Bioaccumulation of heavy metals in aquatic organisms and its effects on human consumption

Nazmul MHM[1*]; Sutha Devaraj[2]; Farzana Y[3]; Nalayanni Vasu[4]; Sergey Gupalo[5]; Saeid Reza Doustjalali[6]; Negar Shafiei Sabet[7]

Received: 13 February 2025; Revised: 19 March 2025; Accepted: 04 April 2025; Published: 20 May 2025

Abstract

Heavy metal contamination in aquatic ecosystems poses a significant threat to both environmental and human health. Bioaccumulation, which is defined as the accumulation of toxic metals like mercury (Hg), cadmium (Cd), lead (Pb), arsenic (As), and chromium (Cr) in water living beings, is concerned with the seafood consumption cycle tying together humanity which brings potentially disastrous consequences. The industrial waste, mining, agriculture, and natural resources which include volcanic eruptions and the weathering of rocks provide environments rich in compiling seafood industry pollutants. Emphasis is given to bioaccumulation processes concerning the retention of diverse species of aquatic life which results in the species experiencing the accumulative effects of toxins over time. Fish and shellfish suffer from various conditions such as basic physiological fitness and reproduction failures as well as impaired growth and stunted release. Contaminated seafood is proven to contribute to a wide range of severe health problems like damage to the nervous system and kidneys along with stunted development. The document substantially discusses international organizational WHO, and FAO policies, presenting their guidelines, and pointing out the necessity of continuous monitoring and risk evaluation. Heavy metal pollution has to be controlled and reduced and so does providing evidence to support the preservation of aquatic diversity coupled with the protection of public health is one of the measures proposed in the conclusion.

1*- School of Medicine, Perdana University, Damansara Heights, Kuala Lumpur, Malaysia.
Email: poorpiku@yahoo.com, ORCID: https://orcid.org/0000-0003-3268-0381.
2- School of Medicine, Perdana University, Damansara Heights, Kuala Lumpur, Malaysia.
Email: sutha@perdanauniversity.edu.my, ORCID: https://orcid.org/0000-0003-0092-840X
3- Faculty of Science, Lincoln University, Petaling Jaya, Selangor, Malaysia.
Email: farzanayasmin@lincoln.edu.my, ORCID: https://orcid.org/0000-0001-9331-9181
4- Faculty of Medicine & Health Sciences, UCSI University, Springhill Campus, Persiaran Springhill, Port Dickson, Malaysia. Email: nalayanni@yahoo.com, ORCID: https://orcid.org/0000-0001-9661-6018
5- Saint James School of Medicine Anguilla, The Quarter, Anguilla. Email: sgupalo@mail.sjsm.org, ORCID: https://orcid.org/0000-0003-3376-1431
6- Faculty of Medicine, SEGi University, Kota Damansara, Selangor, Malaysia.
Email: saeidrezad@gmail.com, ORCID: https://orcid.org/0009-0005-0314-1903
7- Faculty of Medicine, SEGi University, Kota Damansara, Selangor, Malaysia.
Email: negarshafiei24@gmail.com, ORCID: https://orcid.org/0009-0009-5054-4608
*Corresponding author
DOI: 10.70102/IJARES/V5I1/5-1-29

Keywords: Bioaccumulation, Heavy metals, Aquatic organisms, Human health risk

Introduction

The accumulation of heavy metals in water bodies is one of the most critical issues regarding environmental and public health around the globe (Rajeshkumar and Li, 2018). The modern era of industrial development, urban growth, and agricultural expansion has acted like a catalyst in the introduction of heavy metals into water bodies (Figure 1) (Singh *et al.,* 2022). Such metals consist of mercury (Hg), cadmium (Cd), lead (Pb), arsenic (As), and chromium (Cr), which are known to be detrimental to both aquatic organisms and humans (Barile, Carreño and Los Ríos-Escalante, 2024; Suedel *et al.,* 1994). In contrast to organic pollutants, heavy metals are non-organic and non-biodegradable pollutants, meaning they are non-decomposable substances that persist to exist in the environment and get trapped in the tissues of living beings over time due to a process known as bioaccumulation (Gray, 2002).

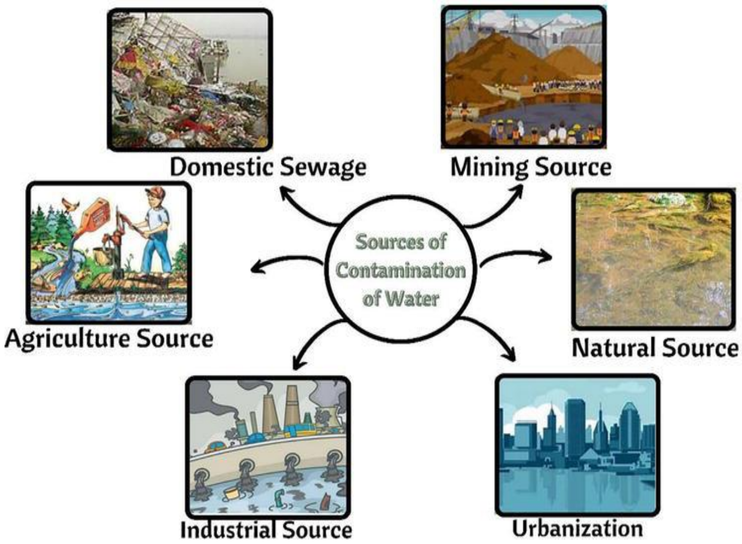


Figure 1: Contamination of water through different sources (Singh *et al.*, 2022)

As defined in (Franke *et al.,* 1994), bioaccumulation is the building-up of harmful substances within the body of an organism. It occurs when the intake of these substances exceeds the rate of elimination from the body. In the case of aquatic ecosystems, heavy metals find their way into the food chain through water, sediments, and living organisms (Figure 2) (Mehana *et al.,* 2020). They are taken up by primary producers like phytoplankton and algae and subsequently consumed by fish and shellfish, which in turn are consumed by humans (Estevez *et al.,* 2020). This phenomenon is also known as biomagnification, which refers to the increase in concentration of these contaminants in top predators such as humans.

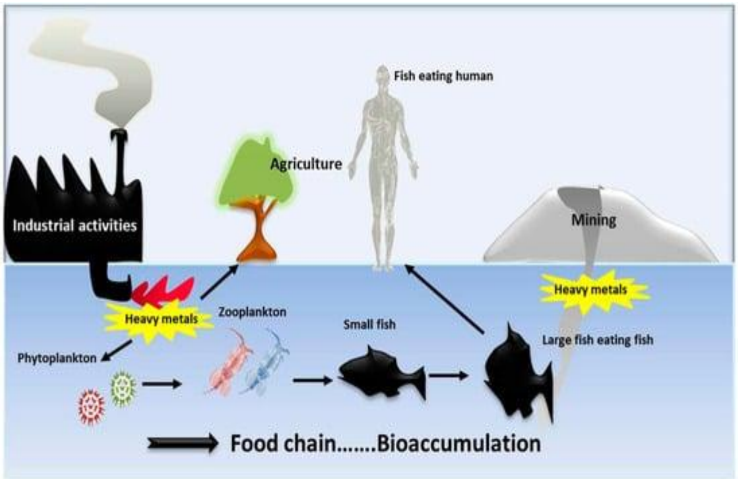


Figure 2: Bioaccumulation of heavy metals in aquatic organisms (Mehana *et al.*, 2020)

The Global Concern of Heavy Metal Contamination

The pollution of water by heavy metals poses a problem worldwide because of its consequences on biological diversity, the balance of ecosystems, and people's health (Ali and Khan, 2019; Vaka and Tamata, 2024). According to WHO, heavy metal pollution is one of the top ten global public health challenges (World Health Organization (WHO), 2021; Lawal and Krishnan, 2020). Most, and especially developing countries, fall short of appropriate wastewater treatment technology and therefore directly discharge industrial and domestic sewage into rivers, lakes and oceans (Rajeshkumar and Li, 2018). The consequences of this pollution extend beyond aquatic life to impact the lives of millions of people who depend on fishery and aquaculture for food and income (Barile *et al.,* 2024), with major sources of heavy metals in aquatic ecosystems summarized in Table 1.

Table 1: Major sources of heavy metals in aquatic ecosystems

Source	Heavy Metals Released	Common Pathways into Water Bodies
Industrial Discharges	Mercury, Cadmium, Lead, Chromium	Wastewater, accidental spills
Mining Activities	Arsenic, Cadmium, Lead	Acid mine drainage, tailing runoff
Agricultural Runoff	Arsenic, Cadmium, Lead	Fertilizers, pesticides, livestock waste
Urban Wastewater	Mercury, Lead, Chromium	Sewage discharge, stormwater runoff
Atmospheric Deposition	Mercury, Lead, Arsenic	Precipitation carrying airborne pollutants

Importance of Studying Bioaccumulation

The reasons for understanding bioaccumulation are numerous:

1. Ecological Impact: Heavy metals contaminate water ecosystems. This leads to changes in birth and death rates, population growth, and the overall survival of different species. Food webs may be altered, biodiversity may be diminished, and ecosystems may fail.
2. Human Health Concerns: The consumption of seafood that has been contaminated with heavy

metals is destructive and can result in neurological damage, kidney problems, heart complications, and cancers.

3. Regulatory Frameworks: Monitoring the bioaccumulation of toxic metals is pivotal for formulating public policy regarding the protection of the environment as well as food safety measures. It participates in determining maximum allowable concentration and limitation values of heavy metals in water and seafood.
4. Sustainable Aquaculture: The thriving aquaculture industry which forms a major contributor to global seafood supply is at risk of persistent heavy metal pollution. Exploration into bioaccumulation can aid in fostering and developing the necessary practices that promote the safe and sustainable farming of fish.

Key Heavy Metals of Concern

Key Heavy Metals of Concern shown in Table 2.

Table 2: Key Heavy Metals of Concern

Heavy Metal	Primary Sources	Toxic Effects in Humans	Affected Aquatic Species
Mercury (Hg)	Industrial waste, coal combustion	Neurological damage, cognitive impairment	Fish, shellfish, marine mammals
Cadmium (Cd)	Mining, battery production, plastics	Kidney damage, bone demineralization	Mollusks, crustaceans, fish
Lead (Pb)	Paint, gasoline, industrial runoff	Developmental issues, nervous system damage	Freshwater fish, invertebrates
Arsenic (As)	Pesticides, mining, fossil fuels	Skin lesions, cancer, cardiovascular diseases	Fish, algae, benthic organisms
Chromium (Cr)	Leather tanning, electroplating	Respiratory problems, skin irritation	Crustaceans, aquatic plants

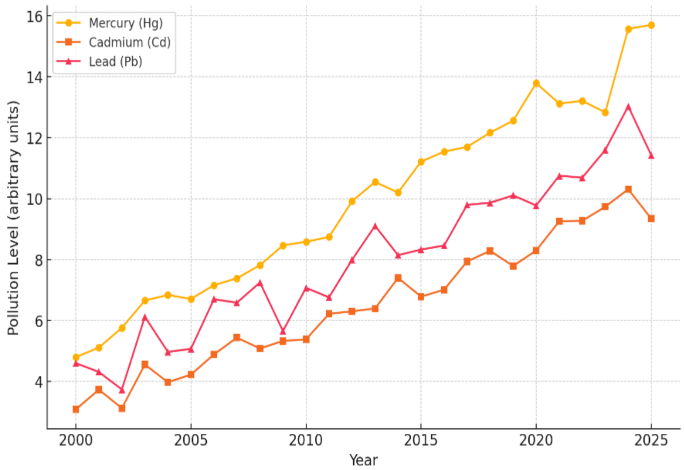
Pathways of Heavy Metal Bioaccumulation

Aquatic organisms bioaccumulate heavy metals through several pathways. Direct uptake from water occurs when aquatic animals extract dissolved metals through their gills, skin, and other external parts, a process particularly evident in fishes and amphibians. Dietary intake is another major route, where animals acquire heavy metals by consuming contaminated prey or organic matter. Additionally, sediment interaction plays a significant role, as bottom-dwelling organisms are heavily exposed to bioaccumulation due to their direct contact with contaminated sediments.

When heavy metals enter an organism, they tend to associate with proteins, lipids, and nucleic acids, disrupting normal cellular activities resulting in toxic effects. Additionally, certain metals such as mercury may be transformed into more toxic derivatives (e.g., methylmercury), enhancing their obliteration of the organism and bioaccumulation.

Factors Influencing Bioaccumulation

The concentration of heavy metals within aquatic species is influenced by several factors. Environmental conditions such as pH, temperature, salinity, and oxygen levels determine the bioavailability of certain metals in water. Biological conditions, including species, age, size, feeding behavior, and metabolic rate, affect the quantity of metal accumulated within organisms. Additionally, chemical speciation plays a crucial role, as the specific chemical form of a metal impacts its toxicity and availability; for example, methylmercury is more toxic and more easily absorbed compared to inorganic mercury. The increasing global levels of heavy metal contamination in aquatic ecosystems between 2000 and 2025, as shown in Graph 1, further amplify the urgency to understand these influencing factors.



Graph 1: Global trend of heavy metal pollution in aquatic environments (2000-2025)

Health Risks Associated with Bioaccumulation

The bioaccumulation of heavy metals in seafood presents both direct and indirect health risks to humans. Fish and shellfish are consumed by many across the globe and serve as a source of protein (Kumar, 2024). The bioaccumulation effect results in heavy metals being stored in human tissues which leads to chronic ailments when contaminated fish and shellfish are consumed (Castro-González and Méndez-Armenta, 2008), as summarized in Table 3.

Table 3: Human health effects of heavy metal exposure through seafood consumption

Heavy Metal	Health Effects in Humans	At-Risk Populations
Mercury (Hg)	Neurotoxicity, developmental delays, memory loss	Pregnant women, young children
Cadmium (Cd)	Kidney damage, bone fragility, respiratory issues	Smokers, people with kidney disorders
Lead (Pb)	Cognitive deficits, hypertension, anemia	Children, pregnant women
Arsenic (As)	Skin cancer, cardiovascular disease, diabetes	Populations with contaminated water
Chromium (Cr)	Lung cancer, dermatitis, liver damage	Industrial workers, urban populations

The Need for Regulatory Measures

In a bid to reduce the dangers posed by the bioaccumulation of heavy metals, international bodies like World Health Organization (WHO) and Food and Agriculture Organization (FAO) of the United Nations have set out limits on the quantity of heavy metals permissible in seafood (Fortin, 2023; Kargar and Zadeh, 2015). Stricter environmental policies targeting industrial emission control and improvement of waste treatment facilities are being enacted in many countries (Kumar and Yadav, 2024).

There is a constant need for surveillance and investigation with respect to new emerging contaminants and environmental changes (Usikalu, Alabi and Ezeh, 2025). The invention of sophisticated instruments for the measurement and removal of heavy metals from water bodies is also of great importance (Wang *et al.,* 2024).

As noted, the bioaccumulation of heavy metals in living organisms accumulates as a function of several environmental, biological, and chemical processes. It is by virtue of these factors, and the ensuing potential health risks attributable to them, that warrants the concern of environmental scientists, public health bodies, and policymakers. With appropriate understanding of bioaccumulation mechanisms and pertinent exposure pathways, strategies can be fashioned to avert threats regarding both ecosystems and humans.

Sources of Heavy Metals in Aquatic Ecosystems

The entry of heavy metals into water bodies emanates from various natural and anthropogenic sources (Akhtar *et al.,* 2021). Combating pollution while safeguarding public health changes differing from region to region which makes the tailored understanding of such sources crucial. The resulting pollution from sustained human activities seems incessant permitting the gradual heavy metal accumulation in water bodies, enabling flora and fauna to accumulate toxins, endangering the health of entire ecosystems heavily dependent on these ecosystems for economic sustenance (Ahamad *et al.,* 2024).

Natural Sources of Heavy Metals

The non anthropogenic sources of heavy metals add to the problem caused due to human activities.

- *Geological Weathering*

Natural processes of weathering rock and soil parent materials result in the release and mobilization of heavy metals that include arsenic, lead, mercury, and cadmium. The weathering of minerals and rocks allow metals to flow into rivers, lakes, and groundwater through surface runoff.

- *Volcanic Activity*

Volcanic activities have the potential to give out a great deal of mercury, arsenic, and lead, which is released into the air. These metals later on are deposited in water bodies by falling from the atmosphere.

- *Atmospheric Deposition*

Heavy metals may be moved over vast distances before being deposited into water bodies through precipitation. This is particularly relevant for mercury, which is capable of circling the globe.

Anthropogenic Sources of Heavy Metals

Aquatic ecosystems are polluted primarily due to anthropogenic factors. There is strong evidence that industrial and urban development as well as agricultural activities greatly increases the presence of these contaminants within bodies of water.

- *Industrial Discharges*

The industrial activities like mining, metal plating, battery production and chemical industries discharge heavy metals such as lead, cadmium, mercury and chromium into nearby rivers and lakes. It is well known that the wastewater from factories is heavily polluted, with common industrial sources of heavy metals outlined in Table 4.

Table 4: Common industrial sources of heavy metals

Industry	Heavy Metals Released	Pathway to Aquatic Systems
Mining	Arsenic, Lead, Cadmium	Acid mine drainage, runoff
Battery Manufacturing	Lead, Cadmium, Mercury	Wastewater discharge
Textile and Tanning	Chromium, Copper	Effluent release
Electronics Production	Lead, Mercury, Cadmium	Industrial effluents
Paint and Pigment	Lead, Chromium	Surface runoff

- *Agricultural Runoff*

Heavy metals can be extensively released into the environment with little regulation, but agricultural activities are one of the most concerning due to the application of fertilizers, pesticides, and animal waste. Irrigation and rainwater runoff contains trace amounts of metals such as arsenic, cadmium, and lead and these materials often leach into water bodies.

- *Urban Runoff and Wastewater*

Heavy metal pollution is exacerbated by urbanization due to stormwater runoff that washes pollutants from streets, buildings, and vehicles into water bodies. Domestic and commercial wastewater, even after some degree of treatment, tends to retain significant quantities of metals.

- *E-Waste and Improper Disposal*

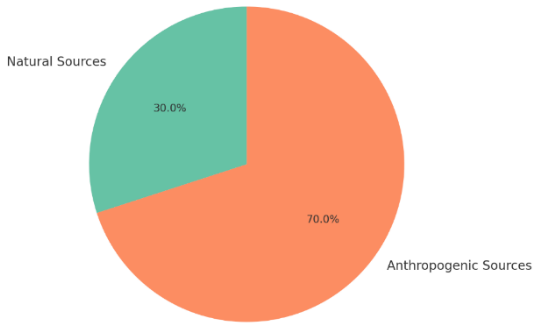
Improper disposal of electronic devices has recently become a notable source of heavy metals like lead, mercury, and cadmium. E-waste placed in landfills can leach into ground or surface water and rain due to seepage.

Comparative Analysis of Natural and Anthropogenic Sources

Heavy metal contamination stems from both Natural and human/external sources; however, there is a distinct difference in the causative factors for both. The Natural sources include the weathering of rocks, volcanic eruptions, forest fires, and erosion of land. Additionally, natural bodies of water also possess arsenic (As), mercury (Hg), and lead (Pb), albeit in small quantities. These processes are gradual and result in low baseline concentrations that can be easily assimilated by ecosystems without causing drastic disruptions.

On the contrary, human-induced activity is the major contributor to heavy metal pollution, representing nearly 70% of global contamination on record

(Graph 2). This primarily includes industrial work such as mining, metallurgy, and manufacturing, along with urban waste disposal and vehicular emissions. There is also agricultural runoff containing fertilizers and pesticides. At every stage of industrial development, a vast amount of toxic metals such as cadmium (Cd), chromium (Cr), and lead (Pb) are introduced into aquatic habitats, far exceeding nature's pace of replenishment.



Graph 2: Contribution of natural vs. anthropogenic sources to heavy metal pollution

Regional Case Studies of Heavy Metal Contamination

- *The Minamata Disaster (Japan)*

Perhaps the most notable example of mercury contamination in Japan is Minamata bay. Widespread mercury poisoning, or 'Minamata disease', as it's known, is endured by most locals due to industrial wastewater from chemical factories.

- *The Ganges River (India)*

The Ganges River is adversely impacted by metalliferous contaminants from industrial and agricultural activities as well as untreated sewage emissions, which have impacted millions of people who use the river for subsistence water and food resources.

Impact of Climate Change on Heavy Metal Distribution

Shifts in temperature and heavy precipitation events substantially worsen the already significant pollution in an area by flood mobilization of contaminated sediments, as well as changes in the precipitation patterns that govern runoff routing.

The existence of heavy metals in water bodies originates from a combination of natural and human activities. The more or less stationary processes such as erosion and vulcanism lead to the metals' presence, while anthropogenic processes greatly increase the presence of pollutants. To manage such an issue, effective active monitoring programs need to be supplemented by strict control over industrial wastewater, low impact farming, and raising public awareness on the consequences of heavy metals in water.

Mechanisms of Bioaccumulation in Aquatic Organisms

Bioaccumulation refers to the gradual build-up of harmful substances in an organism's body over an extended period, and can happen with lifeforms ranging from fish to entire ecosystems (Baros, 2020; Ali, Khan and Ilahi, 2019). When looked at from an aquaculture perspective, this problem creates a major concern for fisheries, biodiversity, and the contamination risk posed to humans who eat polluted fish (Balagopal, 2019; Sankhla *et al.*, 2016). A number of complex mechanisms mediate the bioaccumulation process of heavy metals like mercury (Hg), cadmium (Cd), lead (Pb), arsenic (As), and chromium (Cr) in aquatic organisms which is influenced by environmental and biological factors (Wang and Liu, 2022). These mechanisms need to be understood as part of ecological risk assessment and the formulation of strategies designed to control the pollution impact.

Definition and Overview of Bioaccumulation

As defined in the concept of bioaccumulation, the process includes capturing, holding, and concentrating toxic substances from specific surrounding waters into biological tissues of an organism. This phenomenon takes place when an organism takes in a substance faster than it can break it down, or when it can no longer secrete it. In an aquatic setting, bioaccumulation occurs clearly through two key processes:

Bioconcentration refers to the direct uptake of heavy metals from the surrounding environment—such as water—through an organism's gills, skin, and other bodily tissues. Biomagnification, on the other hand, describes the increasing concentration of toxins as they move up the food chain, with organisms at higher trophic levels accumulating greater amounts through predatory consumption. Both pathways contribute to the bioaccumulation of metals within aquatic organisms, resulting in adverse effects even when environmental concentrations are relatively low.

Pathways of Heavy Metal Uptake

With regard to metals, aquatic organisms absorb them through various pathways that are dependent on the region of living, feeding habits, and physiological traits.

- *Direct Uptake from Water*

As one of the pathways of absorption, many species of water organisms, especially aquatic vertebrates, gills have structures that support efficient gas exchange, equipping them to absorb metal ions from water. For example, fishes have the ability to absorb metals from the water they reside in. As a result, this pathway is common for many aquatic organisms. Some other organisms that absorb metals in this fashion include crustaceans.

Gills serve as a primary site for metal absorption in all fish and many species of crustaceans, as these organisms use gills for respiration. Metals such as cadmium and lead can attach to gill membranes, disrupting ion regulation and impairing gas exchange functions. Similarly, skin and mucous membranes play an important role in metal uptake. Cited that amphibians and some fish species are capable of absorbing metals directly through their skin, particularly in contaminated environments.

- *Dietary Intake*

Absorption of heavy metals from contaminated foods is another important pathway of bioaccumulation. Trophic level organisms that have already bioaccumulated metals. Therefore, predatory fish, and other benthic feeders are often contaminated with metals.

The planktonic route involves phytoplankton and zooplankton, which act as primary absorbers of metals in aquatic environments. These organisms take in heavy metals from the surrounding water and become the initial carriers of contamination to higher trophic level organisms. The benthic route, on the other hand, involves bottom-dwelling fauna that ingest sediments and detritus laden with heavy metals, further contributing to the bioaccumulation process in aquatic food webs.

- *Sediment Interaction*

Benthic species such as mollusks, worms, and crustaceans reside on or near surface sediments, where a significant amount of heavy metals are concentrated. These animals accumulate metals primarily through two mechanisms: pore water uptake, which involves absorbing dissolved metals present in the sediment water, and ingestion of contaminated sediments, where they consume sediment particles laden with heavy metals.

Factors Influencing Bioaccumulation

The amount of accumulation of heavy metal differs from one organism to the other due to a range of ecological and biological reasons.

- *Environmental Factors*

Water chemistry plays a critical role in the solubility and bioavailability of metals, with factors such as pH, temperature, salinity, and dissolved oxygen concentrations being major determinants. For instance, acidic conditions increase the concentration of cadmium, making it more readily absorbable by aquatic organisms. The presence of organic matter also influences metal dynamics, as organic materials can bind to metals, hindering their direct uptake by organisms but facilitating their transport through sediments. Additionally, competition with other ions affects metal absorption, where non-essential toxic metals may be absorbed more rapidly when essential ions like calcium and magnesium compete for the same uptake sites.

- *Biological Factors*

Species-specific differences significantly influence heavy metal accumulation, as functional and structural variations make some species more efficient at accumulating and storing metals. For example, fish generally exhibit lower cadmium concentrations in their bodies compared to mollusks. Age and size also play important roles, with older and larger organisms tending to have higher metal concentrations due to prolonged exposure over time. Additionally, metabolic rate affects accumulation, as organisms with higher metabolic activity, driven by increased water and food intake, may absorb metals at a faster pace.

Cellular and Molecular Mechanisms of Metal Accumulation

At the cellular level, heavy metals impact multiple pathways of biochemistry, causing poisonous damage.

- *Metal Transport Mechanisms*

Metal uptake in aquatic organisms occurs through both passive and active mechanisms. Passive diffusion allows relatively small metal ions, particularly at the gill tissue, to cross cell membranes without the need for energy expenditure. In contrast, active transport mechanisms are involved for certain metals that mimic essential nutrients and require energy-dependent uptake. For instance, cadmium can enter cells by exploiting calcium channels designed for the transport of calcium ions.

- *Metal Binding Proteins*

Organisms produce specific proteins to bind and sequester heavy metals, thereby neutralizing their toxic effects. Metallothioneins, which are low-molecular-weight proteins, have a high affinity for metals such as cadmium and mercury, and by binding these metals, they help maintain cellular homeostasis. Ferritin, primarily involved in iron storage, can also capture other metals like lead and arsenic, reducing their active concentrations within cells and mitigating their harmful effects.

- *Storage and Detoxification*

To reduce the risk of cellular damage, heavy metals are often confined within specific cell compartments or bound to ligands at the cellular surface, where they are maintained in an inactive state. One mechanism is lysosomal sequestration, where metals accumulate within lysosomes, isolating them in areas less likely to interfere with essential cellular processes. Another strategy is the formation of granules, where certain organisms produce insoluble granules that trap metals and prevent them from interacting with critical cellular structures vital for the organism's survival.

Bioaccumulation and Trophic Transfer

*Bio*accumulation closely associates with biomagnification, the increase in concentration of heavy metals along the food chain (Figure 3).

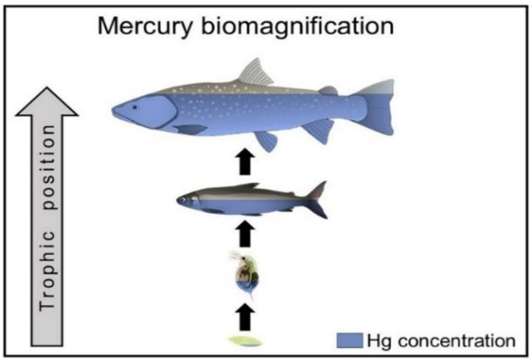


Figure 3: Biomagnification of mercury (Hg) in a simple food web (National Park Service)

- *Trophic Level Differences*

Primary producers such as phytoplankton directly absorb metals from the surrounding water, initiating the bioaccumulation process. Primary consumers like zooplankton feed on phytoplankton and subsequently accumulate higher concentrations of metals. Secondary consumers, including fish, further concentrate metals by consuming contaminated prey. At the top of the food chain are tertiary consumers, such as humans, who are exposed to the highest concentrations of metals like mercury through the consumption of contaminated seafood.

Case Studies of Bioaccumulation in Aquatic Organisms

- *Mercury in Tuna*

As a top predator in marine ecosystems, the methylmercury concentration in tuna is extremely high. Due to the bioaccumulation, health advisories have been issued for consuming seafood, especially during pregnancy.

- *Cadmium in Shellfish*

Cadmium can be found in large quantities in shellfish like oysters and mussels because they filter-feed and come in contact with seabed sediments. In people, eating contaminated shellfish can cause kidney problems and bone diseases.

Health Implications of Bioaccumulated Heavy Metals

Eating contaminated seafood can seriously endanger people's health, with specific health effects summarized in Table 5.

Table 5: Health effects of bioaccumulated heavy metals in humans

Heavy Metal	Primary Sources in Diet	Health Effects
Mercury (Hg)	Predatory fish (tuna, swordfish)	Neurotoxicity, cognitive impairment
Cadmium (Cd)	Shellfish, contaminated rice	Kidney damage, bone demineralization
Lead (Pb)	Contaminated fish and water	Developmental issues, neurological disorders
Arsenic (As)	Fish, shellfish, contaminated water	Skin lesions, cancer, cardiovascular diseases
Chromium (Cr)	Crustaceans, contaminated water	Respiratory problems, skin irritation

The processes through which heavy metals accumulate in aquatic organisms is multi-faceted, integrating geo-ecological factors, biological attributes, and feeding interactions of a given ecosystem. The ecosystem geo-ecological features determine the risk level of humans being exposed to bioaccumulated heavy metals. Well evaluated policies regarding pollution, environmental monitoring, or even vigilance over public health issues all make a sizable difference in preventing bioaccumulation in ecosystems where water is the primary habitat.

Common Heavy Metals and Their Toxicity in Aquatic Species

Heavy metals are elements of high atomic weight and density and are considered highly toxic even at very low concentrations. Mercury (Hg), cadmium (Cd), lead (Pb), arsenic (As), and chromium (Cr) are severe pollutants in water ecosystems as they can deeply affect the ecologic equilibrium as well as biological variety (Ahamad *et al.,* 2024). Heavy metals are particularly dangerous because of their harmful effect on the environment and the ability to accumulate in the tissues of aquatic organisms (El-Ramady *et al.,* 2024). These metals have great toxicity to aquatic species critters thus disturbing the food web and the balance of ecosystem dynamics (Sadulla, 2024).

Overview of Common Heavy Metals in Aquatic Environments

- *Mercury (Hg)*

As one of the most lethal heavy metals in water bodies, mercury Hg, is toxic and serves as a strong indicator of industrial water pollution. Its primary sources are industries, mining activities, and air pollutants like coal burning. Elemental mercury (Hg^0), inorganic form (Hg^2), and the highly toxic organic form methylmercury (CH_3Hg^+) are possible forms of mercury. Gold mining, fossil fuel burning, and industrial effluents are all contributors. Particularly, methylmercury biomagnifies in the entire food chain, achieving extraordinary concentrations in top predators like tuna and swordfish. Moreover, mercury halts crucial biological functions in fish such as metabolism, swimming, and feeding. It also impedes reproductive functions like testicular feminization, and neurotoxic mercury exposure damages enzymes resulting in poor metabolic efficiency.

- *Cadmium (Cd)*

Mining activities together with the manufacture of batteries, plastics, and fertilizers are the primary sources of cadmium. It possesses high toxicity towards aquatic life even in minute concentrations. Engineering electroplating baths, battery manufacturing, and the production of phosphate fertilizers remain the dominant contributors. Due to its long half-life, cadmium is non-biodegradable and has a long residence time in aquatic sediments. In aquatic species, cadmium exposure disrupts osmoregulation while also causing renal damage in fish, excreting oxidative stress and disturbing cell structures on several levels. Furthermore, cadmium markedly retards reproductive and developmental processes together with growth in crustaceans and mollusks.

- *Lead (Pb)*

The primary sources of water bodies lead contamination comprise industrial discharge, leaded gasoline use, and remnants of old paints. The dominant contributors also include mining, battery recycling, and abandoned pipelines. Although lead is tightly bound to sediments, it is capable of re-releasing back to the water column during turbulent conditions. Exposure to lead causes an impaired nervous system which leads to decreased reflex responses. It also provokes growth stunting developmental deformities of bones and tissues in fish larvae, and respiratory gill-neural drowning.

- *Arsenic (As)*

Arsenic is a metalloid element that can be introduced into water systems from both natural geological activities as well as anthropogenic impacts. Residues from pesticide usage, mining activities, and industrial waste are among the major sources. Inorganic arsenic species, while less prevalent, is found to be much more toxic in comparison to organic arsenic compounds. With regards to aquatic organisms, arsenic interferes with energy production in the form of ATP by blocking its synthesis, causes long-term genetic damage which may result in tumor formation, and retards growth and reproduction in many fishes and invertebrates.

- *Chromium (Cr)*

In water bodies, chromium's key forms are the less pernicious trivalent chromium (Cr^{3+}) and hexavalent chromium (Cr^{6+}), the latter being considerably more venomous. The primary industry responsible for chromium pollution includes leather tanning, electroplating, and textile industries. The form Cr 6 is especially terrible due to its high solubility and ease to be absorbed by the aquatic organisms. Cr^{6+} exposure leads to destruction of live tissue and mutations of the DNA, creates pathological gill, liver, and kidney tissue changes in fish, and inhibits photosynthesis in many aquatic plants, including phytoplankton.

Mechanisms of Heavy Metal Toxicity in Aquatic Organisms

Some diverse mechanisms mediate the harmful effects of heavy metals as described below:

- *Disruption of Enzymatic Activity*

The bond of certain heavy metals may inhibit the catalytic activity of some enzymes. Consider the example of lead and δ-aminolevulinic acid dehydratase. Lead inhibits δ-aminolevulinic acid dehydratase, an enzyme involved in the heme synthesis pathway in fish.

- *Oxidative Stress*

Lipid peroxidation and DNA harm cells in aquatic life due to oxidative stress produced by reactive oxygen species (ROS) metals in cadmium and chromium.

- *Bioaccumulation and Biomagnification*

Aquatic organisms' tissues progressively accumulate heavy metals, and their concentration grows as they ascend the trophic level. Such biomagnification in apex predators is especially dangerous because of the high level of toxicity.

- *Endocrine Disruption*

Certain heavy metals can act as endocrine disruptors, interfering with signaling cascades of hormones and consequently impacting processes such as growth, reproduction, and development.

Toxicity Thresholds for Aquatic Species

Aquatic species have different levels of sensitivity to heavy metals. For example, lethal concentration 50 (LC50) is the measure most frequently used which indicates the amount of the toxic substance at which 50% of organisms would die within a given timeframe, as shown in Table 6.

Table 6: LC50 values of common heavy metals for selected aquatic species

Heavy Metal	Species	LC50 (mg/L)	Exposure Duration
Mercury (Hg)	Rainbow trout (*Oncorhynchus mykiss*)	0.01	96 hours
Cadmium (Cd)	Daphnia (*Daphnia magna*)	0.003	48 hours
Lead (Pb)	Zebra fish (*Danio rerio*)	0.8	96 hours
Arsenic (As)	Tilapia (*Oreochromis niloticus*)	1.5	96 hours
Chromium (Cr)	Goldfish (*Carassius auratus*)	2.0	96 hours

Factors Influencing Heavy Metal Toxicity

- *Environmental Factors*

The behavior and toxicity of metals within an aquatic system is influenced by several environmental factors. pH is critically important as increased acidity will enhance metal solubility while also simultaneously increasing toxicity. Water hardness, determined by the concentration of calcium and magnesium, has the potential to reduce the bioavailability of metals because of competition for uptake sites. Also, increased temperature will accelerate the metabolic processing of metals within aquatic organisms which may increase their toxic effects.

- *Biological Factors*

The biological factors determining the sensitivity of heavy metals in aquatic ecosystems are many. Different species of a given taxon have varying coping and detoxification mechanisms associated with heavy metals, making species sensitivity a keystone factor including the toxic impact. Younger or larval stages are more susceptible to metal toxicity, thus life stage also plays a significant role. Furthermore, dietary habits impact the level of exposure, bottom feeding species are more likely to accumulate sediment metals than those active in mid-water feeding.

Case Studies of Heavy Metal Toxicity in Aquatic Ecosystems

- *Minamata Bay, Japan (Mercury Poisoning)*

The Minamata disaster of the 1950s is a glaring example of the effects of mercury contamination. Mercury bioaccumulation in fish and shellfish as a result of industrial wastewater from a chemical plant caused neurological disorders in humans who consumed the contaminated seafood, which is known as Minamata disease.

- *Aral Sea, Central Asia (Heavy Metal Accumulation)*

The Aral Sea suffered severe ecological damage because of heavy metal runoff from industrial and agricultural activities. There was a complete collapse of the aquatic ecosystem resulting in the extinction of native fish species.

- *The Ganges River, India (Lead and Arsenic Pollution)*

Increased pollution from industries and the agricultural sector have led to heavy metal contamination of the Ganges River. This has also lowered fish stocks and posed a greater risk to the health of people using the river for water and food.

Mitigation and Management of Heavy Metal Toxicity

- *Pollution Control Measures*

To reduce heavy metal pollution in aquatic ecosystems, effective management strategies are required. Stringent regulations on industrial effluent discharge are needed especially regarding the waste stream where there is a possibility of the discharge of harmful metals into water bodies. In addition, proper pre-discharge treatment of wastewater requires advanced treatment processes and more complete filtration and bioremediation techniques.

- *Environmental Monitoring*

Modernized monitoring approaches are critical in combating heavy metal pollution. Metal pollution biosensors employing sensitive biological indicators are widely used as realtime monitors of aquatic ecosystems. In addition to these proactive approaches, regular monitoring of the sediment and water quality is essential and proactive to identify pollution hotspots to control and remediate heavy metal accumulation.

- *Ecosystem Restoration*

Active remediation programs focus on sustainable and ecologically sound methods of dealing with heavy metal pollution. Phytoremediation, as a method of removal or stabilization of heavy metals in contaminated sediment and water uses higher plants, which are being with advanced methods developed further. Concurrently, there are also initiatives to improve habitats to rehabilitate and restore degraded aquatic environments to enhance the resilience of the ecosystems and the species recovery is more effectively facilitated.

Mercury, cadmium, lead, arsenic, and chromium are classified as heavy metals, and they are harmful to aquatic species because they can persist for a long time, accumulate in living organisms, and exert toxic effects. Effective risk assessment and management strategies require understanding the mechanisms of toxicity along with species-specific sensitivities and environmental determinants of metal uptake. Protecting aquatic life and humans from the harmful consequences of heavy metal pollution requires advanced policies in technology, regulation, and ecosystem management. Contamination of water with heavy metals endangers human health and requires mitigating response initiatives.

Impact of Heavy Metal Contamination on Human Health

Human health as well as all life within aquatic ecosystems is impacted by heavy metal contamination around the world. Heavy metals are considered to be one of the most dangerous type of pollutants because they are highly toxic and virtually indestructible. Human exposure to highly toxic metals like mercury (Hg), cadmium (Cd), lead (Pb), arsenic (As), and chromium (Cr) occurs through the consumption of fish and shrimp contaminated with these toxic substances. Exposure to cadmium, lead, and various arsenic compounds can cause numerous health complications, some of which may be fatal. Various diseases arise from heavy metal poisoning, with the rate of incidence increasing with greater exposure to lead. Here, we cover the medical impact of cadmium lead and arsenic exposure, pathophysiological processes responsible for changes in different populations, and illustrative vividly alarming case studies documenting the extent of public health neglect.

Pathways of Human Exposure to Heavy Metals

Heavy hobbies include consumption of Seafood, also, anthropogenic activities exposes every individual to a diverse variety of hazardous heavy metals such as mercury and organomercurials.

- *Dietary Intake*

Exposure to heavy metals by humans mainly occurs through consuming aquatic organisms and drinking contaminated water. Certain species of fish and shellfish, especially tuna, swordfish, oysters, and mussels, are high in mercury and cadmium, which pose health risks to the consumers. Moreover, the groundwater well water used for drinking in developing countries contains arsenic and lead which are highly detrimental to health due to the non-existent water filtration systems available in these countries.

- *Occupational Exposure*

Fishermen and Seafood Processors: Employees in fishing industry are likely to suffer greater risk from contaminated water and seafood due to exposure across the lines of work.

- *Other Exposure Routes*

Drawing in inhaled air and contact with skin are ancillary, albeit not the most significant, routes through which humans can be exposed to heavy metals. Humans can be exposed to heavy metals as a consequence of industrial activities because they can be released into the atmosphere in their gaseous form, later precipitating into bodies of water, thus entering the aquatic food web. The exposure potential via dermal contact is relatively low; however, when people have prolonged contact with polluted water, they can be exposed through dermal contact, despite its reputation of being a less important route of exposure than ingestion or inhalation.

Mechanisms of Heavy Metal Toxicity in Humans

Heavy metals have several mechanisms of incurring toxicity as previously explained:

- *Disruption of Cellular Functions*

Cellular proteins and enzymes flagged by heavy metals often lead to important biological processes. In other words, anemia can result from lead's interference in his heme production.

- *Generation of Oxidative Stress*

DNA, lipids and proteins undergo oxidative damage due to reactive oxygen species (ROS) which metals/cadmium and mercury evoke.

- *Endocrine Disruption*

Some metals exhibit effects of endocrine disruptors which simulate and inhibit hormones affecting the non-pregnant women sexual system and reproductive ability.

- *Neurotoxicity*

The central nervous system suffers the most from the assault of mercury and lead which, having crossed the blood-brain barrier, do the most damage to children.

Health Impacts of Specific Heavy Metals

- *Mercury (Hg)*

Methylmercury differentiates itself from the others by having the strongest abilities of bioaccumulation, where it builds up in the tissues of larger fish. Methylmercury exposure can lead to many severe neurological outcomes such as impaired cognition, memory recall difficulties, and stunted developmental milestones for children during early childhood. It was also found to trigger Minamata disease which is a neurological muscular syndrome that results in tremors, speech impairments, and muscle control weakening. Everything related to mercury poisoning and its symptoms can be found in Table 7.

Table 7: Symptoms of mercury poisoning in humans

System Affected	Symptoms
Nervous System	Tremors, memory loss, seizures
Digestive System	Abdominal pain, diarrhea
Cardiovascular System	Hypertension, arrhythmias
Immune System	Autoimmune dysfunction

- *Cadmium (Cd)*

Cadmium gradually leads to chronic toxicity, because of its accumulation within the kidneys and liver. In the kidneys, cadmium exposure leads to renal injury in the form of dysfunctions such as proteinuria and nephropathy. It is also associated with bone diseases, osteitis fibrosa, osteomalacia, and osteoporosis. Aspects of chronic cadmium poisoning featured in Itai-Itai disease, which emerged in Japan, resulting in the afflicted suffering grievous fractures alongside severe bone pain.

- *Lead (Pb)*

Equally as concerning, lead inflicts high levels of damage to the nervous system, whilst being incredibly toxic to the bladder. In children, lead intake results in a decrease in IQ levels, attention span, and an increase in aggressive behaviors. In adults, there is an increase in the likelihood to contract cardiovascular diseases such as hypertension and general heart disease. Moreover, exposure to these increases propensity to reproductive toxicity wherein one becomes infertile with women experiencing elevated chances of miscarrying.

- *Arsenic (As)*

Exposure to arsenic through tainted water and seafood comes with a host of withdrawal symptoms. One such includes actinically induced skin lesions where skin thickening is accompanied by hyperpigmentation and increase of skin cancers. Moreover, prolonged exposure increases the chance of contracting cancerous changes more frequently, depressingly, lung cancer, bladder cancer, and skin cancer are the most likely candidates.

- *Chromium (Cr)*

Everyone agrees that hexavalent chromium (Cr^{6+}) is extremely toxic and carcinogenic. Respiratory ailments due to inhalation of chromium dust may include asthma, chronic bronchitis, and lung cancer. Illnesses stemming from ingestion of chromium-infused food or water include dyspeptic ulcers, pancreatitis, and hepatotoxicity.

Vulnerable Populations at Risk

Some groups suffer greater consequences from the exposure to heavy metals due to their life stage. Pregnant women are at increased risk because they may be exposed to mercury and lead that can cross the womb and harm fetal development. Newborns and toddlers are highly vulnerable because of their immature yet developing nervous system's neuroplasticity and neuroprotection. There is also greater risk for members of communities near mining regions, industrial areas, and bodies of water with high levels of pollution due to their chronic exposure and health consequences.

Case Studies of Heavy Metal Poisoning

- *Minamata Bay, Japan (Mercury Poisoning)*

A chemical factory started dumping methylmercury waste into Minamata Bay during the 1950s. People suffered from Minamata disease, a disease caused by heavily damaged nerves after consuming contaminated fish. Hundreds died due to Minamata disease.

- *Itai-Itai Disease, Japan (Cadmium Poisoning)*

Cadmium discharged while mining in the Toyama Prefecture poisoned rice fields. The disease was coined Itai-Itai which was the result of cracked bones, intense bone fragments, and kidney failure due to consuming the cadmium containing rice.

- *Arsenic Contamination in Bangladesh*

It is widely known that in the groundwater of Bangladesh exists lagging water bodies tainted with Arsenic. The persistent use of arsenic laced water has resulted in grave skin cancers and other necrotic degenerative diseases as well as cardiovascular complications.

Guidelines and Safety Limits for Heavy Metals in Food

To prevent potential health impacts of heavy metals, global organizations have established recommended maximum thresholds of acceptable exposure. These limits are outlined in table 8.

Table 8: WHO/FAO recommended limits for heavy metals in seafood

Heavy Metal	Maximum Limit (mg/kg)	Food Source
Mercury (Hg)	0.5 - 1.0	Fish, shellfish
Cadmium (Cd)	0.1 - 0.5	Mollusks, crustaceans
Lead (Pb)	0.3	Fish, canned seafood
Arsenic (As)	0.1	Drinking water, seafood
Chromium (Cr)	0.05	Various seafood items

Strategies to Reduce Heavy Metal Exposure

- *Dietary Recommendations*

In order to mitigate the risk of exposure to heavy metals, large predatory fish, such as shark and swordfish, should be avoided due to their accumulation of mercury and other toxins. Limiting these seafood species broaden their variety can also reduce the overall exposure risk.

- *Public Health Interventions*

Community campaigns regarding safe consumption practices can greatly lessens health risks by raising awareness and promoting informed choices related to the intake of seafood and water. Proactive monitoring of municipal waters and seafood is integral in preventing and managing heavy metal pollution.

- *Policy and Regulation*

Monitoring compliance with environmental regulations on the discharge of industrial effluents into water bodies is important to reduce the introduction of hazardous heavy metals. Furthermore, public health legislation under international food safety standards needs to take preventive measures to protect the people against heavy metal contamination in food and water supplies.

Future Directions in Heavy Metal Research

Currently, the focus on managing heavy metal contamination is geared towards specific areas. Developing new methods for real-time monitoring of heavy metal pollution, such as designing, constructing, and fabricating highly sensitive biosensors, as well as other molecular techniques, is of utmost importance. Recovering environments contaminated using bioremediation technologies utilizing plants, microorganisms, and algae is a promising avenue. Global pollution trend monitoring and assessing the population health impacts via coordinated international programs also require immediate attention.

Heavy metal contamination of aquatic ecosystems poses a risk to human health from contaminated seafood. Chronic exposure to toxic metals such as mercury, cadmium, lead, arsenic, and chromium can cause devastating neurological, renal, cardiovascular, and dangerous developmental disorders, with pregnant women and children the most vulnerable. Continued progress requires multidisciplinary approaches of tighter environmental regulations, strategic public health legislations, vigilant food safety monitoring, alongside novel remediate technologies and upheld environmental stewardship which together would safeguard the ecological and patient health sustaining aquatic food lifeline.

Regulatory Standards and Risk Assessment for Heavy Metals in Seafood

Seafood is one of the most widely consumed food types because of its high-quality proteins, omega-3 fatty acids, and indispensable minerals. However, the accumulating concentration of heavy metals like: mercury (Hg), cadmium (Cd), lead (Pb), arsenic (As), and chromium (Cr) poses an enormous danger to consumers. In order to protect the health of individuals, there are standards of governance and risk management set globally to control and supervise the concentration of these elements in seafood. In this regard, the current subsections discuss the governance structures, methods of risk assessment, and international policies aimed at lowering the impacts of heavy metals in fish and other aquatic food.

Importance of Regulatory Standards for Heavy Metals

There are multiple reasons why regulatory standards are important. They help improve the overall public health by mitigating extreme toxicity of heavy metals, especially in sensitive populations like pregnant women, toddlers, and infants. There is also protection of food safety by not allowing high-purity grade seafood and water products to be classified otherwise. In addition, the lack of defined proposed standards promotes international trade by improving confidence in product safety and increasing the seafood demand in international markets.

International Guidelines and Regulatory Bodies

Numerous international bodies have created policies aimed at controlling heavy metal pollution in seafood:

- *Codex Alimentarius Commission (CAC)*

Codex Alimentarius, created by WHO and FAO, is the international body responsible for setting standards in food safety, which also includes guidelines on the permissible residue levels of heavy metals in food. Important stipulations are maximum allowable mercury concentrations of 0.5 mg/kg in fish in general and 1.0 mg/kg in predatory fish like tuna and swordfish. For cadmium, the 0.05-0.1 mg/kg range in mollusks and crustaceans is set as acceptable, while 0.3 mg/kg is the limit set for lead in fish and seafood.

- *European Union (EU) Regulations*

The European Commission (EC) has placed stringent restrictions on the limit of heavy metals within seafood under Regulation (EC) No 1881/2006, which specifies limits of food contaminants. Mercury is permitted at the level of 0.5 mg/kg for general fish and 1.0 mg/kg for large predatory fish. For cadmium, 0.05-0.1 mg/kg is allowed in shellfish and crustaceans while lead is capped at 0.3 mg/kg to fishery products.

- *United States Food and Drug Administration (FDA)*

The FDA supervises the enforcement of safety laws pertaining to seafood under the FSMA and follows HACCP principles. the action levels for contaminants is set for mercury at 1.0 ppm (mg/kg) in fish and lead 0.3mg/kg in the seafood.

- *Other National Standards*

Japan, China, and Australia are examples of countries that have set national limits according to local patterns of consumption and risk assessments.

Risk Assessment Framework for Heavy Metals

Risk assessment is evaluating the possible negative impacts on public health posed by food contaminants. This process is often performed in a four step framework.

- *Hazard Identification*

Understanding the effects of heavy metals on health, as well as their domains of concern, is the primary step in dealing with heavy metal contamination. Mercury is a neurotoxin that causes developmental problems while cadmium causes kidney damage and bone demineralization. Lead poisoning causes cognitive dysfunction and cardiovascular disease, whereas arsenic is infamous for its carcinogenic properties and skin lesions. Chromium causes respiratory problems and damages DNA.

- *Hazard Characterization*

Dose-response assessment establishes the type and magnitude of health effects resulting from a given dose of a heavy metal. The benchmark dose (BMD) is used to determine safe levels of exposure, ensuring that no adverse effects will occur based on available epidemiological and toxicological data.

- *Exposure Assessment*

This step concentrates on estimating the probable level of exposure based on food consumption. The estimated daily intake (EDI) is the metric that captures the average amount of a heavy metal consumed from seafood daily, while bioavailability refers to retained metals compared to absorbed ones.

- *Risk Characterization*

This step combines information from all previous steps to evaluate the likelihood of negative health impacts. The Target Hazard Quotient or THQ is frequently utilized for determining non-carcinogenic risks, and the Cancer Risk, or CR model, calculates the risks associated with cancer-causing agents.

Maximum Allowable Limits for Heavy Metals in Seafood

Health risk concerns impose the limitation of maximum allowable limits (MALs), which is intentionally set for specific heavy metals as surveyed. This is encapsulated in table 9.

Table 9: Maximum allowable limits (MALs) for heavy metals in seafood

Heavy Metal	Codex (mg/kg)	EU (mg/kg)	FDA (mg/kg)
Mercury (Hg)	0.5 - 1.0	0.5 - 1.0	1.0
Cadmium (Cd)	0.05 - 0.1	0.05 - 0.1	0.1
Lead (Pb)	0.3	0.3	0.3
Arsenic (As)	0.1	0.1	0.1
Chromium (Cr)	0.05	0.05	0.05

Monitoring and Surveillance Programs

Constant evaluation through monitoring and surveillance to heavy metal load in seafood is a crucial part concerning the regulatory standards effectiveness.

- *Sampling and Testing Methods*

There are various methods for determining heavy metal contamination of seafood. The determination of metal concentration using Atomic Absorption Spectroscopy (AAS) is highly accurate. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) can also detect and measure metals in seafood at very low concentrations. Moreover, the concentration of metals in the samples can be determined by means of quick, non-destructive X-ray Fluorescence (XRF) scanning.

- *Global Monitoring Initiatives*

The GEMS/Food program of WHO works towards monitoring and reporting on food safety issues related to food and its contamination with hazardous substances such as heavy metals. In a similar manner, Rapid Alert System for Food and Feed (RASFF) as a European Union network ensures safety of food and controls pollution of food products with heavy metals and other harmful substances.

Case Studies of Regulatory Failures and Successes

- *Minamata Bay, Japan (1950s)*

An industrial accident contaminated the bay area and caused an outbreak of methylmercury poisoning due to the direct discharge of industrial wastewater into the bay. In retaliation, legislative action was taken which included new policies with limits on emissions of mercury into the environment, and there was an international education campaign about the dangers of heavy metal pollution.

- *Arsenic Contamination in Bangladesh*

The public health challenges posed by one of the world's most devastating incidents of groundwater arsenic contamination affected millions of people. As a response, some control measures were put into place such as the enforcement of the WHO guidelines on safe drinking water and restrictions on the use of water and seafood from the region.

- *Lead Contamination in Flint, Michigan (2014)*

An incident occurred in which the public faced severe health risks due to lead from corroding pipes leaching into the drinking water supply. The result is that the EPA tightened its regulations on the amount of lead allowed in water and initiated programs aimed at educating the public about lead contamination.

Risk Communication and Public Awareness

The appropriate management of risks involves the prompt and continuous interaction of regulators with the seafood industry and the consumers.

- *Public Health Campaigns*

Efforts to raise awareness focus on the consumption of predatory fish, such as shark and swordfish, due to their high mercury content. Additionally, guidance is provided to vulnerable groups, including pregnant women and children, on making safer seafood selections to minimize the risk of heavy metal exposure.

- *Consumer Guidance*

Fish consumption advisories are issued by authorities to restrict the intake of certain seafood, helping safeguard public health. Additionally, labeling requirements mandate clear indications on seafood packaging, informing consumers about the levels of pollution and contamination present in the product.

Challenges in Regulating Heavy Metals in Seafood

Despite stringent standards, several challenges remain in managing heavy metal contamination. The complexity of global trade, with differing regulations across countries, complicates enforcement efforts. Emerging contaminants, which may interact with heavy metals, could amplify toxicity and pose additional risks. Furthermore, climate change and global warming are expected to alter the bioavailability of heavy metals in aquatic organisms and water bodies, further exacerbating the issue.

Future Directions for Heavy Metal Regulation

- *Harmonization of Global Standards*

The attempt to relax some international policies is likely to enhance global trade and food safety.

- *Advanced Monitoring Technologies*

Biosensors are increasingly used to monitor seafood supply chains in real time for the presence of heavy metals, ensuring quick detection and response. Additionally, blockchain technology is being employed to improve the traceability of seafood products, enhancing transparency from the source to the consumer and ensuring safety throughout the supply chain.

- *Integrated Risk Assessment*

Integrating classical toxicology with omics (genomics and proteomics) for holistic risk assessment.

These protective standards and risk assessment processes are necessary to defend public health from heavy metal contamination in seafood. ICES, Codex, EU, as well as FDA, and other regulatory bodies establish safety limits, perform necessary risk assessments, and oversee the quality of seafood available to consumers. These proactive and educational approaches will maximize the protective benefits of new technologies intended to ensure food safety from seafood environmental challenges and emerging changing globe forces. Universal collaborative action is imperative to reinforce food safety frameworks and mitigate health risks arising from consuming seafood laden with heavy metals.

Conclusion and Recommendations

Summary of Key Findings

The contamination of aquatic ecosystems with heavy metals poses a significant threat to the environment and human life. The current article discussed the issue of heavy metals like mercury (Hg), cadmium (Cd), lead (Pb), arsenic (As), and chromium (Cr) which, through bioaccumulation and biomagnification, contaminate aquatic life and subsequently, the human food chain. Eating contaminated seafood is associated with serious health consequences such as neurological disorders, kidney failure, heart disease, stunted development, and cancer. Regulatory frameworks, including those from the Codex Alimentarius, FDA, and EU, help control and monitor heavy metals concentration in seafood violence. Gaps within enforcement, divergent global standard, and emerging environmental concerns require proactive changes to risk assessment and management frameworks.

Strategies

Addressing the risks posed by heavy metal pollution in seafood requires a multifaceted strategy. Marine environment protection policies need to curb industrial discharges. Strictly enforced regulations aimed at minimizing the treatment of wastewater is equally essential. Also, the order of construction and treatment facilities needs to incorporate eco-friendly agricultural components in intersection with watercourses. The monitoring of these systems also has to be more proactive. Informational campaigns aimed educating the public and especially vulnerable groups such as children or expecting mothers about dietary diversity and safe practices that limit exposure. Easy access to comprehensive advice and informative labeling will help empower consumers.

Future Directions

More work is needed to develop real-time tracking technologies, such as biosensors and nanotechnology, for monitoring heavy metals contamination in seafood supply chains. Using plants, algae, and microorganisms to remove toxins from contaminated environments (bioremediation) is promising for reducing heavy metal pollution and offers an environmentally safe solution. In addition, interdisciplinary studies combining toxicology with environmental and public health are critical to address the effects of pollution and the interplay of various toxicants on human health over time. Sustainably managing aquaculture will require the cultivation of species with low bioaccumulation potential, as well as responsible feed management practices which will promote food safety and enhance the health of aquatic ecosystems in a changing climate and surging demand for seafood.

References

Ahamad, M.I., Yao, Z., Ren, L., Zhang, C., Li, T., Lu, H. and Feng, W., 2024. Impact of heavy metals on aquatic life and human health: A case study of River Ravi Pakistan. *Frontiers in Marine Science*, *11*. https://doi.org/10.3389/fmars.2024.1374835

Ahamad, M.I., Yao, Z., Ren, L., Zhang, C., Li, T., Lu, H. and Feng, W., 2024. Impact of heavy metals on aquatic life and human health: A case study of River Ravi Pakistan. *Frontiers in Marine Science*, *11*, p.1374835. https://doi.org/10.3389/fmars.2024.1374835

Akhtar, N., Syakir Ishak, M.I., Bhawani, S.A. and Umar, K., 2021. Various natural and anthropogenic factors responsible for water quality degradation: A review. *Water*, *13*(19). https://doi.org/10.3390/w13192660

Ali, H. and Khan, E., 2019. Trophic transfer, bioaccumulation, and biomagnification of non-essential hazardous heavy metals and metalloids in food chains/webs—Concepts and implications for wildlife and human health. *Human and Ecological Risk Assessment: An International Journal*, *25*(6), pp.1353–1376. https://doi.org/10.1080/10807039.2018.1469398

Ali, H., Khan, E. and Ilahi, I., 2019. Environmental chemistry and ecotoxicology of hazardous heavy metals: Environmental persistence, toxicity, and bioaccumulation. *Journal of Chemistry*, *2019*(1). https://doi.org/10.1155/2019/6730305

Balagopal, M., 2019. Managerial skill for library professionals in the digital library environment. *Indian Journal of Information Sources and Services*, *9*(S1), pp.37–40. https://doi.org/10.51983/ijiss.2019.9.S1.568

Barile, J., Carreño, E. and Los Ríos-Escalante, D., 2024. A review of mollusks farming in Chile. *International Journal of Aquatic Research and Environmental Studies*, 4(1), pp.63–69. https://doi.org/10.70102/IJARES/V4I1/6

Baros, D.K., 2020. Evaluating the efficacy of using computerized shifting information systems (NCSIS) in organizations – Towards effective and computer technology-based administration. *International Journal of Communication and Computer Technologies*, *8*(1), pp.21–24.

Castro-González, M.I. and Méndez-Armenta, M., 2008. Heavy metals: Implications associated with fish consumption. *Environmental Toxicology and Pharmacology*, *26*(3), pp.263–271.

El-Ramady, H., Prokisch, J., Mansour, H., Bayoumi, Y.A., Shalaby, T.A., Veres, S. and Brevik, E.C., 2024. Review of crop response to soil salinity stress: Possible approaches from leaching to nano-management. *Soil Systems*, *8*(1). https://doi.org/10.3390/soilsystems8010011

Estevez, P., Sibat, M., Leão-Martins, J.M., Reis Costa, P., Gago-Martínez, A. and Hess, P., 2020. Liquid chromatography coupled to high-resolution mass spectrometry for the confirmation of Caribbean ciguatoxin-1 as the main toxin responsible for ciguatera poisoning caused by fish from European Atlantic coasts. *Toxins*, *12*(4). https://doi.org/10.3390/toxins12040267

Fortin, N.D., 2023. Global governance of food safety: The role of the FAO, WHO, and Codex Alimentarius in regulatory harmonization. In *Research Handbook on International Food Law*, (pp. 227–242). Edward Elgar Publishing. https://doi.org/10.4337/9781800374676.00024

Franke, C., Studinger, G., Berger, G., Böhling, S., Bruckmann, U., Cohors-Fresenborg, D. and Jöhncke, U., 1994. The assessment of bioaccumulation. *Chemosphere*, *29*(7), pp.1501–1514. https://doi.org/10.1016/0045-6535(94)90281-X

Gray, J.S., 2002. Biomagnification in marine systems: the perspective of an ecologist. *Marine Pollution Bulletin*, *45*(1–12), pp.46–52. https://doi.org/10.1016/S0025-326X(01)00323-X

Kargar, A. and Zadeh, S.A., 2015. Sensitivity analysis of the length joint sets on change shape drilling road tunnels. *International Academic Journal of Science and Engineering*, *2*(2), pp.54–62.

Kumar, A. and Yadav, P., 2024. Experimental investigation on analysis of alkaline treated natural fibers reinforced hybrid composites. *Association Journal of Interdisciplinary Technics in Engineering Mechanics*, *2*(4), pp.25–31.

Kumar, T.M.S., 2024. Integrative approaches in bioinformatics: Enhancing data analysis and interpretation. *Innovative Reviews in Engineering and Science*, *1*(1), pp.30–33. https://doi.org/10.31838/INES/01.01.07

Lawal, S. and Krishnan, R., 2020. Policy review in attribute based access control—A policy machine case study. *Journal of Internet Services and Information Security*, *10*(2), pp.67–81. https://doi.org/10.22667/JISIS.2020.05.31.067

Mehana, E.S.E., Khafaga, A.F., Elblehi, S.S., Abd El-Hack, M.E., Naiel, M.A., Bin-Jumah, M. and Allam, A.A., 2020. Biomonitoring of heavy metal pollution using acanthocephalans parasite in ecosystem: an updated overview. *Animals*, *10*(5). https://doi.org/10.3390/ani10050811

National Park Service, n.d. Tracing mercury through lake food webs. https://www.nps.gov/articles/000/mercury-lake-trout.htm

Rajeshkumar, S. and Li, X., 2018. Bioaccumulation of heavy metals in fish species from the Meiliang Bay, Taihu Lake, China. *Toxicology Reports*, *5*, pp.288–295. https://doi.org/10.1016/j.toxrep.2018.01.007

Sadulla, S., 2024. Optimization of data aggregation techniques in IoT-based wireless sensor networks. *Journal of Wireless Sensor Networks and IoT*, *1*(1), pp.31–36.

Sankhla, M.S., Kumari, M., Nandan, M., Kumar, R. and Agrawal, P., 2016. Heavy metals contamination in water and their hazardous effect on human health – a review. *International Journal of Current Microbiology and Applied Sciences*, *5*(10), pp.759–766.

Singh, A., Sharma, A., Verma, R.K., Chopade, R.L., Pandit, P.P., Nagar, V. and Sankhla, M.S., 2022. Heavy metal contamination of water and their toxic effect on living organisms. In *The Toxicity of Environmental Pollutants*. IntechOpen. https://doi.org/10.5772/intechopen.105075

Suedel, B.C., Boraczek, J.A., Peddicord, R.K., Clifford, P.A. and Dillon, T.M., 1994. Trophic transfer and biomagnification potential of contaminants in aquatic ecosystems. *Reviews of Environmental Contamination and Toxicology*, pp.21–89. https://doi.org/10.1007/978-1-4612-2656-7_2

Usikalu, M.R., Alabi, D. and Ezeh, G.N., 2025. Exploring emerging memory technologies in modern electronics. *Progress in Electronics and Communication Engineering*, 2(2), pp.31–40.

Vaka, T. and Tamata, L., 2024. The effects of salinity on the growth and survival of marine fish larvae. *Aquatic Ecosystems and Environmental Frontiers*, *2*(1), pp.28–32.

Wang, J. and Liu, P., 2022. Pathways of heavy metal bioaccumulation in aquatic organisms: A review. *Environmental Pollution*, *305*.

Wang, L., Ma, L., Wang, J., Zhao, X., Jing, Y., Liu, C. and Xu, M., 2024. Research progress on the removal of contaminants from wastewater by constructed wetland substrate: A review. *Water*, *16*(13). https://doi.org/10.3390/w16131848

World Health Organization (WHO), 2021. *10 chemicals of public health concern*.