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REVIEW ARTICLE

Exploring the impact of heavy metals toxicity in the aquatic ecosystem

M. Sharma[1] · R. Kant[2] · A. K. Sharma[3] · A. K. Sharma[2]

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Abstract
The toxic effects of heavy metals have grown to be a global concern in recent years, posing an enormous threat to both aquatic ecosystems and biodiversity. Heavy metals are introduced to aquatic systems as a result of industrialization, mining, agricultural runoff, and a range of other natural activities, such as the weathering of rocks and volcanic activity. Increasing amounts of heavy metals in aquatic ecosystems have been linked to anthropogenic activities, which are largely responsible for their increasing levels. Fish population exposure to heavy metals has been associated with a few health hazards that can be attributed to repeated contact with them. The presence of heavy metals in aquatic ecosystems has negative effects on the quality of the water, hydrogen ion concentrations, dissolved oxygen concentrations, and turbidity of the water and has devastating effects on aquatic biota, including plankton, fish that are present, and benthos. Several heavy metals are known to cause harmful effects on the growth and development of fish, as well as the reproductive and respiratory systems of those fish. Examples include cd, Pb, Hg, Cu, and Zn. Heavy metal toxicity also impairs feeding, breeding, and fish behavior. A significant amount of heavy metals is accumulating in aquatic ecosystems that can lead to their bio-magnification in the food chain as well as disrupting the aquatic food cycle due to increased heavy metal pollution. Heavy metal pollution will increase the risk of extinction for vulnerable species as a result of increased heavy metal pollution. A number of strategies are employed for the remediation of water resources by removing these heavy metals from them, such as bioremediation and phytoremediation. The aim of this review is to evaluate the toxicity of heavy metals in the aquatic ecosystem as a possible threat to biodiversity and ecosystem functioning, and to evaluate the various strategies involved in removing these heavy metals from the environment.

Keywords Heavy metals · Toxicity · Aquatic biodiversity · Bioaccumulation · Biomagnification · Phytoremediation

Introduction

Urbanization and industrialization have contributed to the rapid spread of harmful compounds and heavy metals in nature, which are destructive to natural resources, such as water ecosystems, soil, and air due to their overuse and misuse (Ahmad et al., 2021). A serious global environmental problem is being caused by heavy metal contamination in the environment, specifically cadmium, lead, arsenic, mercury, and nickel (Okereafor et al., 2020). For aquatic organisms, heavy metals can be either non-essential (Cd, Ni, As, Hg, Pb) or necessary (Mo, Mn, Cu, Ni, Fe, Zn). Heavy metal toxicity is demonstrated in any ecosystem when levels exceed allowable thresholds or the necessary concentration (Raychaudhuri et al., 2021). The permitted limits for various heavy metals are tabulated in (Table 1). At low concentrations, metals that are not necessary can have a toxic effect even when they are present in small quantities. In the

✉ A. K. Sharma
dr.amitcuhp@gmail.com

M. Sharma
rs.munish.cuhp@gmail.com

R. Kant
kant7127@gmail.com

A. K. Sharma
rs.arvindsharma@gkv.ac.in

[1] Department of Plant Sciences, Central University of Himachal Pradesh, Shahpur, Kangra, Himachal Pradesh 176206, India

[2] Department of Animal Sciences, Central University of Himachal Pradesh, Shahpur, Kangra, Himachal Pradesh 176206, India

[3] Department of Zoology and Environmental Science, Gurukula Kangri (Deemed to be University), Haridwar, Uttarakhand 249404, India

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Table 1 Permissible levels of heavy metals in water. Sources: Gautam et al. (2016), Paul (2017)

Permissible limit					
Heavy metal	WHO	CPCB	ICMR	USEPA (mg/l)	ISI (mg/l)
Arsenic	0.05	–	0.05	0.05	0.05
Cadmium	0.005	–	0.01	0.005	0.01
Lead	0.05	–	0.05	0.05	0.1
Chromium	0.1	–	–	0.05	0.05
Copper	1	1.5	1.5	1.3	0.05
Mercury	0.0001	–	0.0001	0.002	0.001
Iron	0.1	1	1	0.3	0.3
Zinc	5	15	0.1	–	5

WHO World Health Organization, *USEPA* United States Environmental Protection Agency, *ISI* Indian Standard Institution, *ICMR* Indian Council of Medical Research, *CPCB* Central Pollution Control Board

environment, heavy metals do not decompose, thus they are one of the most persistent and non-biodegradable pollutants. Heavy metals in ecosystems create a cyclical chain of contamination that includes the atmosphere, soil, water, fish, and humans (Briffa et al., 2020). Because they are so common in the environment and originate from both natural and artificial sources, such as the steel industry, mining, and smelter activities, heavy metals are among the most dangerous toxins that can harm living organisms (Paschoalini & Bazzoli, 2021). Heavy metals can enter water bodies naturally through erosion and weathering or artificially through human activity (Tchounwou et al., 2012). When it comes to the cause of heavy metal contamination in water, anthropogenic contributions are more significant than those from natural sources (Izah et al., 2016). The presence of even minute amounts of heavy metal contamination in hydrological media poses a major threat to aquatic ecosystem and health of human beings (Kaur & Roy, 2021). Heavy metals are typically found in aquatic ecosystems after they have been introduced from industries, such as metal, paint, and textile industries. Moreover, there are indiscriminate use of pesticides and fertilizers in agriculture fields that are contaminated with heavy metals due to the indiscriminate use of these products (Sharma et al., 2022). Additionally, food processing operations, energy generation, and power generation, sugar processing operations, construction, steel production, metals processing, and engineering work, as well as chemical dyeing processes, mining operations, and manufacturing effluent pollution, there are numerous other sources (Izah & Angaye, 2016). As, Hg, Cd, Cr, Cu, Ni, and Pb are a few examples of heavy metals that have both point and non-point sources (Table 2 and Fig. 1). Fish species undergo physiological and biological changes as a result of heavy metals being present in their tissues and blood. Heavy metals enter fish through the gills, damaging the gills (Vinodhini & Narayanan, 2008). According to the US Environmental Protection Agency, arsenic belongs to the class of carcinogens classified as a class A and category 1. In many countries, it is one of the principal dangerous heavy metals that contaminate drinking water (Leong & Chang, 2020). Heavy metals become a substantial contaminant of many small riverine systems because rivers are important routes for the transportation of metals. Heavy metals are strong biodegradation inhibitors. Because these metals are permanent and cannot

Table 2 Sources of most common heavy metal. Sources: Mohan et al. (2021), Paul (2017)

Sr. No	Name of heavy metal	Sources
1	Arsenic (As) (Z = 33)	Tobacco, semiconductors, mining and smelting, power plants, petroleum refining, animal feed additives, volcanoes, and wood preservatives are a few examples of industries that use pesticides and herbicides or fungicides and metal smelters
2	Cadmium (Cd) (Z = 48)	Sewage sludge from urban stormwater, agrochemical waste from agricultural soils, paints and pigments, plastic stabilizers, incineration of wastes making cadmium-enriched plastics, phosphate-containing fertilizers, incineration of waste materials and plastics, and nickel–cadmium batteries are just a few examples
3	Chromium (Cr) (Z = 24)	The electroplating industry, steel industries, fly ash, cement dust, tanneries, solid waste, and sludge
4	Copper (Cu) (Z = 29)	Pesticides, fertilizers
5	Lead (Pb) (Z = 82)	Paint, municipal sewage water, smelting and metalliferous ore mining, lead-containing industrial wastes, combustion of leaded gasoline, etc., battery manufacturing procedures, herbicides, and insecticides
6	Mercury (Hg) (Z = 80)	Heavy metals are released into aquatic environments by volcanic eruptions, forest fires, the burning of fossil fuels, industrial discharges from the production of coal, peat, and wood, caustic soda, and gold-silver mining, agricultural runoff, atmospheric deposition, mining, the burning of fossil fuels, and pharmaceutical waste. Additionally, medical waste, Au–Ag mining, and coal combustion emissions contribute to heavy metal contamination
7	Nickel (Ni) (Z = 28)	Volcanic eruptions, industrial emissions and effluents, steel alloys, kitchen appliances, surgical/operational instruments, forest fires, bursting of bubbles and gaseous exchange in the ocean, weathering of rocks and geological objects, power plants, electroplating, automobile batteries, and so forth
8	Zinc (Zn) (Z = 30)	Mining, metallurgical processes utilizing zinc, biosolids, smelting and refining, and electroplating

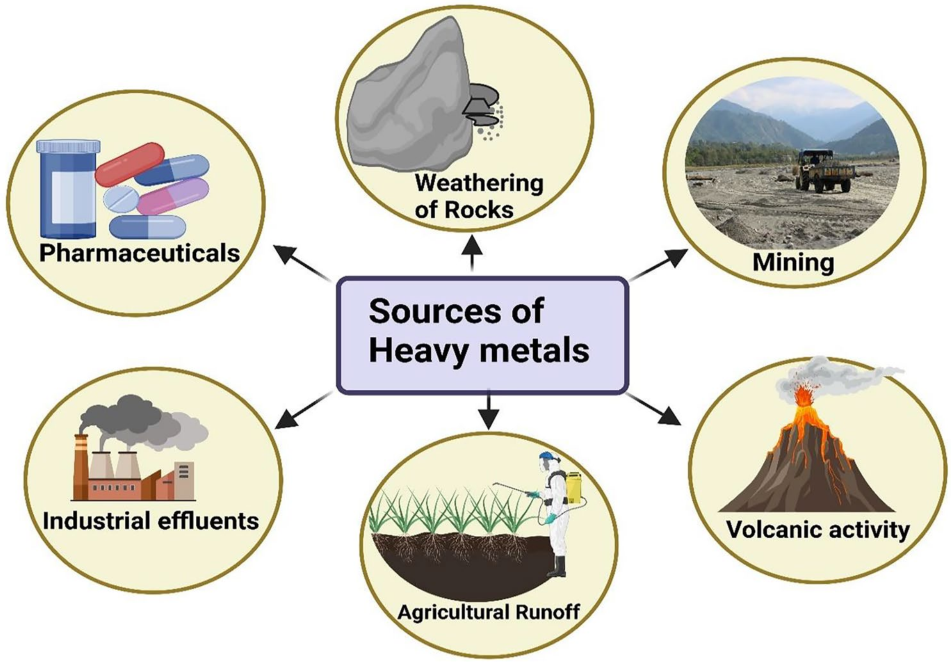

Fig. 1 Different point and non-point sources of heavy metals

decay, it is difficult to get rid of them from aquatic environments (Paul, 2017). The Solan area of Himachal Pradesh has become a center for a variety of industries and severe farming practices are also ongoing, which could significantly increase the amount of heavy metal in surface water as well as cause contaminated runoff into rivers in the region (Rana et al., 2016). A number of heavy metals occur naturally in both freshwater and marine environments, though they are most often found in very minute quantities. Many of the natural water systems across the world have been affected by anthropogenic activities that have led to an increase in the amount of metal ions in the water (Shah, 2021). Other factors that contribute to the rise in metal ion concentration in aquatic ecosystems include mining, offshore oil and gas exploration, textiles, fertilizer, pharmaceuticals, home effluents, agricultural runoff, acid rain, etc. (Ansari et al., 2004). Heavy metals from agriculture enter the aquatic ecosystem through runoff, harming aquatic plants and animals. Heavy metal concentration in water had grown due to anthropogenic activity (Jaiswal et al., 2018). A number of factors, including water quality parameters significantly affect how poisonous heavy metals are to aquatic animals. Pollutants in the food chain negatively impact aquaculture and increase mortality rates (Sonone et al., 2020). In aquatic ecosystems, there are increased levels of emissions of heavy metals that cause intoxication, illnesses, and at times even the mortality of fish as a result. Physicochemical and biological characteristics of both water and sediment were altered as a consequence of the heavy metal pollution (Jaishankar et al., 2014). Chemical treatment is not effective for some contaminants, especially those that irritate the liver, kidney, and nerve. Heavy metal pollution has a detrimental effect on ecological equilibrium as it can contaminate both freshwater and marine environments, which can cause cellular damage to aquatic creatures (Zeitoun & Mehana, 2014). Fish are adversely affected when heavy metals are present in their aquatic ecosystems (such as rivers, lakes, dams, oceans, and lagoons). A toxicant in waterbodies poses a grave danger to aquatic organisms (Gheorghe et al., 2017). These toxins are frequently ingested through drinking water and fish food through the food chain, including bacteria, plants, and fish (Sfakianakis et al., 2015; Thakur et al., 2022). Bioaccumulation is one of the most fascinating phenomena related to heavy metals. In the food chain, heavy metals are among the hazardous contaminants that have a propensity to bio magnify through bioaccumulation into the food chain, which makes them extremely dangerous for human health. Alzheimer's diseases and Itai-Itai diseases are brought on by the bio-magnification of zinc and cadmium (Madhusudan et al., 2003). There have been multiple studies that suggest that the levels of many heavy metals in fish, sediment, and most coastal sites are higher than the environmental limit for many of these metals primarily, namely Co, Cd, Pb, Cu, Cr, Mn, Fe, and Ni. Heavy metal concentrations were higher in bottom-dwelling or sedentary organisms like gastropods and shrimp than in other types of animals (Rakib et al., 2022). Heavy metal pollution of aquatic ecosystems causes acute fish problems, such as delayed embryonic development, deformities, reduced growth of adult to mature fish, resistance to chemical and biological transformation, poisoning, infections, and fish species death. Due to their position at the top of the food pyramid, fish are the primary target for bio-magnification. The number of heavy metals that fish accumulate depends on the environment (salinity, pH, water temperature, and hardness), the method of uptake, the concentration, the length of exposure, and a few other factors, including the fish's feeding habits and age. These metals primarily build up in the fish's liver, kidney, and gills. Fish muscles, when compared to other tissues within the body, have one of the lowest levels of heavy metal accumulation when it comes to heavy metals (Zeitoun & Mehana, 2014). Furthermore, factors, such as water solubility, fish-eating behavior, biology and physiology, size, reproductive status, fish health, and a variety of environments, have also been shown to affect the accumulation of heavy metals. Heavy metals are detrimental to aquatic organisms, especially fish species, even at low concentrations, because they are highly toxic. Due to heavy metal contamination of water and physiochemical changes in the aquatic environment, heavy metal toxicity is creating a hostile environment for aquatic life. Arsenic, chromium, lead, and mercury are commonly found in the environment, and almost all of these metals are carcinogens, according to the International Agency for Research on Cancer and the US Environmental Protection Agency. Freshwater fish are more likely to be overexposed to heavy metals than marine fish (K Al-Taee et al., 2020). The presence of contaminants can directly damage the environment through primary damage, or indirectly through subtle perturbations in the stability of the biological food web, which are only noticeable when the contamination lasts for a long time. Heavy metals have been found to be heavily contaminated in the Nile River and its tributaries in Egypt, and this poses a threat to the ecosystem's biodiversity, as well as to the ecological balance of the aquatic ecosystem (Ghorab, 2018; Thakur et al., 2021a, 2021b). A perspective of this article is how heavy metal toxicity affects water biodiversity and habitat ecology, with a focus on the effects of heavy metals on aquatic ecosystems.

Heavy metal pollution and its sources

A range of natural and anthropogenic sources of heavy metal contamination can be found in aquatic ecosystems. The contamination of water with metals can occur directly from pollutants being discharged into fresh water or marine ecosystems, or indirectly from factors like dry and wet deposition and runoff from agricultural fields. Volcanic activity, rock weathering, and forest fires are some of the natural sources. Mining and industrial effluents are two of the most significant sources of anthropogenic emissions (Ghorab, 2018). The highly industrialized regions around the world account for a significant amount of the heavy metal pollution (Hubeny et al., 2021). The majority of heavy metal pollution is caused by human activities. To a lesser extent, it is caused by natural events. Most of the heavy metals that are found in our environment are lithophiles (lovers of rocks) or chalcophiles (lovers of sulfur ore). Both manmade and natural activities can cause heavy metal contamination (Malik et al., 2020a, 2020b). Natural sources include geological processes including erosion, mineral weathering, and volcanic activity. Intense agricultural methods, a growing population, and industrialization have all contributed to significant environmental issues, including the production and discharge/emission of hazardous wastes, organic pollutants, and heavy metals into water (Malik et al., 2020a, 2020b). Industrial waste and sewage slurry are dumped in nearby fields, water sources, and agricultural soils, continuously polluting the environment with inorganic pollutants such as heavy metals (Fig. 1). Nuclear weapons testing, periodic nuclear disasters, the mining and processing of nuclear fuel, etc. are other examples. Almost 95% of the heavy metals found in the Earth's crust are metals that are associated with iron, which accounts for the majority of the 5% heavy metals. (Malik et al., 2022; Mohan et al., 2021).

Environmental impact of heavy metals on water quality

Potential of hydrogen ion concentration

Water pH is one of the key factors that determines heavy metal toxicity. Zn accumulation in fish causes pH disturbance (Fatima et al., 2020). Metal toxicity is strongly influenced by a number of variables, including the presence of organic or inorganic complexes, metal biological processes, pH, temperature, salinity, and the conditions under which the metal is being reacted (Sonone et al., 2020). Water's pH changes when acidic water is present due to factors such as acid rain or coal and oil burning that cause the water to become acidic. Acids are produced in large quantities by mining and a variety of industrial operations, such as vinegar, battery trash, tanneries, and DDT manufacturing waste. Large-scale fish species are known to live routinely between pH levels of 6.0 and 9.0, while they are unable to tolerate abrupt changes within this range (Malik et al., 2020a, 2020b). When volcanic ash enters the water system, it contaminates the water and lowers its pH, turbidity, and acidity (Fig. 2). Ash from recently erupted volcanoes has the ability to reduce water's pH beyond what is necessary to protect aquatic life (Malik et al., 2021; Sonone et al., 2020).

Dissolved oxygen

Zinc accumulates in gills of fishes and causes respiratory problems that may even lead to mortality due to deficiency of oxygen. Water having low oxygen concentration tends to

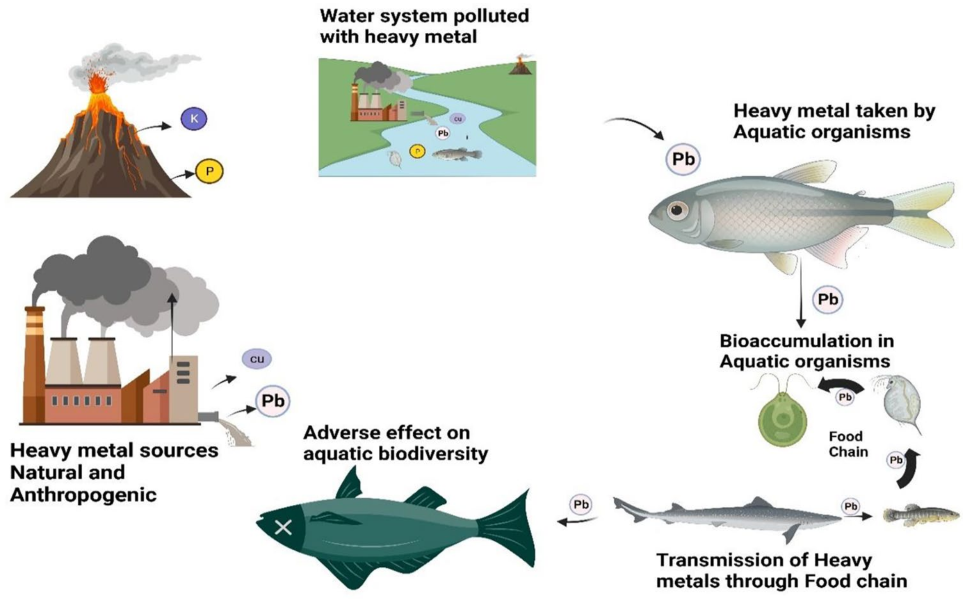

Fig. 2 Impact of heavy metals on aquatic ecology and biodiversity

cause more toxification in fishes (Fatima et al., 2020). Dissolved oxygen content in any body of water is influenced by mixing and aeration, temperature, amount of sunlight, and altitude. For migratory fish species like *Salmo salar* and *Salmo trutta*, which have high DO requirements, this can lead to some issues. In a few instances, the levels of organic pollutants and DO might cause avoidance behavior and act as a barrier that prevents organisms from reaching breeding and spawning areas with high oxygen concentrations. Due to the massive effluents discharged into any water body, the level of soluble oxygen was significantly lowered. Additionally, liquid O_2 is used by bacteria during their physiological processes to break down DO (Malik et al., 2020a, 2020b). Heavy metals will always exist as cations, anions, and hydroxide complexes depending on levels of dissolved oxygen, pH, and organic matter in the water (Duan et al., 2020; Malik et al., 2020a, 2020b).

Turbidity

As dye, pigment, and water turbidity fluctuated, the color of the water gradually changed. Due to significant algal blooms or soil erosion caused by a high nutritional load, both organic and inorganic from both industrial and agricultural wastes, turbidity has increased. Suspended particles can clog/harm gill aperture in several fish species that thrive in turbid water habitats, reducing their susceptibility to numerous diseases and parasites (Malik et al., 2020a, 2020b). The amount of solid organic or inorganic particles in water affects its turbidity, a property that depends on rainfall (sand, soil, microscopic living organism, plankton and loam). Only after significant rainfall was turbidity measured. The turbidity was measured using a portable turbidimeter, the Utech TN 100. Values reported at the sampling site are expressed in nephelometric turbidity units (NTU). Heavy metal concentration in aquatic ecosystems did not change as turbidity rose, nor did turbidity have any impact on it (Marina et al., 2020).

Aquatic biota and heavy metal toxicity

Heavy metals are absorbed by fish and other aquatic creatures both from their diet and from the water that flows through their gills. A heavy metal's absorption rate depends largely on the amount consumed as well as the number of heavy metals that are found in the food or prey that were consumed. There are some predatory fish species that accumulate a lot of heavy metal within their several organ systems (Malik et al., 2018; Vajargah, 2021). Vital component of the marine food chain is phytoplankton, which is the major producer, and zooplankton, which is the primary consumer (Annabi-Trabelsi et al., 2021). Depending on the location of metals in the water column or in sediments within the fish's body, metals can enter the fish's body through the gills, skin, or digestive tract. The amount of exposure, including the number of pollutants present, how long they were present, and major water parameters can all affect how much metal accumulates in fish. A fish's level of metal exposure is strongly determined by the biological traits of the fish, such as age, length, weight, food preferences, habitat, metabolic state, and the species of the fish (Paschoalini & Bazzoli, 2021).

Plankton

Heavy metal pollution has a negative impact on fish species, macrophytes, plankton (including zooplankton and phytoplankton), and macrobenthos (Malik et al., 2020a, 2020b). Cr, Cd, and Pb from the water can all be accumulated by fish species, phytoplankton, and zooplankton. Pb and Cd had the highest bioaccumulation levels in phytoplankton, while fish species were shown to have the lowest levels of bioaccumulation (Tessema et al., 2020). Arsenic directly and indirectly inhibits the photosynthesis process in aquatic primary producers (Mohan et al., 2021). Cu was more toxic to *Daphnia magna* than Pb (Kumar et al., 2023a, 2023b; Verma & Choudhary 2022). Copepods are the most common group of zooplankton in marine food webs. Copepods are a major consumer of other zooplankton species as well as supplying food for a large range of higher trophic levels of marine life. The bio-magnification effect of toxic substances in marine food webs is highly likely to be caused by the bioaccumulation of toxic substances by copepods. The marine food chain is likely to benefit from any hazardous substance that bioaccumulates in copepods (Annabi-Trabelsi et al., 2021). The zooplankton controls the speciation, cycling, and transport of metals in addition to the metal levels in the surrounding environment. This is accomplished by biological absorption and regeneration, particle settle, organic chelator degradation, and redox reaction mediation (Fig. 3). In comparison to other metals, zinc is higher concentrated in zooplankton. How much of a material is bioaccumulated in an organism can be influenced by its rates of absorption, assimilation, metabolism, and excretion. Metal bioaccumulation is higher in zooplankton with high metal absorption and low metal metabolism and excretion rates (Ju et al., 2019). The plankton populations increased phytoplankton and decreased zooplankton in response to changes in the coastal environment. Acidification, warming, eutrophication, salinity, and heavy metals Hg, Zn, and as may all be caused by these changes (Wei et al., 2022).

Benthos

Macrobenthos are aquatic creatures which live on the bed substrate of water bodies and are visible to the naked eye due to their lack of an internal skeleton. The majority of the organisms that live at the bottom include crustaceans, annelids, worms, mollusks, and insect larvae, and pupae. They are excellent indicators of water quality and contamination (Sharma et al., 2023). A key bioindicator for the detection of heavy metals in the environment is benthic macroinvertebrates that serve as bioindicators. A correlation was found between the variety of macroinvertebrate communities in rivers sampled in the UK, the US, and Japan and the amount of metals and protons found in them (Kahlon et al., 2018).

Fishes

Cadmium exposure affected a number of important metabolic substrates, such as glucose, glycogen, lactate, lipids, and proteins in fish, as well as their metabolic activity. Moreover, the metabolism of proteins may be disrupted when exposed to cadmium. Cadmium exposure increased Glutamate amino acyltransferase activity in the gills, liver and kidneys of carp, as well as its activity in alanine amino acyltransferase. In some fish species, mercury exposure may

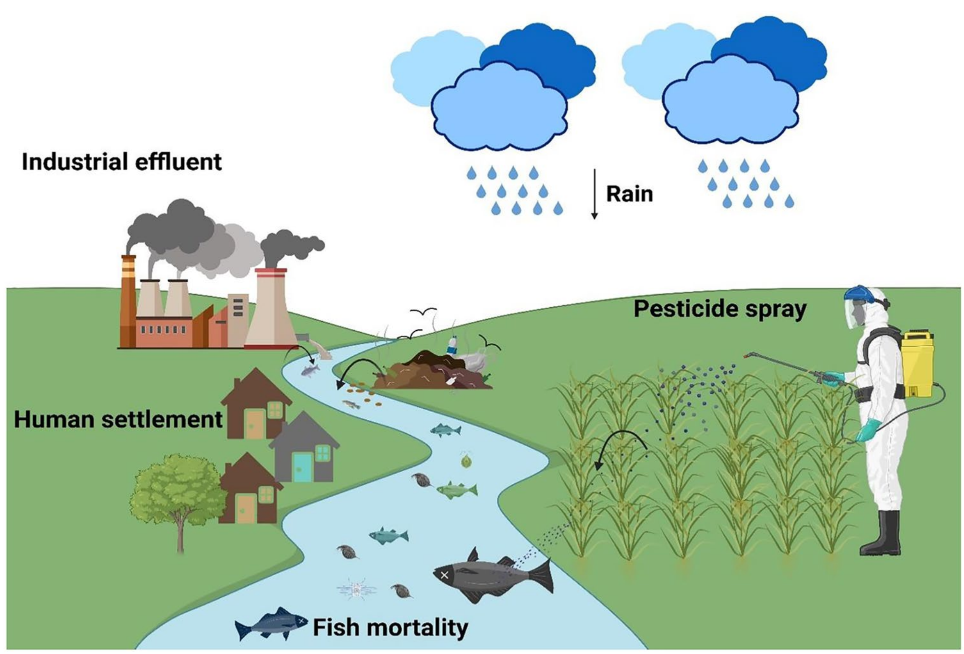

Fig. 3 Bio-accumulation of heavy metals in fishes from different sources

lower brain neurotransmitter levels, whereas lead exposure raises serotonin levels (Espinoza et al., 2012). Heavy metals, such as cadmium, mercury, and lead, have a significant harmful impact on the behavior, growth, and reproduction of fish, and these factors have a significant impact on the harmful effects of environmental toxins on fish (Fig. 3). Molecular pathways, hormonal activity, metabolic processes, and neurotransmitter function are clearly affected by these heavy metals (Mondal et al., 2018). According to the World Health Organization, in 2004, heavy metals were found to be powerful neurotoxins in fish. Catfish, Nile tilapia, and common carp were found to have Cr concentrations that exceeded the permissible limits in their blood (Tessema et al., 2020). Fish's many body parts, such as their gills, fins, muscles, tissues, kidneys, hearts, and bones, collect heavy metals (Izah & Angaye, 2016). Organs with increased metabolic activity displayed higher accumulation levels of heavy metal. Additionally, several environmental studies have demonstrated that trophic and ecological factors might influence the amount of exposure to metals. The most frequently occurring consequences in target organs were oxidative stress, genotoxicity, and various histopathological changes (Paschoalini & Bazzoli, 2021).

Effect on growth rate and development processes

Fish that are exposed to high Pb concentrations cannot mature from fry. Lead and cadmium bind to the calcium sensor protein calmodulin, which has an impact on numerous cellular processes. The fact that cadmium has a significant effect on several enzymes has long been known, and the effects range from the reduction of the activity of citrate synthase to the decrease of succinate dehydrogenase (SDH), glucose-6-phosphate dehydrogenase (G6PDH), and lactate dehydrogenase (Chandel et al., 2023). Fish metabolism and embryo morphology have been hampered by heavy metals. When fish are exposed to heavy metals, their estrogenic and androgenic functions are impaired, which results in abnormal fish differentiation. A number of newly hatched larvae died soon after hatching as a result of lead and copper absorption. Heart problems are observed in embryos which have been altered by high levels of mercury (Kumari et al., 2023). Heavy metals are likely to enter fish bodies through three main routes: through their gills, through their digestive systems, and through the surface of their bodies. Gills are known to be the primary site of metal intake by fishes from the water as they are the primary site of metal absorption. Alterations in the anatomy of the heart and ventilator are also sparked by zinc exposure. Zinc is an essential fish toxin that damages gill tissue, interferes with acid–base and ion control, and results in hypoxia. Fish swimming close to the point of Cr distribution suffer gill injury from the higher Cr intensities (Kumar et al., 2023a, 2023b). Mercury is a significant heavy metal for neurotoxicity. While other factors also play a role in neurotoxicity, mercury (Hg) has a substantial impact on both fish and people. While fetal and postnatal manifestations of monomethyl hg have resulted in an abortion, congenital deformity, and variations in the development of small fry, monomethyl hg causes harm to the brain. Japan's waters are hg-poisoned. Significant neurotoxicity was present in Minamata illness and Hg toxicity (by methyl Hg) (Kumari et al., 2023). When fish are exposed to mercury, they experience hemorrhages, damage to their blood vessels, and a decrease in the amount of blood. As a consequence of anemia, eosinophilia, lymphocytosis, and injuries to the bronchi and kidneys, chromium adversely affects the blood (Kumar et al., 2023a, 2023b).

The presence of arsenic in the body inhibits the production of adenosine triphosphate (ATP) during respiration, coagulates proteins, and forms connections with coenzymes. Several carcinogenic metals, such as cadmium, arsenic, nickel, and chromium, have been linked to base-pair deletion, mutation, and radical oxygen attack on DNA. Fish deformities are caused by cadmium, nickel, mercury, chromium, lead, and arsenic, among other heavy metals. These heavy metals cause numerous physiological changes when they are present in large concentrations. A number of symptoms were identified in the fingerlings as a result of the analyses, including shortening of fins, underdevelopment of gills, liver, and fin functions. Heavy metals like lead, arsenic, cadmium, and zinc also contribute to stress in fish, along with reproduction, hypoxia, overcrowding, and malnutrition (Damseth et al., 2024).

Heavy metals are considered to have the most detrimental effects on fish. They tend to affect a fish's physiological capability, mortality, reproduction, growth rate, and reproduction success. According to information, fish exposed to metals revealed immune system abnormalities that made them more susceptible to infectious diseases and gave them a higher probability of dying. These harmful outcomes include a loss of fitness, interference with reproduction that causes cancer, and ultimately death (Sharma et al., 2020). The presence of pollutants (heavy metals) can cause disruption of enzymatic and metabolic activity and, as a result, can cause abnormalities in biochemical and morphological composition of the body. Liver, spleen, kidneys, and gills are some of the most metabolically active tissues in the body, and they tend to accumulate in these tissues (Damseth et al., 2024). Having high suspended particulate concentrations can suffocate filter-feeding macrobenthos and reduce their feeding effectiveness, which decreases growth rates, increases stress levels, and may even result in mortality. As a result of pollution in the environment, that is both organic and inorganic, a variety of behavioral activity can be affected. Some of these behaviors include eating, engaging in sexual activity, and being sociable and aggressive (Malik et al., 2020a, 2020b).

Fish reproductive health is significantly impacted by mercury in the aquatic environment. Laboratory studies seem to have provided enough proof to connect mercury exposure with reduced fertility in several fish species. T4 levels would have decreased over a protracted period of mercury exposure to the point where they eventually had an impact on serum T3 levels. As a result of dietary exposure to 0.88 g/g of methylmercury for 28 days, female goldfish (*Carassius auratus*) exhibit significantly decreased levels of basal LH and sex steroid hormones after spawning. It was discovered that mercury has negative impacts on gonad development, fish spawning, egg development, fertilization, and hatching. As a potent endocrine disruptor, Pb in the environment can significantly alter the ovarian steroid genesis, gametogenesis, and ovulation of fishes, which may negatively affect fish reproduction and population density. In freshwater fish such as *Cyprinus Carpio*, the plasma levels of cortisol and prolactin were found to be acute and sublethal when exposed to lead nitrate.Lead reduced egg production, slowed ovarian development, lengthened inter-spawn intervals, and inhibited embryo development. It also decreased the number of eggs laid. Because lead adversely affects both estradiol receptors in the body and LH receptors in the ovary, it can have an effect on LH release directly from the pituitary as well as at lower levels of reproductive regulation (Mondal et al., 2018). It has been found that heavy metals have an estrogenic effect on the vitellogenin and zona radiata proteins of the *Prochilodus argenteus*—typically female proteins—to be produced more quickly in the liver in males and altered yolk deposition in females, leading to yolk deficit or over-ripening in vitellogenin follicles (Paschoalini & Bazzoli, 2021).

Recent research has demonstrated that metals can have an impact on neotropical animals at all levels, from the molecular to the behavioral. There has been a great deal of research done on freshwater fish throughout the world and it has shown that these contaminants can have significant impacts on the behavior of freshwater fish at all stages of the life cycle and may also have long-term effects on future generations. Recent research has demonstrated that metals can have an impact on neotropical animals at all levels, from the molecular to the behavioral (Paschoalini & Bazzoli, 2021). A number of fish are capable of exhibiting altered behavior when cadmium, lead, and mercury are present, which are well known neuro-toxicants. In order to establish a comprehensive picture of fish behavior, a wide range of articles were reviewed which discussed the effects of contaminants on a wide variety of behaviors, including locomotion, attraction, avoidance, swimming performance, respiratory behavior, learning, social interactions, reproductive behavior, feeding, and predator avoidance. The study of common carp revealed unpredictable, darting swimming motions, hyper-excitability, capsizing, surface attachments, and modifications in behavior, such as irregular swimming, a modified swimming pattern, etc. Various behavioral abnormalities have been associated with lead exposure. Symptoms included loss of balance, breathing problems, slow motion, capsizing in water, sinking to the bottom of the tank, and mucus secretion. All treatments resulted in behavioral problems, though symptoms became more severe with higher lead acetate levels (Mondal et al., 2018).

Some species may become dominant due to tolerant and resourceful traits, while vulnerable species may go extinct as a result of heavy metal contamination. The resulting tighter trophic links force predatory fish to consume an increasing number of metal-tolerant food species, sometimes even just one kind of them (Mondal et al., 2018). Fish tissues accumulate heavy metals that they ingest (Tessema et al., 2020). As urbanization continues to expand, pesticides are being used increasingly in agriculture, and industries are expanding rapidly, all of these factors have contributed to an increase in heavy metal pollution in aquatic environments. A freshwater ecosystem's entire food chain is affected by this directly and indirectly. A higher an organism's trophic level, the more metals that organism is exposed to, i.e., bio-magnification of those elements in the food chain (Paschoalini & Bazzoli, 2021).

Strategies of removing heavy metals contamination

Several sources of heavy metal contamination, including industrial waste, agricultural runoff, as well as household and commercial use, can easily contaminate the aquatic system. In order to remove toxic heavy metals from water and wastewater, chemical precipitation, chemical coagulation, and flocculation, electrochemical methods of treatment, membrane filtration, ion exchange, and bioremediation are some of the techniques that can be used (Vardhan et al., 2019).

Bioremediation

Aquatic environments can be remediated using biological systems, such as plants, animals, and microorganisms (Vardhan et al., 2019). An organic or inorganic waste can be bio-remediated by converting it into a non-hazardous compound through the process of decomposing or decaying organic matter. Bioremediation works using microorganisms in an enzyme-based process and converting pollutants into harmless molecules. This is a necessary step in order to perform bioremediation effectively. Biofilms are effective biological stabilizers and bioremediation techniques (Tarekegn et al., 2020).

Phytoremediation

Phytoremediation involves using biological elements like plants, fungi, or algae to enhance their ability to absorb heavy metal toxins. In phytoremediation, plants can be used to treat contaminated water, soil, and sediments ex-situ or in situ. All algae, aquatic plants, and terrestrial plants can digest, absorb, metabolize, or detoxify inorganic and organic pollutants. The use of algae in wastewater phytoremediation has been studied globally. A hydroponic culture system using agar is used to harvest *Salsola kali*, *Prosopis* species, and *Brassica* species. Plant species with a high capacity to absorb heavy metals are used in phytoremediation. As a method for removing heavy metals from contaminated water, phytoremediation has been proven to be a safe, cost-effective, and environmentally friendly process. In phytoremediation, there are many variables that can affect the efficacy of the process, including soil pH, soil structure, soil type, soil nutrients, uneven dispersion of pollutants, fluctuations in precipitation, temperature, moisture as well as herbivores (Damseth et al., 2024). Through the use of algae and cyanobacteria, phytoremediation removes or degrades toxicants from contaminated sites. Metal binds to algal surfaces through hydroxyl, carboxyl, phosphate, and amide chemical groups In order to perform their metabolic functions, microalgae rely on heavy metals, such as boron (B), cobalt (Co), copper (Cu), iron (Fe), molybdenum (Mo), manganese (Mn), and zinc (Zn), in trace amounts. *Anabaena, Oscillatoria, Phormidium*, and *Spirogyra* are resilient to heavy metal stress, which makes them ideal for growing in heavy metal-contaminated water Redox mechanisms play a vital role in reducing heavy metals. Some of these mechanisms include heavy metal immobilization, gene regulation, exclusion, and chelation to reduce heavy metals. Several of these processes are examples of redox processes and microalgae self-defense mechanisms. The two-stage process used by microalgae to eliminate heavy metals is a two-step process. Rapid extracellular passive adsorption (biosorption) occurs first, followed by gradual intracellular positive diffusion and buildup (Leong & Chang, 2020; Thakur et al., 2021a, 2021b).

Myco-remediation

Studies have shown that dead fungal biomass of *A. niger*, *Rhizopus oryzae, Saccharomyces cerevisiae*, and *Penicillium chrysogenum* can lessen the toxic effects of Cr (VI) (Tarekegn et al., 2020).

Bio-precipitation and bio-crystallization

Microorganism activity may precipitate or crystallize metal complexes, lowering their toxicity and enabling their use sparingly. The formation of microfossils, the deposition of iron, manganese, and silver, as well as the mineralization of silver and manganese, can all be related to precipitation and bio-crystallization in some biogeochemical processes (Tarekegn et al., 2020).

Bioleaching of metals

Among the many industrial processes that are widely known is bioleaching, which is associated with the use of bacteria, fungi, and microbes as well as their metabolic by-products in order to extract metals from minerals and sulfide materials. Based on the principle of converting sparingly soluble metal compounds (often sulfides) into readily soluble forms, the process of removing metal from the environment is fairly simple. The metal compounds are converted from sparingly soluble forms to forms that can easily be removed. Leaching processes are applied in bio-hydrometallurgy. Microbiological methods can be used to leach metals from oxides and sulfides. Various metals can be recovered using bio hydrometallurgical techniques (Tarekegn et al., 2020).

Biosorption

A biological, physical, and chemical process known as biosorption involves the use of biological substances, including plant biomass or bacteria, in order to absorb or adsorb the target species, such as metal ions. The process combines biological, physical, and chemical elements. Biosorption is a process which involves two phases: the bio sorbent, which is a solid phase made up of living organisms like bacteria and fungi, as well as the sorbate, which is a liquid phase that consists of metal ions and is typically aqueous (Redha, 2020). Biosorption involves the removal of heavy metals and other pollutants from solutions utilizing both living and dead biomass. Microorganisms are capable of absorbing heavy metals or other pollutants with their outer cell walls. Chemical groups present on the surface of cells keep metals together. Normally, this occurs as a result of an ion transfer reaction between metal cations and active groups. In addition, there are different chemical groups in outer structures that play an active role in metal linking that distinguish microbes belonging to different systematic units. Moreover, *C. vulgaris* biomass has been found to be a very potent biosorbent for the removal of $Cd2+$, $Cu2+$, and $Pb2+$, among others. The biosorption of heavy metal cations is excellent at pH 4.0 to 7.0 (Rahman & Singh, 2020). Biological processes have the ability to remove metal, compounds, and particles from a fluid through the process of biosorption. Since metal absorption is a separate, reversible process, biomass can be used as a biosorbent for metal absorption both living and dead. (Priyadarshanee & Das, 2021).

Adsorption

The adsorption mechanism occurs when particles from a gas, liquid, or dissolved solid attach to an adsorbent's active sites, causing the surface of the adsorbent to become coated with an adsorbate film formed as a result (Soliman & Moustafa, 2020). A wide variety of adsorbents can be used to remove toxic heavy metal ions from wastewater effluents regardless of whether they are in their original or altered forms. There are several different types of waste products that are often used in recycling applications, among them industrial waste, activated carbons, zeolites, clay minerals, and biomaterials. In addition to these materials, a wide range of other materials have also been used to purify wastewater from toxic contaminants by serving as effective adsorbents (Burakov et al., 2018). The process of adsorption consists of two types: chemical (chemisorption), in which the adsorbate and the adsorbent undergo chemical reactions to form covalent or ionic bonds, and physical (van der Waals forces), whereby the amount of adsorbate at the interface increases as a result of the chemical reaction. There are a few differences between chemisorption and physical adsorption in terms of characteristics. While chemisorption is selective, it is often irreversible, and it has a significant thermal effect, physical adsorption has very little thermal effect. The first cyclodextrin polymer cross-linked with stiff aromatic chains was developed and used as a first generation adsorbent to remove lead, copper and cadmium in order to produce an adsorbent with a cheap cost and a high effectiveness (He et al., 2017). There is now a wide variety of organic sources of adsorption materials that can be used in the treatment of water, including activated carbon. Scientists are putting a lot of attention on activated carbon because it is beneficial for the removal of heavy metals (Mariana et al., 2021; Panigrahi & Santhoskumar, 2020). The use of rice husk ash, nanomaterials, conducting polymers, as well as coal fly ash as an adsorbent has been used widely for the removal of heavy metals including Cr, Pb, Hg, Zn, and Mn from water. According to a literature review, modified starches have considerable adsorption capacities for dyes and heavy metals when hydroxyl groups are replaced with chemically active groups. There have been several modified starches applied as effective adsorbents for heavy metals clean-up for the past 10 to 15 years, such as starch phosphate and carboxyl methyl starch, respectively. A significant influence on the adsorption capacity and specificity of such functional groups can be attributed to their complexity, richness, and chelating tendency. According to the sorption process, charges complexed, ions exchanged, and electrostatic interactions occurred (Gupta et al., 2021). Carbon-based adsorbent materials perform well at the removal of heavy metals when pH, temperature, starting concentration, and coexisting ions are taken into account, and these factors affect the effectiveness of carbon-based adsorbent materials (Duan et al., 2020).

Components for removing heavy metals

Heavy metal removal with fly ash

The fly ash used as an adsorbent can be used as an effective means of removing heavy metals from wastewater**.** Adsorption processes can be managed using a variety of approaches, such as mass transfer, particle diffusion, chemical reactions, and diffusion control approaches. Several models are used to validate adsorption processes, including kinetic models and intra-particle diffusion models. Due to complex lone pair hybridization or lone pair electrons, SiO_2 and Al_2O_3 are the two major components of fly ash, with SiO_2 having a higher affinity for heavy metal adsorption. The use of titanium dioxide for heavy metal eradication is possible because TiO_2, in a variety of forms, is readily available as anatase, rutile, and photocatalytic materials (Arora, 2019).

Heavy metal removal with zinc oxide

Despite its stability, zinc oxide is a non-toxic and non-corrosive substance. Additionally, it can purify the water by removing the elements, such as cadmium and chromium. It was also developed to adsorb heavy metals with PVA/ZnO composites (Arora, 2019).

Heavy metal removal with polymer

For the reduction of heavy metals, various types of conducting polymers are utilized, whereby polyaniline has grown more popular as a result of its distinctive features. Using a nanocomposite made of rice husk ash and polyaniline, Hg (II) may be removed from aqueous solutions. In order to adsorb heavy metals, researchers have also discussed composite materials made of polyaniline, poly-pyrrole, and sawdust. The Fe_2O_3-based composite is effective in removing heavy metals from heavy metal-contaminated water owing to its affinity with the conducting polymer. The nitrogen atom's accessible lone pair electrons combine with the metal ion in the waste water to produce a metal complex. This way, the process of heavy metal ions adhering to composite materials may be employed (Arora, 2019).

Conclusion

The present review examines aquatic biodiversity and its habitat ecology in relation to heavy metal toxicity. As a result of heavy metal pollution, there are a number of factors that contribute to its toxic effects on aquatic ecosystems and biodiversity, including the type and concentration of heavy metals present. The accumulation of heavy metals was more prominent in metabolically active organs. Considering toxicity, persistence, and bioaccumulation of heavy metals, they pose a serious threat to water pollution. The presence of heavy metals in the water has an adverse effect on plankton, fish, and benthos. Aquatic media contaminated with cadmium (Cd) and lead (Pb) can cause a number of psychological changes in fish, in addition to affecting their development and growth rate. Gills, skin, and gastrointestinal systems are the main routes for metals to enter the body. Efforts should be made to ensure that heavy metals do not exceed the prescribed WHO, USEPA, and ISI acceptable limits. All environmental policies should be strengthened, and public awareness campaigns about the value of preserving aquatic systems and their resident biota should be launched. In conclusion, the critical analysis of heavy metal toxicity and its effects on aquatic biodiversity provide valuable insights into the ecological impacts of these contaminants and their implications for habitat ecology.

Future prospects

Despite the numerous challenges associated with studying heavy metal toxicity in aquatic ecosystems, this research contributes significantly to our understanding of the subject. One of the primary contributions of this analysis is the identification of key ecological impacts. By examining the responses of various organisms, from fish to invertebrates and algae, we gain a comprehensive understanding of the vulnerabilities and sensitivities of different species. This knowledge helps us recognize the critical roles that these organisms play within the ecosystem and the potential consequences of their decline or loss. Furthermore, the study helps uncover the mechanisms through which heavy metals exert their toxic effects on aquatic organisms. By investigating cellular and physiological responses, we gain insights into the specific pathways through which heavy metals impair vital functions. Understanding these mechanisms is crucial for developing targeted mitigation strategies and interventions to minimize the impacts of heavy metal contamination. Another important contribution of this analysis lies in its implications for conservation and management strategies. By identifying vulnerable species and habitats, assessing exposure risks, and understanding the long-term consequences of heavy metal contamination, policymakers and resource managers can implement measures to protect and restore affected ecosystems. This research provides a scientific basis for decision-making, ensuring that conservation efforts are focused and effective. Moreover, the critical analysis of heavy metal toxicity and its effects on aquatic biodiversity has broader implications for public awareness and education. Communicating the findings of this research to the general public, policymakers, and industry stakeholders raises awareness about the importance of reducing heavy metal pollution and promoting sustainable practices. This increased awareness can lead to changes in behavior, regulations, and industrial practices that help safeguard aquatic ecosystems for future generations.

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