legis/env/env4.html>
- 53) Miretzky, P., & Fernandez, A. (2009). Phosphates for PB immobilization in soils: a review. *Sustainable Agriculture Reviews*, 351–370. https://doi.org/10.1007/978-1-4020-9654-9_16
- 54) Nagpure, N. S., Srivastava, R., Kumar, R., Kushwaha, B., Srivastava, S. K., Kumar, P., & Dabas, A. (2014). Assessment of genotoxic and mutagenic potential of hexavalent chromium in the freshwater fish *Labeo rohita* (Hamilton, 1822). *Drug and Chemical Toxicology*, 38(1), 9–15.

Heavy Metal Contamination From Anthropogenic Waste Sources: Environmental Fate, Aquatic Toxicity, And Human Health Implications

- <https://doi.org/10.3109/01480545.2014.900066>
- 55) Nriagu, J., Bhattacharya, P., Mukherjee, A., Bundschuh, J., Zevenhoven, R., & Loeppert, R. (2007). Arsenic in soil and groundwater: an overview. In *Trace metals and other contaminants in the environment* (pp. 3–60). [https://doi.org/10.1016/s1875-1121\(06\)09001-8](https://doi.org/10.1016/s1875-1121(06)09001-8)
- 56) Ogola, J. S., Mitullah, W. V., & Omulo, M. A. (2002). Impact of Gold mining on the Environment and Human Health: A Case Study in the Migori Gold Belt, Kenya. *Environmental Geochemistry and Health*, 24(2), 141–157. <https://doi.org/10.1023/a:1014207832471>
- 57) Oh, C. J., Lee, S. O., Yang, H. S., Ha, T. J., & Kim, M. J. (2003). Selective Leaching of Valuable Metals from Waste Printed Circuit Boards. *Journal of the Air & Waste Management Association*, 53(7), 897–902. <https://doi.org/10.1080/10473289.2003.10466230>
- 58) Pan, B., Han, X., Yu, K., Sun, H., Mu, R., & Lian, C. (2022). Geographical distance, host evolutionary history and diet drive gut microbiome diversity of fish across the Yellow River. *Molecular Ecology*, 32(5), 1183–1196. <https://doi.org/10.1111/mec.16812>
- 59) Rai, P. K., Lee, S. S., Zhang, M., Tsang, Y. F., & Kim, K. (2019). Heavy metals in food crops: Health risks, fate, mechanisms, and management. *Environment International*, 125, 365–385. <https://doi.org/10.1016/j.envint.2019.01.067>
- 60) Rajeshkumar, S., & Li, X. (2018). Bioaccumulation of heavy metals in fish species from the Meiliang Bay, Taihu Lake, China. *Toxicology Reports*, 5, 288–295. <https://doi.org/10.1016/j.toxrep.2018.01.007>
- 61) Rangasamy, S.R., Purushothaman, G., Alagirisamy, B., & Santiago, M. (2015). Chromium contamination in soil and groundwater due to tannery wastes disposals at Vellore district of Tamil Nadu. *International Journal on Environmental Sciences*, 6, 114–124.
- 62) Rao, J. V., Begum, G., Jakka, N. M., Srikanth, K., & Rao, R. N. (2006). Sublethal Effects of Profenofos on Locomotor Behavior and Gill Architecture of the Mosquito Fish, *Gambusia affinis*. *Drug and Chemical Toxicology*, 29(3), 255–267. <https://doi.org/10.1080/01480540600651543>
- 63) Rattan, R., Datta, S., Chhonkar, P., Suribabu, K., & Singh, A. (2005). Long-term impact of irrigation with sewage effluents on heavy metal content in soils, crops and groundwater—a case study. *Agriculture Ecosystems & Environment*, 109(3–4), 310–322. <https://doi.org/10.1016/j.agee.2005.02.025>
- 64) Ribeiro, C. O., Vollaire, Y., Sanchez-Chardi, A., & Roche, H. (2005). Bioaccumulation and the effects of organochlorine pesticides, PAH and heavy metals in the Eel (*Anguilla anguilla*) at the Camargue Nature Reserve, France. *Aquatic Toxicology*, 74(1), 53–69. <https://doi.org/10.1016/j.aquatox.2005.04.008>
- 65) Sabullah, M. K., Ahmad, S. A., Shukor, Y., Gansau, J. A., Syed, M. A., Sulaiman, M. R., & Shamaan, N. A. (2015). Heavy metal biomarker: Fish behavior, cellular alteration, enzymatic reaction and proteomics approaches. *International Food Research Journal*, 22, 435–454
- 66) Salhofer, S. (2017). E-Waste collection and treatment options: A comparison of approaches in Europe, China and Vietnam. In *The handbook of environmental chemistry* (p. 227). https://doi.org/10.1007/698_2017_36
- 67) Satarug, S., Garrett, S. H., Sens, M. A., & Sens, D. A. (2009). Cadmium, environmental exposure, and health outcomes. *Environmental Health Perspectives*, 118(2), 182–190. <https://doi.org/10.1289/ehp.0901234>
- 68) Shahid, M., Pinelli, E., & Dumat, C. (2012). Review of Pb availability and toxicity to plants in relation with metal speciation; role of synthetic and natural organic ligands. *Journal of Hazardous Materials*, 219–220, 1–12. <https://doi.org/10.1016/j.jhazmat.2012.01.060>
- 69) Sharma, P., Bihari, V., Agarwal, S. K., Verma, V., Kesavachandran, C. N., Pangtey, B. S., Mathur, N., Singh, K. P., Srivastava, M., & Goel, S. K. (2012). Groundwater Contaminated with Hexavalent Chromium

Heavy Metal Contamination From Anthropogenic Waste Sources: Environmental Fate, Aquatic Toxicity, And Human Health Implications

- [Cr (VI)]: A Health Survey and Clinical Examination of Community Inhabitants (Kanpur, India). *PLoS ONE*, 7(10), e47877. <https://doi.org/10.1371/journal.pone.0047877>
- 70) Shrestha, R., Ban, S., Devkota, S., Sharma, S., Joshi, R., Tiwari, A. P., Kim, H. Y., & Joshi, M. K. (2021). Technological trends in heavy metals removal from industrial wastewater: A review. *Journal of Environmental Chemical Engineering*, 9(4), 105688. <https://doi.org/10.1016/j.jece.2021.105688>
- 71) Shukla, G. S., & Chandra, S. V. (1987). Concurrent exposure to lead, manganese, and cadmium and their distribution to various brain regions, liver, kidney, and testis of growing rats. *Archives of Environmental Contamination and Toxicology*, 16(3), 303–310. <https://doi.org/10.1007/bf01054947>
- 72) Singh, A. K., & Chandra, R. (2019). Pollutants released from the pulp paper industry: Aquatic toxicity and their health hazards. *Aquatic Toxicology*, 211, 202–216. <https://doi.org/10.1016/j.aquatox.2019.04.007>
- 73) Singh, A. K., Kumar, A., & Chandra, R. (2022). Environmental pollutants of paper industry wastewater and their toxic effects on human health and ecosystem. *Bioresource Technology Reports*, 20, 101250. <https://doi.org/10.1016/j.biteb.2022.101250>
- 74) Singh, N., & Saxena, B. (2020). Behavioral and morphological changes in fresh water fish, *Channa punctatus* under the exposure of Cadmium. *Environment Conservation Journal*, 21(3), 187–193. <https://doi.org/10.36953/ecj.2020.21323>
- 75) Stapleton, H. M., Allen, J. G., Kelly, S. M., Konstantinov, A., Klosterhaus, S., Watkins, D., McClean, M. D., & Webster, T. F. (2008). Alternate and new brominated flame retardants detected in U.S. house dust. *Environmental Science & Technology*, 42(18), 6910–6916. <https://doi.org/10.1021/es801070p>
- 76) Suchana, S. A., Ahmed, M. S., Islam, S. M. M., Rahman, M. L., Rohani, M. F., Ferdusi, T., Ahmmad, A. K. S., Fatema, M. K., Badruzzaman, M., & Shahjahan, M. (2020). Chromium Exposure Causes Structural Aberrations of Erythrocytes, Gills, Liver, Kidney, and Genetic Damage in Striped Catfish *Pangasianodon hypophthalmus*. *Biological Trace Element Research*, 199(10), 3869–3885. <https://doi.org/10.1007/s12011-020-02490-4>
- 77) Sultan, S., & Hasnain, S. (2003). Pseudomonad strains exhibiting high level CR(VI) resistance and CR(VI) detoxification potential. *Bulletin of Environmental Contamination and Toxicology*, 71(3), 473–480. <https://doi.org/10.1007/s00128-003-8805-1>
- 78) Tanaka, A. (2004). Toxicity of indium arsenide, gallium arsenide, and aluminium gallium arsenide. *Toxicology and Applied Pharmacology*, 198(3), 405–411. <https://doi.org/10.1016/j.taap.2003.10.019>
- 79) Tanimoto, Y., & Kizaki, H. (2002). Proteasome Inhibitors Block Ras/ERK Signaling Pathway Resulting in the Downregulation of Fas Ligand Expression during Activation-Induced Cell Death in T Cells. *The Journal of Biochemistry*, 131(3), 319–326. <https://doi.org/10.1093/oxfordjournals.jbchem.a003106>
- 80) Taslima, K., Al-Emran, M., Rahman, M. S., Hasan, J., Ferdous, Z., Rohani, M. F., & Shahjahan, M. (2022). Impacts of heavy metals on early development, growth and reproduction of fish – A review. *Toxicology Reports*, 9, 858–868. <https://doi.org/10.1016/j.toxrep.2022.04.013>
- 81) Tchounwou, P. B., Yedjou, C. G., Patlolla, A. K., & Sutton, D. J. (2012). Heavy metal toxicity and the environment. *Proceedings of the Fourth International Symposium on Polarization Phenomena in Nuclear Reactions*, 101, 133–164. https://doi.org/10.1007/978-3-7643-8340-4_6
- 82) Tripathy, A., Dixit, P., & Panigrahi, A. (2021). Impact of effluent of Pulp & Paper industry on the flora of river basin at Jaykaypur, Odisha, India and its ecological implications. *Environmental Research*, 204(Pt A), 111769. <https://doi.org/10.1016/j.envres.2021.111769>
- 83) TSose, A. T. 2. J. K. *. 3. (2017). Oil industry – Analysis, effect and removal of heavy metals. Zenodo (CERN European

Heavy Metal Contamination From Anthropogenic Waste Sources: Environmental Fate, Aquatic Toxicity, And Human Health Implications

- Organization for Nuclear Research). <https://doi.org/10.5281/zenodo.1012468>
- 84) Tue, N. M., Goto, A., Takahashi, S., Itai, T., Asante, K. A., Kunisue, T., & Tanabe, S. (2015). Release of chlorinated, brominated and mixed halogenated dioxin-related compounds to soils from open burning of e-waste in Agbogbloshie (Accra, Ghana). *Journal of Hazardous Materials*, *302*, 151–157. <https://doi.org/10.1016/j.jhazmat.2015.09.062>
- 85) Tulasi, S., Reddy, P., & Rao, J. R. (1992). Accumulation of lead and effects on total lipids and lipid derivatives in the freshwater fish *Anabas testudineus* (Bloch). *Ecotoxicology and Environmental Safety*, *23*(1), 33–38. [https://doi.org/10.1016/0147-6513\(92\)90019-y](https://doi.org/10.1016/0147-6513(92)90019-y)
- 86) Velusamy, S., Roy, A., Sundaram, S., & Mallick, T. K. (2021). A review on heavy metal ions and containing dyes removal through Graphene Oxide-Based Adsorption Strategies for textile wastewater treatment. *The Chemical Record*, *21*(7), 1570–1610. <https://doi.org/10.1002/tcr.202000153>
- 87) Vidyadhar, A. (2016). A Review of Technology of Metal Recovery from Electronic Waste. *InTech eBooks*. <https://doi.org/10.5772/61569>
- 88) Wong, M., Wu, S., Deng, W., Yu, X., Luo, Q., Leung, A., Wong, C., Luksemburg, W., & Wong, A. (2007). Export of toxic chemicals – A review of the case of uncontrolled electronic-waste recycling. *Environmental Pollution*, *149*(2), 131–140. <https://doi.org/10.1016/j.envpol.2007.01.044>
- 89) World Health Organization (WHO). (2010). *Exposure to cadmium: A major public health concern*. <https://www.who.int/ipcs/features/cadmium.pdf>
- 90) Wu, Z., Zhang, D., Xia, T., & Jia, X. (2022). Characteristics, sources and risk assessments of heavy metal pollution in soils of typical chlor-alkali residue storage sites in northeastern China. *PLoS ONE*, *17*(9), e0273434. <https://doi.org/10.1371/journal.pone.0273434>
- 91) Yılmaz, A. B., Yanar, A., & Alkan, E. N. (2017). Review of heavy metal accumulation on aquatic environment in Northern East Mediterranean Sea part I: some essential metals. *Reviews on Environmental Health*, *32*(1–2), 119–163. <https://doi.org/10.1515/reveh-2016-0065>
- 92) Zeitoun, M. M., & Mehana, E. E. (2014). Impact of water pollution with heavy metals on fish health: Overview and updates. *Global Veterinaria*, *12*(2), 219–231.