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Environmental and Public Health Impacts of Heavy Metal Contamination in Coastal and Freshwater Edible Species

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Abstract

Heavy metal contamination in aquatic environments has become a critical global concern, posing significant risks to both ecosystem and human health. This study examines the environmental and public health impacts of heavy metal pollution in coastal and freshwater edible species. It explores the major sources of contamination including industrial discharge, agricultural runoff, mining activities, and atmospheric deposition and how these pollutants bioaccumulate through aquatic food webs. The research highlights key metals of concern such as mercury (Hg), cadmium (Cd), lead (Pb), arsenic (As), and chromium (Cr), which are frequently detected at concentrations exceeding international safety limits. Their persistence and toxicity contribute to biodiversity loss, ecosystem imbalance, and adverse human health outcomes including neurotoxicity, renal dysfunction, and carcinogenic effects. It also reviews existing regulatory frameworks and emphasizes the need for more stringent control measures, improved waste management, and public awareness campaigns. Overall, this paper explains the urgent necessity of integrating environmental management and food safety policies to safeguard both aquatic life and human populations dependent on these resources for nutrition and livelihood.

Keywords: Heavy metals, coastal ecosystems, freshwater species, bioaccumulation, food safety, public health, environmental pollution, mercury, cadmium, lead, risk assessment, aquatic contamination.

1.0 Introduction

Water is an essential requirement for all life forms on Earth. Clean water is vital for maintaining health, since contaminated water can jeopardize public health through direct or indirect exposure to hazardous chemicals [1]. Environmental contamination has been intensified by the industrial revolution and human activities [2]. Substantial pollutant emissions into the water have caused considerable threats to coastal ecosystems [3]. Heavy metals (HMs) are very detrimental environmental pollutants due to their chronic toxicity, non-biodegradability, and propensity for bioaccumulation [4]. Heavy metals can be transmitted and biomagnified across food systems, posing significant risks to human health [5, 6]. There is a significant demand for effective monitoring and surveillance of heavy metal concentrations in the marine environment [7]. Concerns over the concentration of heavy metals (HMs), along with their impacts, distribution, and environmental origins, are currently being raised at local, regional, and national levels [8].

The bioaccumulation patterns of heavy metals, including mercury (Hg), arsenic (As), nickel (Ni), cobalt (Co), copper (Cu), cadmium (Cd), and chromium (Cr), significantly impact the lifespan of most organisms [9]. Heavy metals from various distribution sources adversely affect marine biota [10]. These heavy metals affect beneficial creatures, including fish and various invertebrates [10]. Heavy metals from the ambient water and food sources accumulate in marine organisms [11]. In specific instances, elevated concentrations of heavy metals in marine ecosystems are directly associated with environmental pollution. Numerous research investigations indicate that the levels of heavy metal bioaccumulation varied significantly among marine species. The disparities in heavy metal accumulation among aquatic creatures may be attributed to their distinct habitats, dietary habits, and trophic levels [12, 13].

This review aims to elucidate the distribution of heavy metal sources in aquatic ecosystems and addresses heavy metal contamination in marine food constituents such as fish. Moreover, the impact of these components on the environment and human health is comprehensively examined to elucidate the physiological and molecular mechanisms associated with the utilization of metallic poisons in aquatic food sources. These management measures are closely associated with human population safety by preventing or reducing the passage of heavy metal contaminants from the aquatic environment to the food chain.

2.0 Sources and Pathways of Heavy Metal Contamination

Cadmium (Cd), zinc (Zn), mercury (Hg), arsenic (As), silver (Ag), chromium (Cr), copper (Cu), iron (Fe), and platinum (Pt) are all heavy metals (HMs) [14]. They are elements with a higher density and atomic mass that can harm people and the environment. One of the worst things that may happen to the ecosystem is heavy metal pollution in water, which affects plants, animals, and people [15, 16]. Heavy metals are dangerous even in small amounts because they don't break down in the environment [17, 18]. There are three classes of metals and metalloid ions. The first group has metals including mercury, cadmium, and lead that are dangerous even at low levels. The second group of metals is less harmful (bismuth, indium, arsenic, thallium), and the third group includes important metals like zinc, cobalt, copper, iron, and selenium, which are only harmful at high levels [19]. Heavy metals build up in the earth, human and animal tissues because they are absorbed or, in some cases, breathed in, or because of accidents or bad handling [20].

The primary contributors to increased environmental toxicity due to heavy metals are human and manmade influences. Natural sources of heavy metals (HMs) are things like soil that has blown in by the wind, forest fires, volcanic eruptions, biogenic processes, and marine salt. Mining, pesticides, fertilizers, and herbicides are all human-made sources of HMs contamination. Irrigating crop fields with industrial and sewage water is also a source of HMs contamination (Fig. 1). Trace amounts of heavy metals in fertilizers are a major source of heavy metal contamination in our food. Inappropriate industrial waste management, traffic pollution, use of lead (Pb) as fuel antiknock, aerosol cans, metallurgy and smelting, discharge of sewage and construction materials are the anthropogenic practices responsible for HMs contamination [17-20].

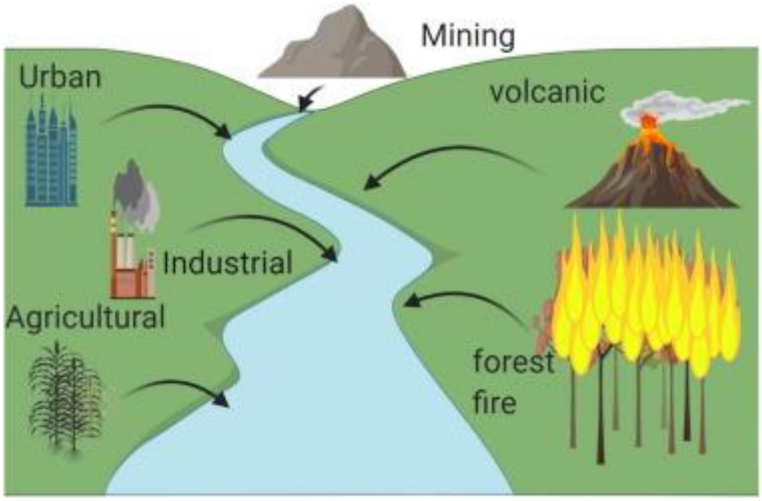

Figure 1: Source of HMs

The pharmaceutical production, paper and pulp preservatives, agricultural, chlorine and caustic soda sectors all let mercury (Hg) into the air [21]. Cadmium is present in soils and rocks, including coal and mineral fertilizer. Cadmium (Cd) is commonly utilized in electroplating for several purposes, including batteries, pigments, textiles, and metal coatings [22]. All of these actions are to blame for the higher levels of HMs pollution in the environment.

3.0 Heavy Metals of Concerns

Heavy metal pollution is becoming as a worldwide concern. Heavy metals can infiltrate fish via three pathways: the gills, the integumentary surface, and the gastrointestinal system [23]. Fish juveniles and larvae exhibit rapid growth, with their body length and mass directly correlated to appropriate temperature and adequate food availability [24]. Conversely, fish development is impeded by contaminated diet rich in heavy metals. A conspicuous indicator of metal toxicity in fish is growth suppression. Consequently, heavy metal concentrations in tissues induce a range of metabolic, physiological, and histological alterations in fish and other freshwater species by modifying different enzymes and metabolites [25].

The feeding process varies among fish species due to factors such as developmental influences, psychological issues, and lifetime. Heavy metals accumulate in the tissues of fish inhabiting contaminated environments [26, 27]. Metal intensity, expression duration, metal absorption, environmental variables (temperature, pH, hardness, and salinity), and intrinsic agents, such as fish age and feeding activities are all factors in the selection of body organs for HMs deposition. Metals predominantly concentrate in the kidneys, gills, and liver [28, 29]. Zinc accumulates in fish gills, obstructing the oxygen flow to tissues and resulting in hypoxia, ultimately causing mortality [30]. Nonetheless, a decrease in water pH may result in the mobilization and release of heavy metals into the water column, jeopardizing marine animals, including crustaceans and insects [31]. These poisonous sediments exterminate benthic species and diminish food availability for the larger organism.

At moderate levels, heavy metals present in the environment and food are essential for good health; nevertheless, excessive quantities can be detrimental or hazardous [32]. Their toxicity can diminish energy and impact the brain, lungs, kidneys, liver, blood, and other essential organs. Prolonged exposure ultimately leads to degenerative physical, tissue, and neurological processes that mimic diseases such as Alzheimer's, Parkinson's, muscular dystrophy, and multiple sclerosis [33, 34, 35]. Acute lead (Pb) exposure can induce appetite loss, headaches, hypertension, stomach discomfort, renal dysfunction, fatigue, insomnia, arthritis, hallucinations, and vertigo. Mercury toxicity results in acrodynia or pink disease [36]. Increased mercury exposure may impact cerebral structure and induce shyness, tremors, cognitive decline, irritability, and visual or auditory impairments [37]. Inhalation of elevated levels of metallic mercury vapors for a brief duration may lead to pulmonary injury, emesis, diarrhea, nausea, dermal eruptions, and hypertension [38]. Organic mercury toxicity signs and symptoms include depression, memory problems, tremors, fatigue, headache, and hair loss. Because these signs and symptoms are frequently associated with other diseases, circumstances may be difficult to recognize [39, 40].

4.0 Contamination in Coastal and Freshwater Edible Species

The evaluation of bioaccumulation is a critical indicator for monitoring the geochemical cycle of heavy metals within aquatic ecosystems. The toxicological effects and oxidation states of heavy metals differ according to their specific forms and kinds. Chromium (Cr) typically occurs in six oxidative states (+1 to +6), with hexavalent Cr causing detrimental consequences in fish [41]. Fish in aquatic systems contaminated with heavy metals present a significant risk, as they accumulate metals in several critical bodily tissues (gills, liver, kidneys, skin, muscle, etc.), as depicted in Figure 2. Fish necessitate increased energy, derived from stored foods such as proteins, lipids, and carbs, to adapt to this stressful condition. Certain metals (As, Cd, Cr, Cu, Fe, Hg, Ni, Pb, Zn) possess redox potential and react to generate reactive oxygen species (ROS), which are crucial for sustaining specific physiological functions in fish. Reactive oxygen species (ROS) serve as a marker of oxidative stress, which impedes cellular function by destroying proteins, lipids, and DNA. Heavy metals bioaccumulate in various aquatic creatures via the food chain, leading to significant human health concerns upon the eating of contaminated fish [42, 43, 44, 45, 46].

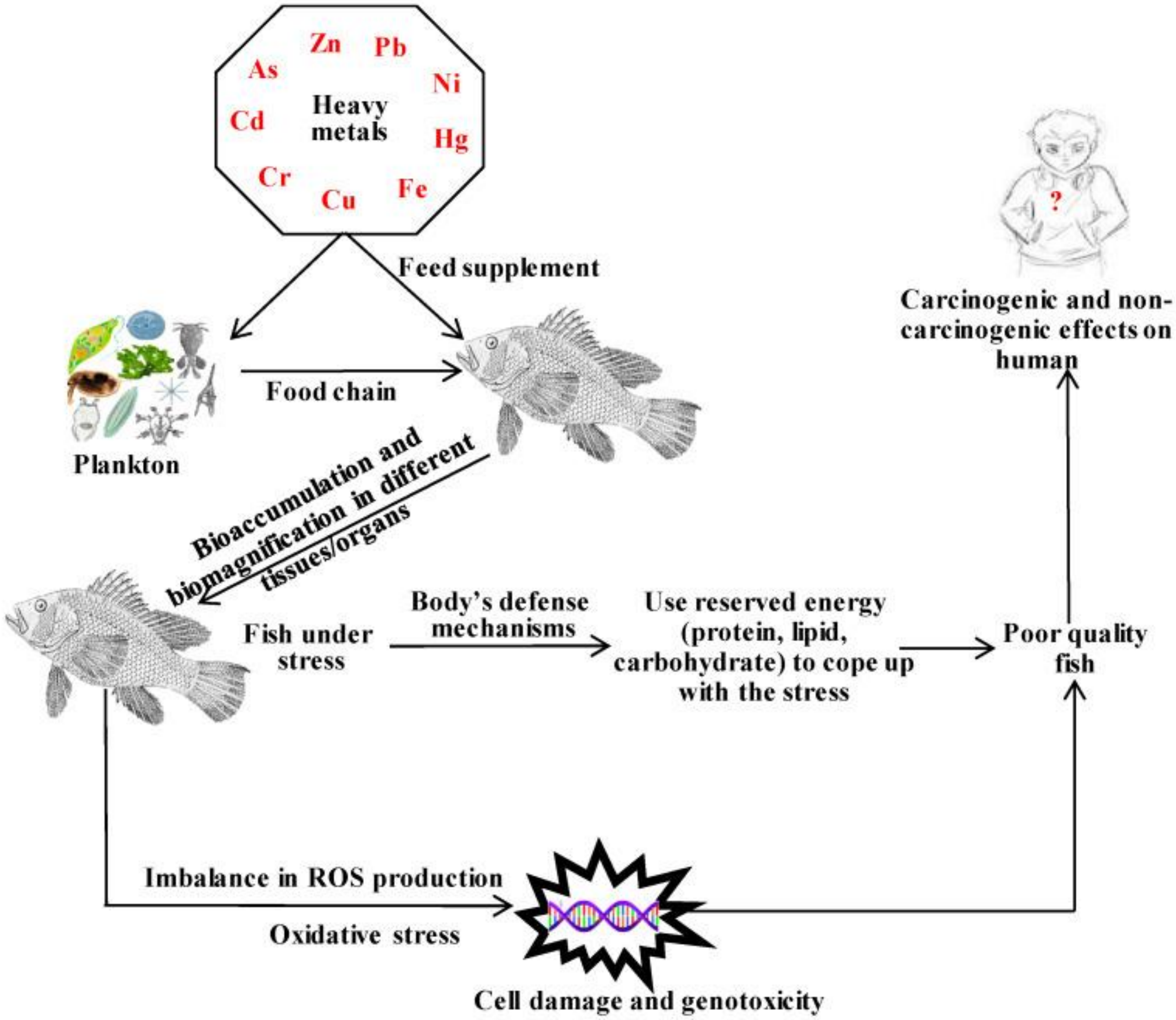

Figure 2: Mechanism of the contaminations of Heavy metals

Arsenic is one of the most hazardous heavy metals that contaminates aquatic ecosystems through numerous natural and anthropogenic activities [47]. Inorganic arsenic has been observed to be more hazardous than organic forms [48, 49]. Accumulation occurs in several organs of fish at disparate rates [50, 51]. The maximum concentration of As (10.04 ± 2.99 µg/g) was detected in the liver, while the minimum (3.74 ± 3.38 µg/g) was found in muscle after 20 days of exposure in Oreochromis niloticus [52]. Numerous studies have indicated that arsenic exposure adversely affects fish, resulting in diminished growth and productivity, alterations in hemato-biochemical parameters, hormonal dysregulation, histopathological abnormalities, delays in embryonic and larval development, and other disorders [53, 54, 55, 56, 57].

Furthermore, toxicity substantially impacted the hematological and immunological parameters of various fish species [58, 59, 60, 61]. An elevated dosage of arsenic led to increased mucus secretion, atypical swimming behavior, and impaired equilibrium in Anabas testudineus and Danio rerio [62, 63]. Induced various cytotoxic and genotoxic effects in medaka, Oryzias latipes [64]. Furthermore, pollution impaired the reproductive functions of fish by hindering gametogenesis, thereby diminishing the quality and quantity of sperm and ova, as well as reducing fertilization and hatching success [65, 66, 67].

Cadmium is very poisonous and carcinogenic to humans and several animals, including fish. The Agency for Toxic Substances and Disease Registry of the United States identifies this metal as the eighth most dangerous substance. Numerous studies indicate that the aquatic environment is markedly polluted with cadmium (Cd) [68, 69, 70]. The assimilation and bioaccumulation of this hazardous metal have been seen in various aquatic organisms. Cadmium toxicity has caused dysfunction in various vital organs of fish, including the liver, kidneys, and gills, thereby impacting their physiology and inhibiting growth. Furthermore, Cd modifies hematological parameters by disrupting iron metabolism and inducing anemic conditions [71, 72]. Cadmium inhibits antioxidant enzymes, leading to lipid peroxidation in animals [73, 74]. Furthermore, cadmium exposure adversely impacts the reproductive efficacy of fish by reducing sperm lobule size, inducing testicular fibrosis, and diminishing sperm motility and viability [75, 76, 77].

Chromium is a pervasive metal that degrades environmental quality, originating from several industrial sources [78, 79]. Numerous investigations have documented the bioaccumulation of chromium in many organs of Cyprinus carpio [80, 81], and Carassius auratus [82], O. aureus [83]. Chromium poisoning disrupts the physiological activities of fish, leading to several inflammatory reactions and organ system failures [84, 85, 86, 87]. Furthermore, chromium toxicity markedly modifies the protein, lipid, and glycogen levels in the muscle, liver, and gills of Labeo rohita and C. mrigala, induces hepatic stress in C. auratus, disrupts the functions of vital organs (liver, kidney) in Ctenopharyngodon idella, and leads to dysfunctions of the endocrine system in various freshwater fish species. Chromium was observed to modify the blood profile, leading to cellular and nuclear anomalies in Pangasianodon hypophthalmus [87]. Numerous investigations indicated that elevated chromium levels in fish diets markedly reduced the development and feed efficiency of various fish species [88]. Furthermore, prolonged exposure to chromium led to reproductive complications in fish, including reduced spawning success [89, 90], and impaired oocyte development [91].

Copper is a substantial pollutant in aquatic systems that induces stress in aquatic species and markedly impedes the growth and physiology of fish [92, 93, 94]. Numerous studies indicate that the liver is the primary organ that accumulates a substantial amount of copper relative to other organs [95, 96, 97]. Excess copper in the fish diet diminished appetite, hence adversely impacting feed consumption and development in fish [98]. Furthermore, Cu poisoning led to malformations in reproductive organs and significantly decreased the GSI, fecundity, fertilization, and hatching rates of various fish species [99].

Manganese is frequently seen in diverse contexts. Manganese was discovered to leach into aquatic environments via multiple human activities [100]. Various factors, such as fish species, age, and water quality, can influence Mn toxicity in fish [101]. Mn toxicity diminishes when water hardness increases [100]. The bioaccumulation of manganese in the liver, gills, and muscles of Argyrosomus japonicus disrupted glucose metabolism and modified the ionic composition of blood plasma [102]. Manganese influences fish physiology and can occasionally produce severe and lethal outcomes. Manganese exposure induces oxidative stress in Carassius auratus [103]. Manganese (Mn) contributes to numerous neurogenetic disorders by promoting the generation of free radicals and the inactivation of certain enzymes linked to antioxidant capacity [104]. Moreover, manganese adversely affects the liver and promotes cellular death in grouper [105].

Nichrome is widely utilized in several industrial processes and is regarded as a principal pollutant of aquatic ecosystems. In aquatic ecosystems, nickel (Ni) interacts with many chemical components to create soluble salts that can adsorb onto other molecules, resulting in multiple synergistic and antagonistic effects [106]. The severity of nickel toxicity is contingent upon several elements, including nickel content, water quality, and the physiological condition of organisms [107]. Numerous investigations demonstrated that nickel accumulated in various organs of fish, particularly in the gills, leading to complications in respiratory processes [108, 109, 110, 111, 112]. Furthermore, Ni was observed to accumulate in the intestinal tract of fish, impairing its function [113, 114]. Nickel disrupts normal physiology and results in the mortality of certain freshwater fish species [115]. Nickel pollution causes various histological alterations in the gills of Orechromis niloticus, including hyperplasia, hypertrophy, and fusion of gill lamellae [116]. Moreover, Ni toxicity disrupts ion control [117, 118, 119] and provokes oxidative stress in fish [120, 121, 122, 123, 124]. Two investigations found no substantial effects on fish growth [125, 126]; however, they demonstrated significant affects on the growth of pulmonate snails [127] and zebrafish [128].

Lead is a very toxic metal that bioaccumulates in aquatic species via water and food sources [129]. Lead is bioaccumulated in various fish organs, including the liver, kidneys, gills, spleen, and digestive system [130, 131, 132, 133, 134, 135, 136]. Lead substantially alters the hematological parameters of fish [137, 138, 139, 140, 141]. Furthermore, Pb toxicity leads to a marked modification in enzyme activity within the blood plasma and liver of fish, resulting in various diseases in the cell membrane and damaging liver cells. Lead adversely impacts fish growth and feed efficiency by diminishing weight gain, specific growth rate, and feed consumption [142, 143, 144, 145]. Furthermore, lead (Pb) adversely affects reproductive performance, resulting in subpar sperm and ovum quality, diminished fertilization and hatching rates, and decreased survival of embryos and larvae.

Zn is a crucial micronutrient that significantly influences the growth and reproduction of fish; nevertheless, excessive Zn levels can have detrimental effects on fish. Zn pollution in aquatic habitats is well-documented [146, 147]. The liver and renal tissues are the primary locations for zinc bioaccumulation [148]. Zn poisoning adversely impacts the growth [149, 150, 151], homeostasis [152], feed consumption [153, 154, 155], and osseous development of fish [156]. Zinc poisoning prompts ammonia excretion, leading to deteriorated water quality and stressful environments for fish. Furthermore, zinc poisoning adversely affects the hepatic tissue of fish by elevating the activities of alanine aminotransferase (ALT) and aspartate aminotransferase (AST) [157, 158, 159]. Furthermore, elevated Zn concentrations markedly diminish the protein and fat content in fish, potentially leading to the oxidation of these macromolecules and inadequate protein consumption [160, 161].

The bioaccumulation of heavy metals in freshwater fish has significant ecological, environmental, and social ramifications. When metals are present at elevated concentrations in the environment, species acquire greater quantities. Inducing biomagnification of metals within the trophic web, adversely affecting aquatic ecology, which depends on these metals in multiple direct and indirect manners [162, 163].

5.0 Public Health Implications

Heavy metals are transferred through the food chain via many pathways, primarily originating from anthropogenic and natural sources [164]. Plants are crucial to this transfer process as they employ specific transport mechanisms to absorb heavy metals from the soil. Plants that accumulate heavy metals may undergo alterations in physiological and biochemical processes that impair their growth and development. Additionally, plants cultivated in soil contaminated with heavy metals may have nutrient deficiencies as a result of the adverse effects of heavy metals on plant nutrition. Due to the potential for heavy metals to bioaccumulate in food sources, this contamination presents significant health hazards [165].

Conversely, HM can be transported via air, water, or diverse species to numerous nearby sites, including rivers, ponds, lakes, and oceans. Aquatic creatures, especially fish, that bioaccumulate toxins subsequently expose other animals, including humans, through the food chain. A 2023 investigation in the Gulf of Guinea indicated the concentrations of heavy metals (HMs) in Penaeus notialis and D. angolensis, namely Cu: 12.08 ± 1.46 µg/g, Zn: 19.20 ± 2.27 µg/g, As: 8.46 ± 2.42 µg/g, Cd: 0.03 ± 0.01 µg/g, and Hg: 0.14 ± 0.03 µg/g in D. angolensis [166]. Mercury was found in significant concentrations in D. angolensis [166]. The cancer risk associated with the ingestion of P. notialis surpassed the 10^{-6} threshold for all age demographics, according to publications [166].

While fish serves as a superior source of nutrients, environmental factors affect its nutritional value. Small quantities of metals pose a greater worry due to their potential for bioaccumulation and non-biodegradability [167]. Heavy metal toxicity, which can damage vital organs including the brain, central nervous system (CNS), and blood, may arise from the consumption of fish sourced from contaminated aquatic habitats [167-169]. Prolonged exposure can also induce neurological, muscular, and physical disorders such as Parkinson's disease, Alzheimer's disease, and multiple sclerosis in people [170-172]. A multitude of individuals experience allergies and extended exposure to certain metals that may lead to cancer [173, 174]. Toxicity from chemically significant heavy metals can result in disease, diminished quality of life, and ultimately death [175]. Due to their persistence, non-biodegradability, and capacity to accumulate in organs and tissues over time, heavy metals constitute a continual and non-biodegradable issue.

Heavy metals and metalloids are common environmental pollutants present in both aquatic and terrestrial environments [176, 177]. Their toxicity, bioaccumulation potential, and persistence all affect their level of hazard. The heavy metals and metalloids (Cr, Ni, Cu, Zn, Cd, Pb, Hg, and As) present the most significant hazards. The trophic transmission of these components in food chains significantly affects animal and population health. The concentrations of toxic heavy metals and metalloids in diverse environmental elements and local biota must be assessed and monitored. It is imperative to address hazardous heavy metals and metalloids that might cause significant harm to humans prior to their use, to alleviate their detrimental effects on human health and the environment.

6.0 Mitigation Strategies and Policy Recommendations

Bioremediation is an effective and environmentally benign method for restoring polluted ecosystems by eliminating harmful metals. Bioremediation of toxicants can be achieved through adsorption [178, 179, 180], physio-biochemical mechanisms [181, 182, 183, 184], and molecular mechanisms [185, 186, 187]. Various enzymes (superoxide dismutase, SOD; catalase, CAT; glutathione S transferase, GST) and nonenzymatic substances (reduced glutathione, GSH) are pivotal in maintaining the balance of reactive oxygen species (ROS) through detoxification. SOD may convert superoxide radicals into hydrogen peroxide, which is then transformed into non-toxic oxygen and water by CAT enzymes [188]. Conversely, GST neutralizes toxicants by catalyzing electrophiles to glutathione (GSH). Furthermore, GSH undergoes nonenzymatic oxidation to form glutathione disulfide when interacting with electrophilic molecules, such as free radicals and reactive oxygen species (ROS).

Phytoremediation is a widely utilized bioremediation method that employs diverse plants and microorganisms to mitigate pollution in aquatic ecosystems. Microbial enzymes are crucial in transforming harmful pollutants into benign substances by modifying their chemical structure. Certain Lactobacillus species effectively remediate heavy metals by acidifying the environment and by biosorption or by establishing connections between heavy metals and their cellular components. Microorganisms exhibit resistance to heavy metals through several processes, including extracellular sequestration, internal sequestration, reduction of heavy metal ions by the microbial cell, and the formation of extracellular barriers.

A diverse array of microorganisms, including bacteria, fungus, and algae species, have been employed to detoxify heavy metals and maintain environmental cleanliness. Alongside natural microbes, many genetically modified microorganisms, particularly those with surface engineering, have been produced for the remediation of certain heavy metals [189]. Numerous studies indicate that genetically modified microorganisms possess superior capabilities compared to wild microbes in the removal of organic substances, including heavy metals, within natural environmental systems [190, 191].

Various engineering techniques, such as single-gene editing, metabolic pathway modification, and gene sequence alteration (both coding and regulatory), are effectively utilized to alter the genetic composition of microorganisms, thereby converting them into engineered microorganisms that more efficiently eliminate several heavy metals, including Ni, Hg, Cd, Fe, As, and Cu. The utilization of modern engineering methodologies (genomics, metagenomics, proteomics, metabolomics, and transcriptomics) has resulted in genetically engineered bacteria that are essential for the bioremediation of various heavy metals [192].

The utilization of genetically modified Pseudomonas putida and Escherichia coli strain M109 has effectively eliminated Hg from polluted locations [193]. The introduction of mer genes into Deinococcus geothemalis and Cupriavidus metallidurans strain MSR33 [194] has demonstrated effective mercury reduction. Furthermore, transporters in microbial membranes substantially enhance the bioremediation of heavy metals from the environment. Research has demonstrated that dietary Lactobacillus plantarum mitigates aluminum (Al) toxicity in tilapia [195]. Furthermore, dietary probiotics have been shown to mitigate the adverse effects of cadmium on the growth and hematological parameters of Oreochromis niloticus [196]. EDTA markedly diminished the body cadmium concentration, hence enhancing the blood profile of Clarias gariepinus [197].

Therefore, mitigating the environmental and public health impacts of heavy metal contamination in coastal and freshwater edible species requires a multifaceted and collaborative approach that integrates scientific monitoring, regulatory enforcement, and community participation. The first critical step involves strengthening environmental monitoring and surveillance systems. Regular assessment of water, sediment, and aquatic species using advanced analytical tools such as ICP-MS and AAS can help detect contamination trends and identify pollution hotspots early. Establishing a centralized database for heavy metal monitoring would enable policymakers, researchers, and environmental agencies to track exposure levels and evaluate intervention outcomes more effectively.

Also, controlling pollution at the source is essential to prevent heavy metals from entering aquatic ecosystems. Governments should enforce strict regulations on industrial effluents, mining operations, and agricultural runoff, requiring industries to adopt cleaner production technologies and implement waste treatment before discharge. It is important to encourage the use of environmentally friendly alternatives to metal-based fertilizers and pesticides can also minimize diffuse pollution. In coastal regions, integrating pollution control into watershed management and urban planning will further reduce contamination from multiple sources.

From a policy standpoint, updating and harmonizing environmental and food safety standards with international guidelines such as those established by the WHO, FAO, and EPA—is necessary to ensure consistent protection levels. Policies should mandate routine inspection of seafood and freshwater fish sold in markets, with clear labeling of contamination risk levels to inform consumers. Public health authorities must develop and communicate consumption advisories, particularly for vulnerable populations such as children, pregnant women, and communities that rely heavily on fish as a dietary staple. Lastly, community education and stakeholder engagement play a vital role in sustaining long-term mitigation. Raising awareness about the sources and health effects of heavy metal contamination can empower local populations to advocate for cleaner environments and adopt safer fishing and consumption habits. Partnerships among governments, academia, NGOs, and the private sector should be fostered to support research, capacity building, and technology transfer. Through coordinated policy actions, scientific innovation, and public involvement, it is possible to significantly reduce heavy metal exposure and protect both aquatic ecosystems and human health.

Conclusion

Heavy metal contamination in coastal and freshwater ecosystems presents a serious threat to environmental sustainability, food security, and public health. The persistence and bioaccumulative nature of metals such as mercury, cadmium, lead, arsenic, and chromium enable them to infiltrate aquatic food webs, ultimately reaching humans through the consumption of contaminated fish and other edible species. The resulting health risks ranging from neurological and renal damage to developmental disorders and cancer explain the urgency of addressing this global issue through science-based interventions and robust policy actions. The findings of this study highlight that mitigating heavy metal pollution requires a holistic approach that connects environmental management with public health protection. Strengthening pollution control at industrial and agricultural sources, enforcing strict regulatory standards, and enhancing environmental monitoring are essential to reducing contamination levels. Equally important are ecosystem restoration initiatives and sustainable aquaculture practices that minimize bioaccumulation and ensure the long-term health of aquatic habitats. Ultimately, safeguarding human and ecological well-being demands collective responsibility among governments, researchers, industries, and communities to ensure cleaner water systems and safer food sources. By integrating scientific evidence into policy and promoting public awareness, societies can build resilient frameworks that not only reduce heavy metal exposure but also protect future generations from its enduring consequences.

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