

## Assessment of Heavy Metal Pollution in Surface Waters and Bioaccumulation in Fish: Implications for Human Health Risk

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### Abstract

Heavy metal pollution in surface waters, driven by rapid industrialization, urbanization, agricultural runoff, and geogenic weathering, poses a persistent global threat due to the metals' non-biodegradable nature, high toxicity, and tendency to bioaccumulate and biomagnify through aquatic food chains. This comprehensive review examines the geochemical and anthropogenic sources of key metals (Hg, Pb, Cd, Cr, As, Ni, Cu, Zn), the physicochemical factors (pH, temperature, redox, salinity, seston) governing their speciation and bioavailability, and the mechanisms of uptake, tissue-specific distribution, and trophic transfer in fish. Fish serve as critical bioindicators, with highest accumulations typically observed in liver, kidney, and gills (via metallothionein sequestration), while muscle tissue often shows lower levels except for highly lipophilic methylmercury.

Standard metrics Bioconcentration Factor (BCF), Bioaccumulation Factor (BAF), Biomagnification Factor (BMF), and Trophic Magnification Factor (TMF) quantify exposure pathways, revealing pronounced biomagnification of mercury. Human health risk assessment frameworks, including Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), Hazard Index (HI), and Carcinogenic Risk (CR), demonstrate that chronic consumption of contaminated fish can exceed safe thresholds, leading to neurotoxicity, nephrotoxicity, carcinogenicity, and developmental disorders. The review also evaluates conventional and emerging remediation strategies (chemical precipitation, bioremediation, biochar, and nanotechnology such as nZVI) and highlights regional vulnerabilities exacerbated by climate change. Findings underscore the urgent need for integrated monitoring, stricter emission controls, and sustainable remediation to protect aquatic ecosystems and safeguard public health.

**Keywords:** Heavy Metal Pollution, Surface Water Contamination, Bioaccumulation, Biomagnification, Fish Tissues, Human Health Risk Assessment, THQ, EDI, Carcinogenic Risk, Metallothionein, Bioremediation, Nanotechnology, Climate Change Interactions, Aquatic Food Chain

### 1. Introduction

The systemic contamination of aquatic ecosystems by heavy metals represents one of the most significant environmental challenges of the contemporary era, driven by the intersecting trajectories of rapid industrialization, burgeoning urbanization, and intensifying agricultural

practices (Habimana et al., 2024). Heavy metals, typically defined by an atomic density exceeding 4 g/cm<sup>3</sup>, are uniquely hazardous due to their non-biodegradable nature, high toxicity even at trace concentrations, and propensity for bioaccumulation within the food chain (Javed & Usmani, 2016). Unlike organic pollutants, which may undergo microbial degradation or thermal decomposition, heavy metals persist indefinitely in the environment, alternating between dissolved phases in the water column and sequestered states in surface sediments (Saha, 2016). This persistence creates a long-term reservoir of toxicity that can be remobilized by shifts in environmental conditions, such as temperature fluctuations or acidification, thereby posing a continuous threat to aquatic biodiversity and the human populations that depend on these resources for sustenance (Zhang et al., 2023).

## 2. Geochemical Origins and Anthropogenic Drivers of Metal Flux

The introduction of heavy metals into surface waters occurs through a dual pathway of natural geogenic processes and anthropogenic interventions. Natural sources are fundamentally dictated by the local geology and the weathering of the Earth's crust (Rajendiran, 2025). The interaction between water and various rock types, such as limestone, dolomite, shale, and sandstone, facilitates the gradual release of elements like iron, manganese, and calcium into riverine systems (Abarca et al., 2020). Igneous formations, including basalt and granite, further contribute trace elements through geochemical weathering and rock-water interaction (Akhtar et al., 2021). Natural phenomena such as volcanic eruptions, hydrothermal vents, and the atmospheric deposition of marine salts represent significant, albeit often localized, contributors to the background concentrations of metals like mercury, lead, and arsenic in pristine environments (Cas et al., 2024). The acceleration of human activity since the mid-19th century has profoundly altered these natural balances. Evidence suggests that by the mid-1800s, nearly 40% of the rivers and lakes in industrializing nations like Britain had already experienced significant degradation due to human behavior (Colombier et al., 2023). In modern contexts, industrial effluents from the metallurgical, chemical, and electronics sectors represent point sources of intense contamination (Ahmed & Hasan, 2019). Activities such as shipbreaking, gas production, and coal combustion release complex mixtures of chromium, cadmium, lead, and nickel into coastal and inland waters (National Research Council, 2000). Furthermore, agricultural runoff introduces significant quantities of cadmium through the use of phosphate fertilizers and arsenic via metal-based pesticides (Gurganari et al., 2024).

### 2.1. Point and Non-Point Sources of Specific Heavy Metals

The following table delineates the specific origins and transport pathways for the primary heavy metals of environmental concern, highlighting the diversity of industrial and natural contributors

**Table 1. Natural and Anthropogenic Sources and Transport Pathways of Primary Heavy Metals**

Heavy Metal	Natural Sources	Anthropogenic Sources	Environmental Pathway
Mercury (Hg)	Volcanic activity, rock weathering	Coal combustion, waste incineration, gold mining, chemical manufacturing	Atmospheric deposition, direct industrial discharge, runoff
Lead (Pb)	Weathering of sedimentary and igneous rocks	Petrol additives, battery manufacturing, lead-based paints, smelting	Urban runoff, aerosol precipitation, industrial effluent

Cadmium (Cd)	Soil minerals, volcanic eruptions	Phosphate fertilizers, Ni-Cd battery disposal, electroplating, mining	Agricultural runoff, landfill leachate, industrial waste
Chromium (Cr)	Chromite weathering, ultramafic rocks	Tanning industry, metallurgy (steel/alloys), electroplating, pigments	Industrial wastewater, direct discharge
Arsenic (As)	Mineral dissolution, geothermal vents	Pesticides, wood preservatives, fossil fuel combustion, mining	Groundwater infiltration, agricultural runoff, mining waste
Nickel (Ni)	Earth's crust weathering	Corroded metal pipes, stainless steel production, electronic waste	Urban construction, industrial discharge
Copper (Cu)	Hydrothermal vents, rock erosion	Electronic industry, copper piping, algicides, mining	Mining drainage, urban runoff, industrial waste
Zinc (Zn)	Geochemical weathering	Galvanizing, rubber manufacturing, tire wear, mining	Municipal sewage, urban runoff, industrial wastewater

### 3. Physicochemical Dynamics Governing Metal Bioavailability

The environmental impact of heavy metals is not determined solely by their total concentration but by their bioavailability the fraction of the total metal that is available for uptake by living organisms (World Health Organization, 2017). Bioavailability is governed by a complex set of physicochemical parameters, including pH, temperature, salinity, redox potential, and the presence of organic ligands (Stielow et al., 2023).

#### 3.1. The Influence of pH and Speciation

Water pH is perhaps the most critical factor influencing metal speciation and solubility. Under acidic conditions (low pH), the solubility of most heavy metals increases significantly as hydrogen ions compete for binding sites on organic and inorganic particles, leading to the release of free metal ions into the water column (Brezonik et al., 2020). These free ions are generally the most bioavailable and toxic forms of the metal. Conversely, in alkaline environments (high pH), heavy metals tend to form insoluble hydroxides or carbonates and precipitate into the sediments (Pan et al., 2022). While this reduces the immediate concentration in the water column, it builds up a long-term toxic reservoir in the benthos that can be remobilized if the pH subsequently drops (Peana et al., 2021).

#### 3.2. Synergistic Effects of Temperature and Metabolic Rates

Temperature fluctuations, exacerbated by global climate change, play a dual role in metal toxicity. Higher water temperatures increase the kinetic energy of chemical reactions, potentially accelerating the release of metals from sediments by disrupting carbonate and hydroxide bonds (Khatun, 2024). More significantly, temperature increases the metabolic rate of aquatic biota such as fish. Elevated metabolic rates necessitate higher respiration, leading to increased water flow across the gills, which facilitates the rapid uptake of dissolved metals (Kwong, 2024). This synergy between low pH and high temperature creates a "perfect storm" for aquatic toxicity, particularly for elements like aluminum and zinc (Habimana et al., 2024).

#### 3.3. Seston and Sediment-Water Interactions

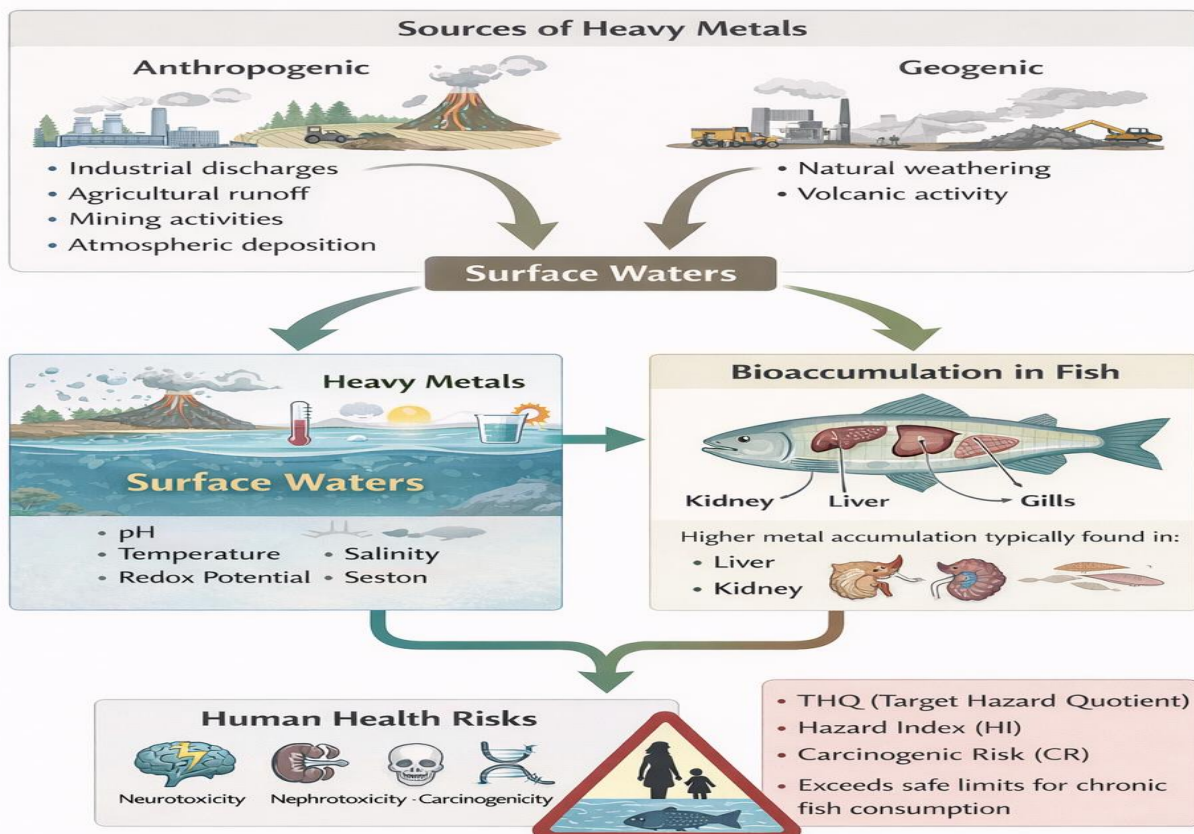
Seston, which includes suspended particles like mineral grains, organic matter, and biological

debris, serves as a vital vector for heavy metal transport in the water column. Heavy metals have a high affinity for these particles, often reaching concentrations in seston that are up to four times higher than those in the surrounding water (Tripathi et al., 2021). This particulate-bound metal can enter the food web when filter-feeders or macroinvertebrates ingest the seston (Mallik et al., 2024). Sediments act the ultimate repository for approximately 85% of heavy metals in global aquatic systems. However, they are not permanent sinks. Changes in redox potential, salinity, or dissolved oxygen (DO) levels can trigger the release of metals back into the overlying water (Rajendiran, 2025). For example, in the Wuliangshuai Lake, research has shown that an increase in salinity and temperature shifts the speciation of zinc in sediments from residual fractions to more mobile organic and sulfide-bound fractions, thereby increasing the risk of secondary pollution (Tian et al., 2020).

#### 4. Bioaccumulation Mechanisms and Trophic Transfer in Fish

Fish are considered excellent bioindicators of heavy metal pollution due to their position in various trophic levels and their ability to integrate metal exposure over time through both water and diet (Oros, 2025). The accumulation of metals in fish tissues is the net result of uptake (bioconcentration and dietary ingestion) minus the rate of elimination through metabolic excretion and growth dilution (Saidon et al., 2024). Heavy metals introduced into aquatic environments undergo complex biogeochemical transformations that influence their mobility and bioavailability within aquatic food webs. Fish integrate metal exposure from both dissolved phases in water and contaminated dietary sources, making them important indicators of environmental pollution and potential vectors of human exposure. The conceptual pathway of heavy metal transfer from environmental sources to aquatic organisms and ultimately to human consumers is illustrated in Figure 1.

**Figure 1.** Pathways and Human Health Risks of Heavy Metals in



#### 4.1. Pathways of Uptake and Elimination

Fish absorb heavy metals through three primary pathways: the gills, the skin, and the gastrointestinal tract (Malik et al., 2017). Respiratory uptake via the gills is particularly efficient for dissolved free metal ions, while dietary uptake is the dominant pathway for organometallic compounds like methylmercury and for metals associated with sediment particles or prey (Panigrahi et al., 2021). Once absorbed, metals are transported via the blood to various organs where they can bind to cellular proteins or be sequestered in specialized organelles (Toxics Review Authors, 2025).

#### 4.2. Quantifying Bioaccumulation and Biomagnification

To standardize the assessment of metal enrichment, researchers use several mathematical ratios. These metrics provide insight into whether a metal is simply being concentrated from the water or is being magnified as it moves through the food web (Selvaggi et al., 2020).

**Table 2. Standard Mathematical Metrics for Quantifying Bio-uptake and Trophic Transfer**

Metric	Calculation Formula	Ecological Interpretation
Bioconcentration Factor (BCF)	$BCF = C(\text{fish}) / C(\text{water})$	Assesses metal uptake specifically from the dissolved phase in water.
Bioaccumulation Factor (BAF)	$BAF = C(\text{fish}) / C(\text{environment})$	Assesses total uptake from water, diet, and sediment exposure.
Biomagnification Factor (BMF)	$BMF = BAF(\text{predator}) / BAF(\text{prey})$	A $BMF > 1$ indicates that metal concentrations increase up the food chain.
Trophic Magnification Factor (TMF)	$\log(C) = a + b(\text{TP})$	The slope 'b' indicates the rate of biomagnification per trophic level (TP).

Methylmercury is the quintessential example of a biomagnifying contaminant. Due to its high lipid solubility and strong affinity for muscle proteins, it is absorbed with nearly 95% efficiency from the gastrointestinal tract and is eliminated very slowly, leading to massive enrichment in apex predators like shark, swordfish, and tuna (Ogwu et al., 2025). In contrast, metals like lead and cadmium bioaccumulate significantly within individual organisms but often show lower rates of biomagnification because they are frequently sequestered in non-edible tissues like bone or kidney (McIntyre & Beauchamp, 2007).

### 5. Tissue-Specific Distribution and Metabolic Sequestration

The distribution of heavy metals within a fish's body is rarely uniform. It is governed by the metal's chemical affinity, the organ's metabolic activity, and the presence of detoxification mechanisms (Javed & Usmani, 2016). Generally, the highest concentrations are found in the liver, kidney, and gills, while the muscle tissue often exhibits lower levels for many metals (Ahmed & Hasan, 2019).

#### 5.1. The Liver and Gills: Primary Accumulation Sites

The liver serves as the primary metabolic hub for detoxification. Many fish species produce metallothioneins low-molecular-weight, cysteine-rich proteins that bind and sequester heavy metal ions, thereby protecting vital cellular components from damage (Kumar, 2025). This sequestration leads to high concentrations of metals like copper, zinc, and cadmium in hepatic tissues (Singh & Sharma, 2024). The gills, being in constant contact with the external environment and having a large surface area, often show elevated levels of metals like iron, lead, and zinc, particularly in the initial stages of exposure (Shah et al., 2020).

## 5.2. Muscle Tissue and Human Exposure

Muscle tissue typically accumulates metals to a lesser extent than metabolic organs. For example, a study of freshwater fish in Quetta, Pakistan, found that while iron levels in the liver and gills exceeded World Health Organization (WHO) limits, the concentrations in the muscle tissue remained within safe levels for human consumption (Ali et al., 2021). However, this trend is reversed for mercury. Because methylmercury binds to the sulfhydryl groups of muscle proteins, it concentrates in the edible flesh, making it the most significant metal-related risk for fish consumers (Saleem et al., 2022).

## 5.3. Comparative Tissue Concentrations in Cyprinid Species

The following data highlights the tissue-specific accumulation patterns observed in common freshwater fish species, emphasizing the disparity between metabolic organs and edible muscle (Scharnweber et al., 2021).

**Table 3. Tissue-Specific Heavy Metal Concentrations (ppm) in Selected Cyprinid Species**

Species	Tissue	Iron (Fe) ppm	Zinc (Zn) ppm	Manganese (Mn) ppm	Cadmium (Cd) ppm
<i>O. mosambicus</i>	Liver	2.156	0.635	0.067	0.022
	Muscle	0.065	0.408	0.064	0.018
<i>C. carpio</i>	Gills	0.572	10.920	0.140	0.077
	Muscle	0.052	0.262	0.052	0.026
<i>T. putitora</i>	Liver	1.252	0.971	0.126	0.037
	Muscle	ND	0.214	0.090	0.040
<i>L. rohita</i>	Liver	1.900	2.600	0.180	0.035
	Muscle	0.045	0.770	0.050	0.020

## 6. Toxicological Mechanisms of Heavy Metals in Human Systems

When humans consume contaminated fish, heavy metals interfere with a wide range of biological processes. Most exert their toxicity through the generation of reactive oxygen species (ROS), which leads to oxidative stress, DNA damage, and the inactivation of critical enzymes (Jayakumar et al., 2021). Furthermore, many metals act as molecular mimics, displacing essential ions like calcium, zinc, and iron from their binding sites (Permyakov, 2021).

### 6.1. Neurotoxicity and Developmental Impacts

Mercury and lead are particularly notorious for their neurotoxic effects. Methylmercury (MeHg) has a strong affinity for sulfhydryl (-SH) groups, allowing it to bind to neuronal proteins and disrupt neurotransmission (Zahed et al., 2024). It also impairs mitochondrial function, reducing ATP synthesis and triggering apoptosis in brain cells. The developing brains of fetuses and children are especially vulnerable; exposure during these critical periods can lead to permanent cognitive deficits, as seen in the historical Minamata tragedy (Basu, 2023). Lead (Pb) interferes with calcium-dependent signaling and disrupts the blood-brain barrier, contributing to disorders like encephalopathy (Wu et al., 2024).

### 6.2. Nephrotoxicity and Skeletal Disorders

Cadmium (Cd) is a potent nephrotoxin that primarily accumulates in the proximal tubules of the kidney, leading to proteinuria and eventual renal failure. Because cadmium is excreted very slowly, its concentration in the body increases with age (Marini et al., 2023). Chronic exposure is also

linked to skeletal damage, notably Itai-itai disease, where cadmium displaces calcium in the bones, leading to severe demineralization and osteoporosis (Satarug et al., 2020).

### 6.3. Cardiovascular and Carcinogenic Risks

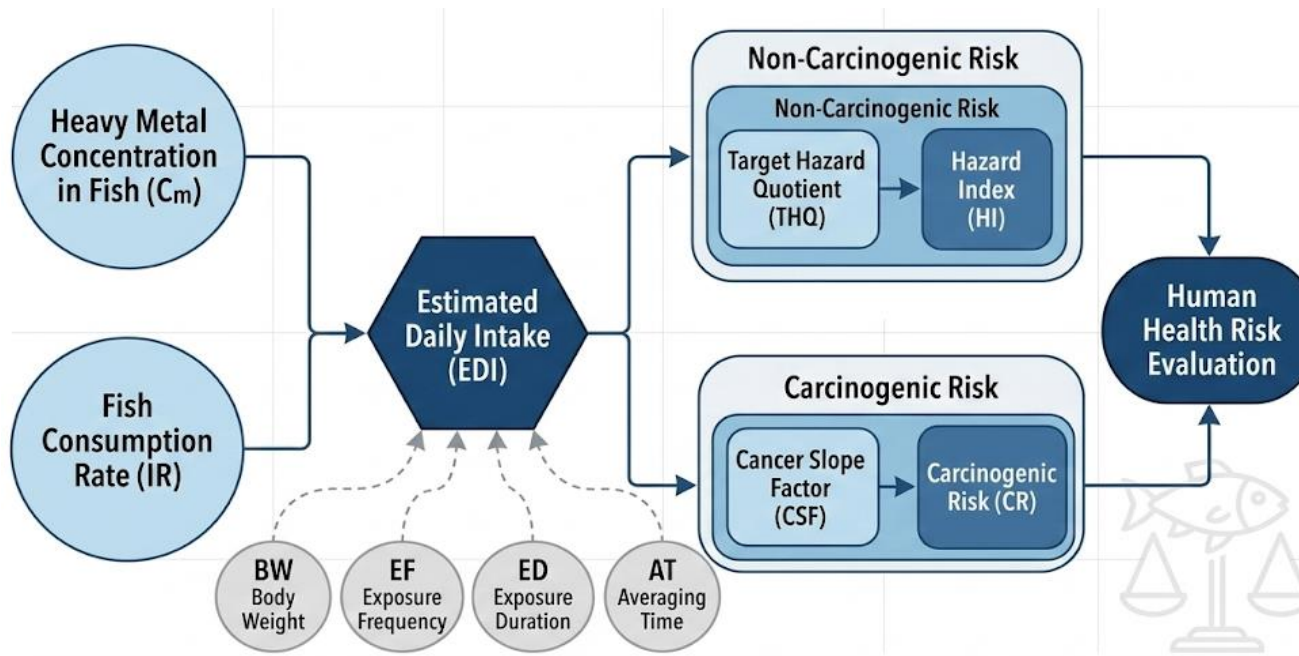
Arsenic (As) and Chromium (Cr) are major drivers of carcinogenic risk. Inorganic arsenic interferes with DNA repair mechanisms and cell signaling, increasing the risk of skin, lung, and bladder cancers (Ozturk et al., 2022). Hexavalent chromium (Cr VI) is highly mobile and can enter cells through sulfate transporters, generating free radicals that cause genomic instability (Liu, 2025). Furthermore, lead and cadmium have been linked to hypertension by inducing endothelial dysfunction and oxidative stress (Nail et al., 2023).

**Table 4. Primary Target Organs and Health Consequences of Major Heavy Metal Exposure**

<b>Metal</b>	<b>Primary Target Organ</b>	<b>Key Toxic Mechanism</b>	<b>Major Health Consequence</b>
Mercury (Hg)	Brain (CNS), Kidneys	Binding to thiol groups, mitochondrial inhibition	Minamata disease, tremors, cognitive delay
Lead (Pb)	Brain, Blood, Bones	Mimicking Ca <sup>2+</sup> and Zn <sup>2+</sup> , enzyme inhibition	Anemia, ADHD, cardiovascular disease
Cadmium (Cd)	Kidneys, Bones	Oxidative stress, DNA methylation, Ca displacement	Itai-itai disease, renal failure, cancer
Arsenic (As)	Skin, Lungs, Liver	DNA repair inhibition, signaling disruption	Skin lesions, peripheral neuropathy, cancer
Chromium (Cr)	Lungs, Kidneys, Skin	Intracellular reduction (Cr <sup>6+</sup> to Cr <sup>3+</sup> ), ROS	Respiratory disorders, ulcers, cancer

### 7. Quantitative Human Health Risk Assessment Framework

To determine the level of risk posed by consuming contaminated fish, a standardized framework is utilized by international agencies. This process involves calculating daily exposure and comparing it to established safety thresholds (Paustenbach et al., 2024). Human health risk assessment models integrate contaminant concentrations in edible fish tissues with exposure parameters such as ingestion rate and body weight to estimate potential toxicological impacts. The overall framework used to evaluate non-carcinogenic and carcinogenic risks associated with heavy metal consumption through fish is summarized in Figure 2.



**Figure 2.** Conceptual framework for human health risk assessment associated with the consumption of heavy metal-contaminated fish, illustrating the calculation pathway from estimated daily intake (EDI) to non-carcinogenic risk indicators (THQ and HI) and carcinogenic risk (CR).

### 7.1. Estimated Daily Intake (EDI)

The Estimated Daily Intake (EDI) is the primary metric for quantify exposure. It accounts for the metal concentration in the fish, the amount consumed, and the individual's body weight (Ayanniyi et al., 2024).

$$EDI = (C_m \times IR \times EF \times ED) / (BW \times AT)$$

In this equation, C<sub>m</sub> represents the metal concentration in fish muscle (mg/kg), IR is the daily ingestion rate (kg/day), EF is the exposure frequency (365 days/year), ED is the exposure duration (e.g., 70 years for a lifetime), BW is average body weight, and AT is the averaging time (Malik et al., 2017).

### 7.2. Non-Carcinogenic Risk: Target Hazard Quotient (THQ)

The non-carcinogenic risk is evaluated using the Target Hazard Quotient (THQ), which is the ratio of the EDI to the oral Reference Dose (RfD). The RfD is the maximum daily dose of a metal that is considered safe for humans over a lifetime (World Health Organization, 2017).

$$THQ = EDI / RfD$$

A THQ < 1 implies that the exposure level is below the safety threshold, while a THQ ≥ 1 indicates a potential for non-carcinogenic health risks. When multiple metals are present, their THQ values are summed to calculate the Hazard Index (HI) (Hoo Fung et al., 2017).

### 7.3. Carcinogenic Risk (CR)

The probability of developing cancer over a lifetime is assessed using the Carcinogenic Risk (CR) metric. This is calculated by multiplying the EDI by the Cancer Slope Factor (CSF), which represents the risk of cancer per unit dose (Samaila et al., 2021).

$$CR = EDI \times CSF$$

Regulatory agencies generally consider a CR value between 10<sup>-6</sup> and 10<sup>-4</sup> as the acceptable range. Values exceeding 10<sup>-4</sup> are deemed unsatisfactory (Meseret et al., 2020).

#### 7.4. Reference Doses and Regulatory Thresholds

The following table provides the oral Reference Doses (RfD) and Cancer Slope Factors (CSF) established for major heavy metals.

**Table 5. Summary of Oral Reference Doses, Cancer Slope Factors, and Regulatory Limits**

Heavy Metal	Oral RfD (mg/kg/day)	Cancer Slope Factor (CSF) (mg/kg/day-1)	WHO Drinking Water Limit (mg/L)
Mercury (Hg)	0.0003	-	0.001
Lead (Pb)	0.0040	0.0085	0.010
Cadmium (Cd)	0.0010	6.3000	0.003
Arsenic (As)	0.0003	1.5000	0.010
Chromium (Cr)	0.0030	-	0.050
Nickel (Ni)	0.0200	1.7000	0.070
Copper (Cu)	0.0400	-	2.000
Zinc (Zn)	0.3000	-	3.000

#### 8. Advanced Remediation and Sustainable Mitigation Strategies

Environmental management must focus on both reducing source emissions and active remediation. Traditional techniques, while effective for bulk removal, often fall short of meeting increasingly stringent quality standards (Khatun, 2024).

##### 8.1. Conventional Physicochemical Methods

Methods such as chemical precipitation, ion exchange, and reverse osmosis are frequently used. However, these methods can be energy-intensive and often produce high volumes of toxic sludge (Zhang et al., 2023). Physical adsorption using materials like activated carbon is common but limited by low adsorption capacities (Zhang et al., 2023).

##### 8.2. Bioremediation and Eco-Friendly Approaches

Bioremediation offers a cost-effective alternative by utilizing living organisms. This includes biosorption, bioaccumulation, and phytoremediation. Certain bacterial strains have demonstrated impressive removal efficiency for lead. Biochar, produced from agricultural waste, has emerged as a powerful adsorbent for water remediation (Saha, 2016).

##### 8.3. Nanotechnology: The Cutting Edge

Nanomaterials represent a significant leap in efficiency. Nanoparticles possess an extremely high surface-area-to-volume ratio. Nanoscale zerovalent iron (nZVI) has shown an adsorption capacity for lead of 1667 mg/g. Other modern tools include chitosan-functionalized magnetic nanoparticles and biogenic nanostructures (Rajendiran, 2025).

**Table 6. Performance Characteristics and Advantages of Conventional and Modern Remediation Techniques**

Remediation Technique	Targeted Metal(s)	Reported Efficiency / Capacity	Advantage
nZVI Nanoparticles	Pb(II)	1667 mg/g	Extreme adsorption capacity

<i>Bacillus subtilis</i> (Bioremediation)	Cr(VI)	95.19% removal	Eco-friendly, sustainable
Chitosan-Magnetic NPs	Pb(II)	498.6 mg/g	Ease of recovery, high capacity
Activated Carbon	General metals	Variable	Established technology
Biochar	Cd, Pb, Cu	High	Cost-effective, waste repurposing

## 9. Global Perspectives and Regional Vulnerabilities

Heavy metal pollution is a global crisis, but its impact varies significantly depending on regional industrialization and climate (Habimana et al., 2024).

### 9.1. Arid and Semi-Arid Regions

In regions such as Balochistan, Pakistan, water scarcity intensifies the pollution problem. Rivers often receive untreated sewage, leading to high concentrations of metals in limited water volumes. Studies in the Siwa Oasis highlighted carcinogenic risks from cadmium and lead, exacerbated by high evaporation rates (Gurganari et al., 2024).

### 9.2. Tropical and Subtropical Coastal Lagoons

Coastal ecosystems like the Tampamachoco Lagoon are influenced by hydrometeorological variability. Rainy seasons trigger the transport of metals from industrial zones to lagoons, where they associate with seston. In these regions, cadmium concentrations have been found to exceed safe thresholds during peak rainy periods (Scharnweber et al., 2021).

### 9.3. Industrialized River Basins

In developing areas like the Indo-Gangetic plain, industrial activities combined with agricultural runoff have degraded river quality. The Satluj River has been reported to contain high concentrations of lead and chromium, ultimately affecting downstream consumers (Ahmed & Hasan, 2019).

## 10. Synthesis of Findings and Future Research Directions

Assessment reveals a persistent and multi-dimensional threat. The transition of toxic elements to biological tissues is dynamic, mediated by changing environmental conditions and amplified by biomagnification. While muscle tissue in many fish remains within current safety limits, high concentrations in metabolic organs signal a deepening crisis (Panigrahi et al., 2021).

### 10.1. Emerging Trends in Environmental Monitoring

There is a shift toward using smart water sensors and real-time data platforms for continuous measurements. Furthermore, the focus is expanding to metal speciation, which provides a more accurate prediction of toxicological risk (ASHRAE, 2025)

### 10.2. Future Research Gaps

1. **Multi-Metal Synergies:** Most assessments focus on individual metals; understanding synergistic interactions is essential (Basu, 2023).
2. **Climate Change Interaction:** As oceans warm, more research is needed to predict how climate change will remobilize heavy metal reservoirs (Shah et al., 2020).

3. **Molecular Mechanisms:** Underlying molecular pathways of bioremediation require further elucidation (Singh & Sharma, 2024).
4. **Vulnerable Population Subgroups:** Detailed assessments are needed for high-risk groups, including infants and communities with fish-dependent diets (Toxics Review Authors, 2025).

## Conclusion

Heavy metal contamination of surface waters and subsequent bioaccumulation in fish constitute a complex, multi-scale environmental and public health crisis that transcends national boundaries and persists across generations. The non-biodegradable character of these metals, coupled with their efficient uptake via gills and diet, efficient sequestration in metabolically active organs, and pronounced biomagnification (especially of methylmercury), creates a direct pathway of chronic human exposure through fish consumption the primary route for many populations. Quantitative risk assessments consistently show that while muscle tissue may remain within permissible limits for some metals, cumulative exposure through multi-metal mixtures frequently elevates THQ and CR values above safe thresholds, increasing risks of irreversible neurological, renal, skeletal, and carcinogenic effects, particularly in vulnerable groups such as children, pregnant women, and high-fish-consuming communities.

Climate-driven changes in pH, temperature, and redox conditions further threaten to remobilize long-buried sedimentary reservoirs, amplifying future risks. Effective mitigation therefore requires a paradigm shift from reactive end-of-pipe treatments to proactive, source-oriented strategies: stringent regulation of industrial and agricultural discharges, adoption of precision farming to minimize fertilizer-derived cadmium and arsenic, implementation of real-time water-quality monitoring with metal-speciation sensors, and widespread deployment of cost-effective, eco-friendly remediation technologies such as biochar-amended bioremediation and engineered nanoparticles.

Ultimately, safeguarding aquatic ecosystems and human health demands integrated, interdisciplinary action combining advanced geochemical modeling, molecular toxicology, sustainable remediation engineering, and community-based monitoring to break the cycle of contamination, bioaccumulation, and exposure. Only through such holistic efforts can we ensure the long-term safety of global fisheries and protect the foundational role of freshwater and marine resources in food security and human well-being.

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