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Effects of Heavy Metals on Aquatic Organisms: A Review

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Abstract

Aquatic ecosystems are a vital component of the biosphere and harbor immense biodiversity. Over the past century, pollution caused by heavy metals has increased significantly due to the expansion of industrialization, urbanization, and agricultural activities. This review article analyzes the impact of key heavy metals such as cadmium, mercury, lead, chromium, copper, nickel, zinc, and arsenic on aquatic organisms. The primary objective of this study is to examine the sources of these metals, their distribution in water, processes of bioaccumulation and biomagnification, and their adverse physiological, biochemical, and cellular effects on aquatic life. Existing scientific studies indicate that heavy metal pollution not only affects individual organisms but also disrupts food webs, posing a serious threat to the stability and functioning of the entire aquatic ecosystem. Therefore, controlling pollution, implementing effective sewage treatment, conducting continuous environmental monitoring, and enforcing stringent regulations are essential for the conservation of aquatic ecosystems.

Keywords: *Aquatic ecosystems, Biosphere, Biodiversity, Heavy Metal, Biochemical, Cellular*

Introduction

Water is the basis of life; large areas of the earth are covered with oceans, rivers, lakes, ponds and wetlands, bodies of water that support countless organisms and aquatic ecosystems. Water is not only essential for life but plays a vital role in regulating the water cycle, purifying air, absorbing carbon dioxide, and recycling nutrients. Human society relies on a variety of water-based systems such as fisheries, drinking water supply, irrigation for agriculture, and water transport distribution but due to pollution by human activities, water quality gradually deteriorates over time. Heavy metals are significant in the context of pollution because they are non-biodegradable; they persist in the environment for extended periods and accumulate in the bodies of living organisms. Unlike pesticides and other organic compounds, heavy metals cannot be destroyed through chemical processes; they merely change form or migrate from one location to another. Consequently, even low-level, long-term exposure leads to their accumulation in aquatic organisms, resulting in toxicity (Förstner and Wittmann, 1981; Nriagu and Pacyna, 1988). Conservation of aquatic biodiversity is a major concern of contemporary environmental science. Fish and plankton occupy various layers of food webs; therefore, disturbance at one level affects the entire system. Primary producers such as phytoplankton convert solar energy into chemical energy, after which the materials stored in them are passed on to higher level organisms. Thus, the ecological importance of aquatic organisms lies not only in their numbers but also in their contribution to overall ecosystem stability (Rainbow, 2002).

Studies conducted over the past few decades on rivers such as the Ganges, Yamuna, Indus, and China's Yangtze, as well as on European seas and Indian rivers, indicate that industrial waste, untreated sewage, and runoff from mining and agriculture are continuously increasing metal concentrations in the water (Islam and Tanaka, 2004; Yi et al., 2011). Cadmium and mercury levels have been found to be high enough to pose a threat to human health (Storelli, 2008). Such reports reflect growing scientific and societal concerns regarding heavy metal pollution.

This review aims to consolidate scattered research literature and present a comprehensive picture of heavy metal effects on aquatic organisms. Article sources of metals, their behavior in aquatic systems, biosorption processes, adverse effects on various organisms, physical biochemical ecological results, relevant monitoring methods, and management measures. Comparative and critical analyses are also discussed.

2. Heavy Metals and Their Sources

2.1 Definition of Heavy Metals

The term 'heavy metal' typically refers to metals with a density exceeding 5 g/cm^3. However, some scholars object that this term is not chemically well-founded (Duffus, 2002). Various definitions based on criteria such as density, atomic weight, and atomic number have been used; yet the term heavy metals in environmental science often include cadmium, mercury, lead, and arsenic, elements that are toxic to living things even in lesser amounts.

2.2 Classification of Heavy Metals

Biologically, heavy metals are classified into two categories. The first category includes lesser amounts of copper, zinc, iron, manganese, cobalt, and other essential elements needed for life processes which function as cofactors for enzymes yet are toxic when levels exceed controlled limits. These are harmful even in exceedingly lesser amounts (Wood et al., 2012). Based on this distinction, toxicologists establish water quality standards for metals.

2.3 Natural Sources

Heavy metals occur naturally in the Earth's crust. Minerals are released into water and soil through the weathering of rocks. During volcanic activity, mercury, arsenic, and cadmium are dispersed into the air as vapors and molten rock, eventually settling into water bodies with rainfall. Soil erosion carries these elements into rivers and lakes. These natural sources have existed for a long time, maintaining a baseline level of metals in the water (Nriagu 1989); however, recent estimates indicate that the contribution from human activities far exceeds that from natural sources.

2.4 Anthropogenic Sources

Human activities release many times more heavy metals into water than natural resources. Metal mining and refining, including the smelting of lead, zinc, and copper, is a major source of cadmium and other metals. Acid mine drainage severely pollutes nearby water bodies. Industries such as electroplating, tanning, and chemical manufacturing discharge various metals in their wastes. Paper manufacturing also contributes to metal discharge. In agriculture, phosphate fertilizers, and pesticides, including fungicides, carry cadmium, copper, and arsenic into the soil. Untreated municipal sewage is also rich in metals. Thermal power plants burn coal and release mercury and arsenic into the atmosphere, which eventually settle into water bodies. Urban runoff collects lead, zinc, and copper from streets and carries them into receiving waters (Nriagu and Pacyna, 1988; Bryan and Langston, 1992). It is the combination of these multiple sources that has complicated metal pollution in modern water bodies.

3. Heavy Metals in Aquatic Ecosystems

Once heavy metals enter an aquatic environment, they do not remain stationary; instead, they continuously cycle between water layers, suspended particles, sediments, and aquatic organisms. Metals exist in two primary forms: dissolved and particle bound. The dissolved form is typically more 'bioavailable' (easily utilized by organisms) because dissolved metal ions can be readily absorbed by aquatic life and can adhere to biofilms and other organic matter. In contrast, particle-bound metals are often associated with suspended matter and sediments, although they can become available again under changing environmental conditions (Rainbow, 2002, 2008).

Mobility and bioavailability of heavy metals in aquatic environments is significantly affected by physicochemical characteristics of water. Factors such as pH, alkalinity, dissolved organic carbon, salinity, and temperature play important roles in determining metal chemical speciation, distribution, and bio accessibility. They often promote metal precipitation, resulting in their accumulation in sediments. Water hardness also affects metal toxicity, as ions such as calcium and magnesium compete with metal ions for biological binding sites, thereby reducing metal uptake and reducing toxic effects on aquatic organisms (Spry and Wiener,1991).

Sediment is a major sink for metals in the water system. Suspended particles encroach on the metal (adsorption) and gradually settle on the substrate (precipitation); thus, metal concentrations in sediments can be hundreds or thousands of times higher than in the water column. But deposition is not just passive aggregation; because of changes in pH, hypoxia, or biological activity, metals trapped in the sediment are released back into the water (remobilization), making them bioavailable again (Förstner and Wittmann, 1981; Bryan and Langston, 1992).

Chemical changes in metals significantly alter their toxicity. The best-known example is found in mercury, where inorganic mercury is organically converted to methylmercury by sediment microorganisms; this form is highly toxic and readily accumulates in the body of the organism (Boening, 2000; Wiener et al., 2003). Similarly, chromium shows different toxicity in trivalent form (Cr III) and is more harmful in hexavalent form (Cr VI). From these examples, toxicology evaluation requires not only total metal concentration, but also chemical form (speciation) of the metal.

The persistence of metals is a major water system problem. Because these elements do not decompose, they remain in water and sediment for decades once in. Even after source removal, metals accumulated in sediments affect organisms for a long time. This persistence makes heavy metal pollution more difficult than bio pollutants (Luoma and Rainbow, 2008).

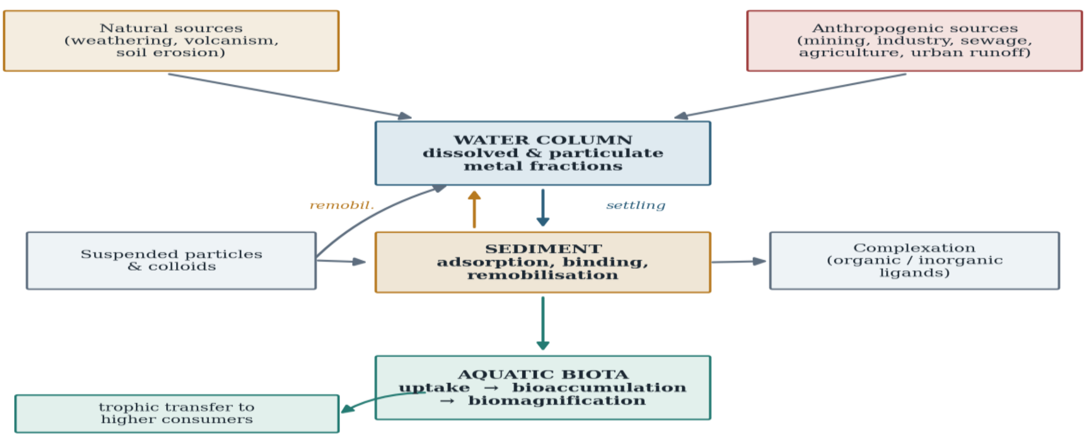

Figure 1. Pathways of heavy metals in aquatic ecosystems, showing input from natural and anthropogenic sources, partitioning between the water column and sediment, and transferring to aquatic biota.

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4. Major Heavy Metals Affecting Aquatic Organisms

While there are many metals on the periodic table, few are particularly dangerous to aquatic life. Below, the eight major metals are discussed in order, summarizing the sources, prevalent concentrations in water, toxicity, and environmental behavior of each. Table 1 summarizes these major sources.

Table 1. Major heavy metals of concern in aquatic systems and their principal sources.

Metal	Principal natural sources	Principal anthropogenic sources
Cadmium (Cd)	Zn/Pb ore weathering, volcanic emission	Ni–Cd batteries, electroplating, phosphate fertilisers, pigments, smelting
Mercury (Hg)	Volcanic degassing, cinnabar weathering	Chlor-alkali plants, gold mining, coal combustion, fungicides
Lead (Pb)	Galena weathering, soil erosion	Leaded fuel residues, batteries, paints, mining, smelting
Chromium (Cr)	Chromite weathering	Tanneries, electroplating, stainless-steel and dye industry
Copper (Cu)	Sulphide-mineral weathering	Mining, antifouling paints, algicides, wiring, fungicides
Nickel (Ni)	Ultramafic-rock weathering	Alloys, electroplating, battery, and petroleum industry
Zinc (Zn)	Sphalerite weathering	Galvanising, smelting, fertilisers, tyre wear, corrosion
Arsenic (As)	Geothermal water, arsenopyrite weathering	Pesticides, wood preservatives, mining, coal combustion

Compiled from Nriagu and Pacyna (1988); Eisler (1985, 1987, 1998); Tchounwou et al. (2012).

Cadmium

Cadmium is a non-essential and highly toxic metal with no known biological use. It enters water from nickel and cadmium power cells, the coatings industry, phosphate fertilizers, and pigment manufacturing. Cadmium concentrations in unpolluted freshwater are usually less than 0.01 µg/l, but they increase many-fold in the presence of industrial effluents. Cadmium particularly interferes with calcium metabolism, as it enters the cells via calcium receptors (calcium channels); this impairs bone mineralization and ion balance (Hollis et al., 2000). It is associated with a protein called metallothionein, however upon prolonged exposure it accumulates in the kidney and liver causing chronic toxicity (Eisler, 1985; Wood et al., 2012).

Mercury

Mercury (Hg) is the most dangerous metal in the water system, primarily because of its methylmercury form. The major sources are coal burning in thermal power plants, gold mining, and alkali plants. Sediment anaerobic bacteria convert inorganic mercury to methylmercury, which is highly bio receptive and strongly accumulates in the living body. This form grows to elevated levels in the food web by biomagnification, so its concentration is highest in top predatory fish (Boening, 2000; Wiener et al., 2003). Nervous system is its major target; this can lead to neuronal damage, behavioral disorders, and reproductive damage (Clarkson and Magos, 2006).

Lead

Lead is a toxic metal known since ancient times. In the past, leading gasoline was a major source; currently, the main sources are electrodes, dyes, mining, and metal refining. Lead in water usually exists in particle-attached form and therefore accumulates in sediment. In fish, it accumulates in the gills, liver, kidneys, and bones. Lead inhibits heme synthesis by inhibiting the enzyme δ-aminolaevulinic acid dehydratase (δ-ALAD); this causes anemia. Moreover, it disrupts the nervous system and behavior (Eisler, 1988; Sorensen, 1991). By attaching it to the bone, it remains in the body for a long time.

Chromium

Chromium toxicity is highly dependent on its chemical form. Trivalent chromium (Cr III) is essential and is toxic in lesser amounts, but hexavalent chromium (Cr VI) is very toxic, mutagenic, and carcinogenic. Tanners, dyeing, steelmaking, and the dye industry are major sources. Cr VI readily crosses the cell wall and is reduced to trivalent form inside, generating free radicals, which cause oxidati ve stress and DNA damage (Vutukuru, 2005). Respiratory distress, blood count changes, and biochemical disturbances were observed in Indian major carp Labeo rohita (Rohu) on exposure to Cr VI.

Copper

Copper is an essential micronutrient, a component of many enzymes; however, when the dose exceeds control, it is highly toxic, especially to fish larvae and invertebrates. Mining, antifouling paints, algaecides, and agricultural fungicides are major sources. Copper directly damages the gill membrane, impairs ion balance (Na^+/K^+ regulation), and impairs olfaction; even at low concentrations, the olfactory ability of fish is reduced (Grosell, 2012). Water hardness and dissolved biochar reduce its toxicity.

Nickel

Nickel is a little-known metal, but enters water from alloy manufacturing, paint coatings, and the electroplating and petroleum industry. Nickel is often less toxic to aquatic organisms than other metals, yet at high concentrations cause growth inhibition, respiratory distress, and chromosomal damage (Pyle and Couture, 2012). It induces oxidative stress and reproductive decline. Its toxicity is also affected by water quality, especially magnesium concentration.

Zinc

Zinc (Zn) is an essential micronutrient that is a vital component of many enzymes and proteins. Under normal conditions, aquatic organisms can control their concentration in their bodies, but when excessive amounts enter the aquatic environment from sources such as metallurgical refining, galvanizing industries, fertilizers, and tire wear, it begins to have toxic effects. At high concentrations, zinc causes hypocalcemia (low calcium levels), damages gill epithelium and affects respiration (Hogstrand 2012). Thus, zinc is one of those metals that is essential for organisms in limited amounts, but can have severe toxic effects in excess, representing an important example of balancing need and toxicity.

Arsenic

Chemically, arsenic is a metalloid, but due to its toxic properties, it is often classified alongside heavy metals. Its presence in the aquatic environment is primarily linked to the natural contamination of groundwater particularly in the Gangetic and Brahmaputra plains—as well as to pesticides, wood preservatives, and mining activities. Arsenic exists in trivalent [As (III)] and pentavalent [As(V)] forms, with As (III) considered more toxic; it inhibits the activity of various enzymes by binding to thiol (–SH) groups within cells and disrupts cellular respiration processes. Furthermore, arsenic has been associated with oxidative stress, DNA damage, and an increased risk of cancer (Tchounwou et al., 2012). Its accumulation in aquatic organisms adversely affects growth, development, and reproductive capacity, while also posing a serious risk to human health through the food chain.

5. Absorption and Bioaccumulation

Heavy metals enter water sources in several ways. Aquatic organisms absorb metals not only directly from water but also through their diet. The relative importance of these two pathways, the waterborne pathway and the trophic pathway, depends on metals, fauna, and environmental conditions (Wang and Fisher, 1999).

Gills are the major portal for metal absorption in aquatic fish and invertebrates. The gill membrane is very thin, wide, and vascularized; its main function is gas exchange and ion control, but the same large surface also facilitates the penetration of metals. Metals are often camouflaged (ionic mimicry) through transporters of essential ions (such as calcium and sodium); for example, cadmium enters the body through the calcium pathway and leaves the body through the calcium pathway (Playle, 1998; Wood, 2001). This is the basis of the biotic ligand model, where competition of metals with binding sites on the gill surface determines toxicity (Di Toro et al., 2001; Niyogi and Wood, 2004).

Organisms that consume contaminated food absorb these metals into their intestines, leading to an increased metal burden. These metals are a type of metal that is not very soluble in water but binds strongly to food particles (such as methyl groups). Studies have shown that the absorption of metals occurs to a greater extent through digestion than through water exposure (Reinfelder and Fisher, 1991; Fisher and Reinfelder, 1995). The skin also serves as another route of absorption, particularly for organisms with thin skin and for amphibians.

The process by which metals are gradually accumulated within an organism's body is known as 'bioaccumulation'. The accumulation of metals in an organism depends primarily on the balance between the rates of uptake and elimination (excretion) from the body. When the rate of metal uptake exceeds the rate of elimination, metals gradually accumulate in various parts of the body. Different organisms employ different strategies to manage metals; some are capable of actively regulating the levels of essential metals, while others are not (Rainbow, 2002, 2007; Depledge and Rainbow, 1990). This is why certain organisms are considered excellent 'bio-indicators', as the metal content in their bodies provides a reliable indication of metal pollution levels in the surrounding environment.

Metallothionein is a low molecular weight, sulphur-rich protein that plays a crucial role in the regulation and detoxification of metals. By binding to metals such as cadmium, copper and zinc, this protein reduces the concentration of free toxic metal ions within the cell, thereby mitigating their harmful effects. Since its synthesis is induced by exposure to metals, metallothionein levels can serve as an effective biomarker for metal pollution (Roesijadi, 1992; Amiard et al., 2006; Viarengo, 1989).

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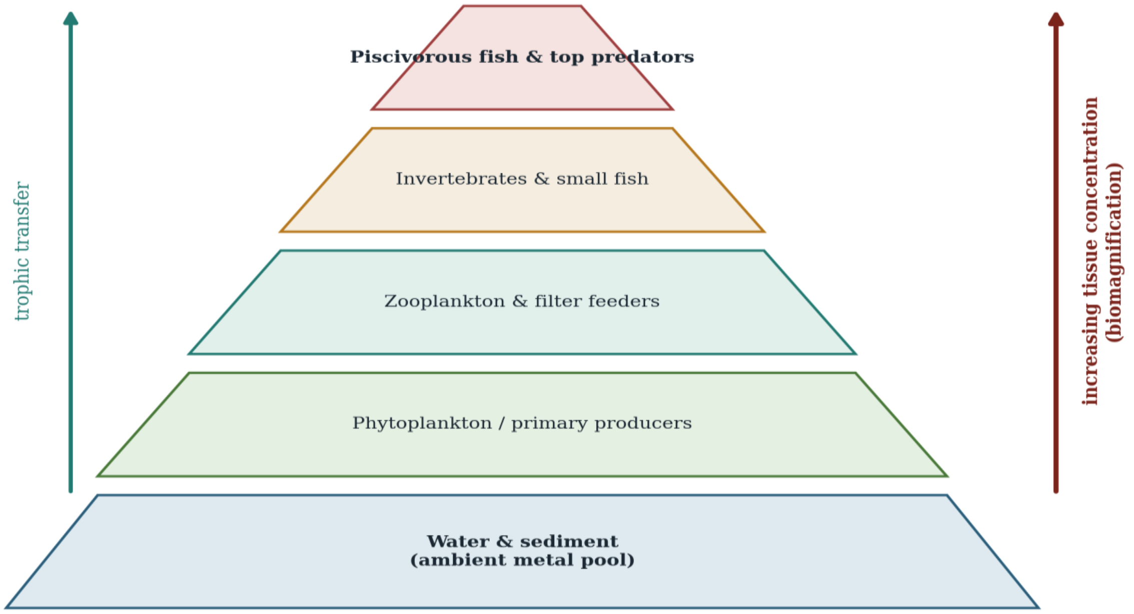

Figure 2. Bioaccumulation and biomagnification of heavy metals along the aquatic food chain: tissue concentration tends to increase from primary producers to top predators, most notably for methylmercury.

Increasing the concentration of metals in the food web to higher levels is called biomagnification. Not all metals grow equally; it is methylmercury that shows obvious biomagnification, as it is tightly bound to the organism and slowly released. Many other metals (zinc, copper, etc.) are controlled by organisms and therefore do not grow at elevated levels; some, however (such as cadmium), accumulate only in certain organisms (Rainbow, 2002; Wang and Fisher, 1999). The order of this magnification is summarized in Table 3.

Table 3. Representative bioaccumulation patterns of heavy metals in aquatic organisms.

Metal / organism	Main target tissue	Accumulation pattern	Reference
Cd — freshwater fish	Kidney, liver, gill	Slow uptake, strong retention; poorly biomagnified	Eisler (1985)
MeHg — piscivorous fish	Muscle	Efficient dietary uptake; strongly biomagnified	Boening (2000)
Pb — fish	Bone, gill, kidney	Sequestered in bone; long half-life	Sorensen (1991)
Cu, Zn — fish	Liver, gill	Regulated; limited net accumulation	Grosell (2012); Hogstrand (2012)
Cd, Cu, Zn — bivalves	Whole soft tissue	Net accumulators; good biomonitors	Rainbow (2002)
Metals — crustaceans	Hepatopancreas	Metal-specific regulation vs. accumulation	Depledge & Rainbow (1990)

MeHg = methylmercury. Patterns are generalised; actual values vary with species, size, season, and water chemistry.

6. Effects on Aquatic Organisms

The effects of heavy metals vary depending on species. Organism size, age, trophic level, regulatory capacity, and habitat water quality determine susceptibility. Below, the effects observed in diverse groups of organisms are discussed separately; Table 2 collects the major toxic effects.

6.1 Fishes

Fish are the most studied organisms of the aquatic system, as they form a major part of the human diet and occupy an elevated position in the food web. Gill damage, respiratory difficulty, ion balance disorders, blood count changes (hematological changes), and liver and kidney damage are common in fish due to metal exposure (Heath, 1995; Sorensen, 1991). Cyprinus carpio, Clarias gariepinus, Labeo rohita, Oreochromis mossambicus etc. Studies of species show that liver and kidney are often the sites of highest accumulation, while muscle is the site of lowest accumulation (Vinodhini and Narayanan, 2008; Kotze et al., 1999) and growth injury, reproductive damage, and immunodeficiency manifest upon chronic exposure (Van der Oost et al., 2003).

6.2 Crustaceans

Small aquatic organisms such as shrimp, crabs, and Daphnia are considered highly suitable model organisms for studying metal uptake and toxicity in aquatic environments. In these organisms, the hepatopancreas serves as the primary organ for metal accumulation. Exposure to heavy metals adversely affects processes such as moulting, growth, and reproduction. Daphnia species are extremely sensitive to metals, even at exceptionally low concentrations; consequently, they are widely used as standard test organisms in toxicity assessments (Rainbow, 2002; Depledge and Rainbow, 1990). Different crustacean species employ distinct strategies for metal regulation, resulting in significant variations in the patterns of metal accumulation and distribution within their bodies.

6.3 Molluscs

Molluscs, specifically bivalves such as Mytilus edulis and Perna viridis, are used globally to monitor and assess levels of metal pollution. These organisms are sedentary, filter-feeding, and long-lived; furthermore, they possess a high capacity for metal accumulation. Consequently, the metal content in their tissues serves as a reliable indicator of pollution levels in the surrounding aquatic environment. Based on this principle, the 'Mussel Watch' monitoring program was initiated worldwide (Goldberg, 1975; Phillips and Rainbow, 1993). Exposure to heavy metals reduces the filtration rate, growth, and reproductive capacity of these organisms, while processes such as lysosomal stability and protein synthesis are impaired at the cellular level (Viarengo, 1989; Cajaraville et al., 2000).

6.4 Zooplankton

Zooplankton play the role of primary consumers in the aquatic food chain and serve as a crucial link in transferring heavy metals to higher trophic levels. Microscopic aquatic organisms such as copepods and cladocerans are extremely sensitive to metal toxicity. Elevated levels of heavy metals adversely affect their lifespan, reproductive rates, and population growth (Reinfelder and Fisher, 1991; Wang and Fisher, 1999). Zooplankton constitutes fundamental links in the aquatic food web, any disruption at this level can impact on the structure, energy flow, and ecological balance of the entire aquatic ecosystem.

6.5 Phytoplankton

Phytoplankton are primary producers in the ecosystem and form the energy base for the entire aquatic food web. Heavy metals inhibit phytoplankton growth by interfering with processes such as photosynthesis, chlorophyll synthesis, and cell division. Copper acts as an effective algaecide by inhibiting enzymes associated with photosynthesis. Conversely, metals like iron and zinc serve as essential micronutrients for phytoplankton growth and metabolic activities when present in low concentrations. Thus, the impact of metals on phytoplankton is twofold: they can be beneficial as nutrients in lesser amounts, whereas they exert toxic effects at high concentrations (Sunda and Huntsman, 1998). Variations in sensitivity to metals among distinct species can lead to changes in aquatic community structure, species diversity, and ecological balance.

6.6 Amphibians

Amphibians like frogs and salamanders serve as effective indicators for detecting metal pollution due to their thin skin, life cycles that span both water and land, and sensitive ovaries. Their skin absorbs metals directly, and their eggs and larvae are extremely sensitive. Exposure to metals has been linked to embryonic deformities, delayed metamorphosis, stunted growth, and increased mortality. Metal pollution may also be a contributing factor to the global decline in amphibian populations observed in the late twentieth century (Sharma and Agrawal, 2005).

6.7 Aquatic Insects

Aquatic insects such as mayflies (Ephemeroptera), stoneflies (Plecoptera), caddisflies (Trichoptera), and chironomid eggs are prevalent biological indices of runoff water quality. Some of these groups are hypersensitive to metals, others tolerant so their species composition reflects water quality. The disappearance of sensitive species and the dominance of tolerant species are commonly found in metal-contaminated streams, causing a decrease in community diversity (Bryan and Langston, 1992). This is the change that is taken as the basis of many biomonitoring indices.

Table 2. Representative toxic effects of major heavy metals on aquatic organisms.

Metal	Representative organism(s)	Reported toxic effect	Reference
Cd	Rainbow trout, carp	Disrupted Ca^{2+} balance, gill damage, hypocalcaemia	Hollis et al. (2000)
Hg (MeHg)	Piscivorous fish	Neurotoxicity, behavioural and reproductive impairment	Wiener et al. (2003)
Pb	Freshwater fish	δ-ALAD inhibition, anaemia, neurotoxicity	Sorensen (1991)
Cr (VI)	Labeo rohita	Oxidative stress, altered haematology and metabolism	Vutukuru (2005)
Cu	Salmonids, algae	Gill/olfactory damage, ionoregulatory failure, growth inhibition	Grosell (2012)
Zn	Fish	Gill epithelial damage, hypocalcaemia, respiratory stress	Hogstrand (2012)
As	Fish, invertebrates	Enzyme (–SH) inhibition, oxidative stress, genotoxicity	Tchounwou et al. (2012)
Mixed	Clarias gariepinus	Elevated oxidative-stress biomarkers in polluted river	Farombi et al. (2007)

MeHg = methylmercury; δ-ALAD = δ-aminolevulinic acid dehydratase.

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7. Physiological Effects

The physiological effects of heavy metals often manifest at the whole organism level because of the underlying molecular and cellular damage they cause. Growth inhibition is among the most common effects. Exposure to metals compels organisms to expend more energy on detoxification, tissue repair, and the maintenance of ionic balance. Thereby reducing the energy available for vital biological processes such as growth and reproduction. This principle forms the basis of the energy budget theory, which posits that an increased metal burden raises metabolic costs and inhibits growth (McGeer et al., 2000; Handy, 2003). Another serious consequence of prolonged metal exposure is reduced reproductive capacity, which directly impacts populations. Heavy metals adversely affect egg production, sperm quality, embryonic development, and egg viability. Irregularities in vitellogenesis, yolk formation, and impaired egg maturation have also been observed in fish. Furthermore, many metals disrupt growth in reproductive processes by interfering with hormonal balance, particularly within the thyroid and reproductive hormone systems (Van der Oost et al., 2003). Metabolic disorders are also widely observed due to heavy metals as they interfere with the metabolism of carbohydrates, proteins, and fats. Under stress, organisms rapidly deplete their hepatic glycogen stores and fluctuations in blood sugar levels are observed. Significant alterations in carbohydrate, protein and fat profiles have been recorded in Channa punctatus following exposure to metal pollution (Javed and Usmani, 2015). Such metabolic changes are often regarded as early indicators of metal-induced stress.

Immunosuppression is a secondary but important consequence of metal toxicity. Organisms loaded with metals are more susceptible to disease bacteria and parasites, as they have weaker white blood cell activity and immune response. Thus, in addition to direct toxicity, metal pollution increases disease susceptibility and indirectly depletes populations (Sorensen, 1991; Wright and Welbourn, 2002).

8. Biochemical and Cellular Effects

Oxidative stress is believed to be the focus of heavy metal toxicity at the molecular level. Transition metals such as copper and iron produce reactive oxygen species (ROS) by Fenton and Haber–Weiss reactions; Cadmium, mercury, and lead indirectly weaken antioxidant defenses and increase the accumulation of ROS. Excess ROS cause lipid peroxidation, protein damage, and DNA damage (Livingstone, 2001; Di Giulio and Meyer, 2008; Lushchak, 2011).

To counter this, organisms rely on antioxidant systems, of which superoxide dismutase (SOD), catalase (CAT), glutathione peroxidase (GPx), and glutathione (GSH) are key components (suppression). For this reason, these enzymes are commonly used as sensitive biomarkers of metal stress (Farombi et al., 2007; Lushchak, 2011).

Enzyme inhibition serves as a direct mechanism of metal toxicity. At enzyme active sites, various metals bind to thiol groups (–SH groups), thereby inhibiting their activity. Well-known examples include the inhibition of δ-ALAD by lead, which disrupts hematopoietic synthesis; similarly, the inhibition of the neurotransmitter acetylcholinesterase (AChE) adversely affects neurotransmission. Inhibition of the Na^+/K^+-ATPase ion pump also disrupts ion balance (Sorensen, 1991; Vutukuru, 2005).

DNA damage and genotoxicity are among the primary causes of the long-term adverse effects of heavy metals. Chromium (VI), arsenic, and cadmium induce DNA strand breaks, base alterations, and chromosomal aberrations, either directly or through the generation of reactive oxygen species (ROS). Such genetic damage has been assessed in fish erythrocytes using the Comet Assay and the Micronucleus Assay (Tchounwou et al., 2012). These genetic aberrations not only affect the health of individual organisms but, by being transmitted across generations, can also pose a serious threat to the long-term stability and survival of the population.

Histopathological changes provide unmistakable evidence of the molecular damage. Glomerular fusion, hypertrophy, mucus secretion, and the rupture of thin walls are common occurrences. Atrophy, vacuolation and necrosis are observed in the liver and kidneys. These changes serve as sensitive indicators of water quality and organism health, and are therefore used in biomonitoring (Van der Oost et al., 2003; Authman et al., 2015). The primary mechanisms of toxicity are illustrated in Figure 3.

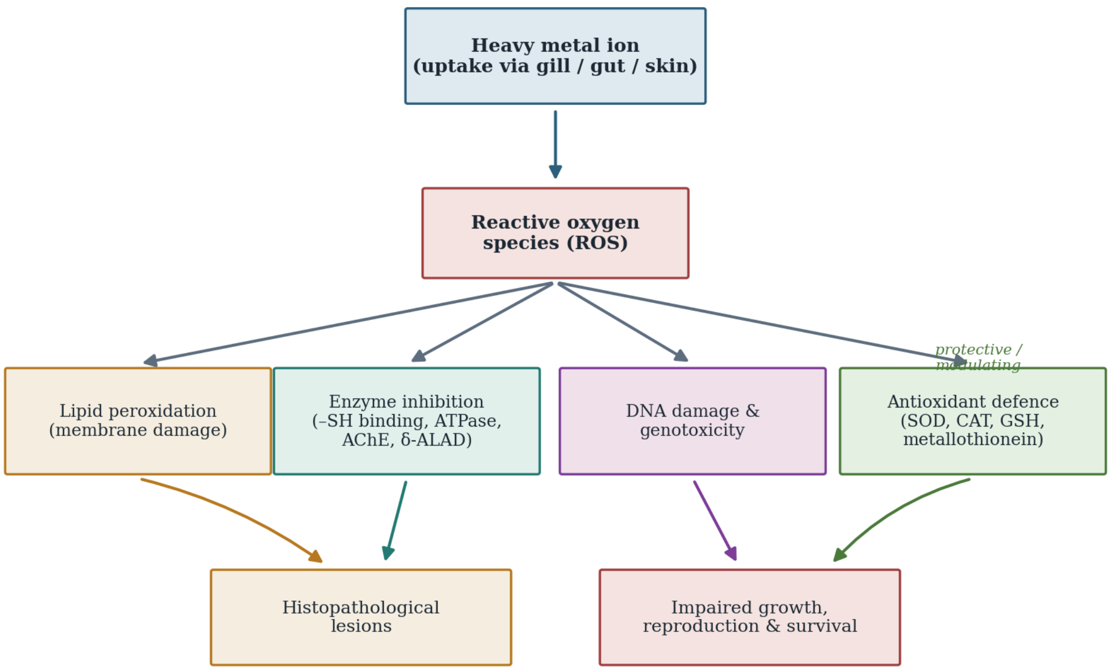

Figure 3. Principal mechanisms of heavy-metal toxicity in aquatic organisms: metal uptake generates reactive oxygen species, leading to lipid peroxidation, enzyme inhibition, and DNA damage, which are partly counteracted by antioxidant and metallothionein defences.

9. Ecological Consequences

Effects observed at the individual organism level in turn permeate to the overall community-ecosystem level. Loss of biodiversity is a major consequence. Metal-sensitive species gradually disappear from the contaminated area, and tolerant species gain preference; thus, species richness and evenness are reduced. This change is often detected by bioindicators even before visible destruction (Bryan and Langston, 1992; Islam and Tanaka, 2004).

Food web change is the second serious consequence. When zooplankton or phytoplankton are depleted in the basal layer, food for higher level organisms decreases. Biomagnification also carried a higher metal load to top predators, thus affecting their reproduction and lifespan. Thus, food web structure and energy flow are disrupted (Wiener et al., 2003; Rainbow, 2002).

Population decline is the cumulative result of reduced fertility, increased egg-laying mortality, and susceptibility to disease. Prolonged exposure to even low concentrations will gradually impair the

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reproductive capacity of the population, which is often not revealed in rapid toxicity tests and therefore long-term effects need to be studied in ecological risk assessment (Newman and Unger, 2003; Walker et al., 2012).

There are great differences in species sensitivity; it is on this basis that the species sensitivity distribution tool is used in setting water quality standards. Elimination of sensitive species disrupts ecosystem imbalances that disrupt nutrient recycling, primary production, and energy flows. Overall, the system also depletes ecosystem services which are also essential for human well-being (Luoma and Rainbow, 2008).

10. Biomonitoring and Assessment

Measuring metal concentrations in water and sediments alone did not fully reveal the biological effects of pollution, as that measurement is transient and does not show metal bioavailability so biomonitoring using organisms has proven extremely useful to assess contamination and its effects (Phillips and Rainbow, 1993; Zhou et al., 2008).

Bioindicators are organisms that accumulate environmental metals in their bodies in a concentrated manner. Bivalves are the best for this, as they are stable, water-filtering, long-lived and net accumulators; therefore, the Mussel Watch program initiated worldwide ocean monitoring (Goldberg, 1975). Fish, algae, and aquatic insects have also been used as indicators for a variety of purposes (Rainbow, 2002; Authman et al., 2015).

Biomarkers are measurable biochemical or physiological changes induced by metal stress in the living body. Prevalent biomarkers of metallothionein concentrations, antioxidant enzyme activity, δ-ALAD inhibition, lipid peroxidation, DNA damage, and histological abnormalities. These markers provide an early signal (early warning) before direct destruction (Van der Oost et al., 2003; Cajaraville et al., 2000). However, the singular marker is often unspecified; therefore, the multi-biomarker approach gives a more reliable picture.

An ecological risk assessment summarizes this evidence to determine the magnitude of the danger. In this process, the risk ratio is calculated by comparing the measured environmental concentration with the predicted non-impact concentration. Water quality standards (water quality criteria), as set by the USEPA, were developed on this basis (USEPA, 1986; Newman and Unger, 2003). Table 4 shows some representative biomonitoring studies.

Table 4. Selected biomonitoring studies of heavy metals in aquatic systems.

Bioindicator / biomarker	Metal(s)	System / focus	Reference
Marine mussels (Mussel Watch)	Cd, Cu, Zn, Pb, Hg	Global coastal monitoring concept	Goldberg (1975)
Aquatic invertebrates (tissue metals)	Various	Bioavailability interpretation	Rainbow (2002)
Fish biomarkers (multi-biomarker)	Various	Environmental risk assessment framework	Van der Oost et al. (2003)
Coastal biomarkers (Iberian coast)	Mixed	Practical field biomonitoring	Cajaraville et al. (2000)
Catfish oxidative-stress markers	Mixed	Ogun River, Nigeria	Farombi et al. (2007)
Sediment + fish (risk assessment)	Multiple	Yangtze River basin, China	Yi et al. (2011)

After Phillips and Rainbow (1993) and Zhou et al. (2008).

Table 5. Comparative findings of representative previous studies.

Study	Focus	Key finding

Bryan & Langston (1992)	Metals in UK estuarine sediments	Sediment: Major Collection; Bio permeability is controlled by water chemistry.
Wang & Fisher (1999)	Assimilation efficiency in invertebrates	The alimentary canal contributes much more than the waterway.
Rainbow (2002)	Trace-metal accumulation strategies	Regulation and accumulation strategies vary by species.
Boening (2000)	Mercury fate and effects	Only methylmercury shows strong bio enhancement.
Vutukuru (2005)	Cr (VI) in Labeo rohita	The most prominent ones are antioxidation and holometabolic disturbances.
Vinodhini & Narayanan (2008)	Metals in Cyprinus carpio organs	Accumulation is high in the liver and kidneys and low in the muscles.
Yi et al. (2011)	Yangtze sediment + fish risk	elevated risk of depression; Human health hazard in fish.

11. Management and Mitigation Strategies

The first and best approach in managing heavy metal pollution is source control. Limiting metal concentrations in industrial effluents to adopt cleaner production and reducing waste prevents it from getting to root levels. Because the metal does not corrode, they are difficult to remove once inserted; For this reason, prevention is better than refinement (Förstner and Wittmann, 1981).

Wastewater treatment is the second major measure. Chemical precipitation, ion exchange, adsorption, such as activated carbon, and membrane filtration are common methods for metal removal. Biosorption, phytoremediation, uptake of metals by aquatic plants, and constructed wetlands have been investigated as environmentally friendly and economical options (Ali et al., 2013). It also depends on local conditions.

Regular monitoring is an essential part of management; routine measurement of metal concentrations and biomarkers in water cut the legal framework for pollution control in half. Organizations such as WHO, FAO and UNEP provide international guidance (WHO, 1989). Sentinel organisms disclose trends in contamination and evaluate the impact of management measures. The legislation supports equally necessary water quality standards, Nissar standards, and their strict adherence.

Ecosystem protection is the foundation for long-term solutions. Wetland protection, coastal zone management, rehabilitation of polluted areas, and community participation enhance the natural resilience of the system. One approach by itself is not enough; Source control, cleanup, monitoring, law regulation, and conservation are effective strategies only in coordination (Luoma and Rainbow, 2008).

12. Conclusion

From the evidence considered in the present review, heavy metals pose multiple levels of danger to aquatic organisms. Entering the water system through natural and anthropogenic sources, these metals circulate in dissolved, granular, sedimentary bio forms, long in sediment. Their bio accessibility and toxicity are determined not only by overall concentration, but metal chemical form, water quality, and bioregulation as previous research has repeatedly demonstrated.

At the organism level, metals are absorbed into cells intestines, causing oxidative stress, inhibiting enzyme function, and damaging DNA and tissue, impairing growth, reproduction, and immunity. Some metals, such as methylmercury, grow in the food web and threaten top predators and humans. Well supported in studies such as Boening (2000), Wiener et al (2003). Starting at the level of individual organisms, these impacts are extended to the level of whole communities and ecosystems, leading to biodiversity loss, food web dysfunction, and system imbalances.

The combination of indicator organisms and biomarkers in the monitoring area can reveal danger before direct destruction, so it is valuable for management and fruitful only when source control, sewage treatment, routine monitoring, strict legal regulation, and ecosystem protection are combined. Since heavy metals do not decompose, prevention is the best strategy. Research published up to 2016 shows that although the toxicological mechanisms are well understood, in-depth studies of corrosive effects, polymetallic mixtures and species-specific susceptibilities are still needed, and this alone will direct the direction of future research.

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