Impact of Heavy Metals Toxicity in Fishes: A Review

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Abstract: Heavy metals, which include lead (Pb), mercury (Hg), cadmium (Cd), chromium (Cr), arsenic (As), nickel (Ni)and zinc (Zn), serve as persistent environmental pollutants that pose significant risks to aquatic ecosystems and human health. This review article provides a comprehensive analysis of the toxicological effects of heavy metals on fish, underscoring the pathways of exposure, biological implications, and methodologies for mitigating toxicity. We examine the sources of heavy metal contamination, such as industrial discharges, agricultural runoff, domestic sewage, and mining activities, which contribute to the accumulation of these deleterious substances in aquatic environments. The review clarifies the processes through which heavy metals penetrate fish tissues and the resulting physiological and biochemical alterations, including bioaccumulation, toxicity, oxidative stress, growth inhibition, and behavioral changes. The manuscript details various analytical methodologies employed to detect and quantify heavy metals in fish tissues, while also addressing the difficulties associated with monitoring and assessing contamination levels. Moreover, we evaluate the ecological consequences of heavy metal accumulation in fish populations and the potential risks posed to human health through the consumption of contaminated fish products. The review further considers recent innovations in bioremediation techniques, such as the use of microbial and phytoremediation systems, aimed at alleviating heavy metal pollution in aquatic environments. By synthesizing existing research findings and identifying areas where knowledge is lacking, this review seeks to provide a valuable resource for researchers, policymakers, and environmental advocates. It underscores the necessity for continuous monitoring, more rigorous regulatory frameworks, and novel remediation strategies to address the on-going challenge of heavy metal toxicity in fish, thereby safeguarding both aquatic ecosystems and public health.

Keywords: Aquatic, Environments, Heavy metals, Industrial, Oxidative stress, Toxicity.

Introduction: Heavy metal pollution in aquatic environments is a pressing environmental issue with significant implications for both ecosystem health and human safety (**M. Sarkar, J.B. Islam, S. Akter,** ***2016***) [1]. Metals such as lead (Pb), mercury (Hg), cadmium (Cd), and arsenic (As) are of particular concern due to their persistence in the environment, bioaccumulative properties, and toxic effects on living organisms (**M. Mahmuda** ***et.al***; ***2020***) [2]. These metals often originate from various anthropogenic sources, including industrial activities, agricultural runoff, mining operations, and improper waste disposal. Fishes, as key components of aquatic ecosystems, are especially vulnerable to heavy metal contamination (**L.I. Ezemonye** ***et.al;*** **2019**) [3]. Their exposure occurs through the uptake of contaminated water and sediment, as well as through the consumption of polluted prey (**M. Sarkar** ***et.al; 2021***) [4]. Once inside fish tissues, heavy metals can cause a range of detrimental effects, including oxidative stress, enzyme inhibition, and disruption of metabolic processes, these toxic effects can impair growth, reproduction, and overall health, ultimately affecting fish populations and biodiversity(**Shahjahan, et.al;** ***2021***)[5]. Research has demonstrated that heavy metal exposure can lead to significant physiological and biochemical alterations in fish, such as oxidative damage, alterations in enzyme activity, and changes in reproductive success for instance, mercury is known to bioaccumulation in fish, leading to neurological and developmental disorders, similarly cadmium has been linked to renal damage and disruption of calcium homeostasis (**M. Shahjahan** ***et.al; 2019***)[6].Moreover, the transfer of heavy metals through aquatic food webs poses a risk to human health, particularly through the consumption of contaminated fish. Studies have shown that heavy metal contamination in fish can exceed safety thresholds set by regulatory bodies, raising concerns about public health (**A.S. Abdel-Baki** ***et.al; 2011***) [7]. Given these concerns, it is crucial to understand the mechanisms of heavy metal toxicity, the extent of contamination, and effective mitigation strategies (**C. Fernandes et.al;*****2008***) [8]. This review aims to synthesize current research on heavy metal toxicity in fish, providing insights into sources of contamination, biological impacts, and potential solutions for managing and reducing pollution(**M.F. Rohani et.al;** ***2021***) [9]. Heavy metals can disrupt essential physiological processes in fish, including respiratory and digestive functions, chronic exposure may lead to organ damage, reduced growth rates, and impaired reproductive success, heavy metal exposure can alter fish behavior, including feeding patterns, predator-prey interactions, and migration, which can have cascading effects on the aquatic ecosystem (**S. Akter** ***et.al; 2021***) [10]. The health of fish populations is crucial for maintaining ecosystem balance, heavy metal toxicity can lead to declines in fish populations, affecting species diversity and the stability of aquatic ecosystems (**R.F. Wang** ***et.al; 2020***) [11]. Heavy metal contamination in aquatic environments has emerged as a significant environmental and public health concern. Metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) are commonly found in industrial discharges, agricultural runoff, and urban wastewater(**S. Saffari et.al; ,*2018***) [12]. These pollutants can have detrimental effects on aquatic ecosystems, particularly on fish, which are integral components of aquatic food webs and are crucial for the ecological balance and human consumption (**Z.-X. Song *et.al; 2017***) [13].

Their multiple industrial, domestic, agricultural, medical, and technological applications have led to their wide distribution in the environment, raising concerns over their potential effects on human health and the environment. Their toxicity depends on several factors including the dose, route of exposure, and chemical species, as well as the age, gender, genetics, and nutritional status of exposed individuals. Because of their high degree of toxicity, arsenic, cadmium, chromium, lead, and mercury rank among the priority metals that are of public health significance.(**Tchounwou *et.al*;*2012***) [14].

The concentrations of Hg, Pb, Cd, Zn and As in various fish tissues (muscle, gill and liver) of (Abramisbramadanubii, Alburnusalburnusalburnus, Barbusmeridionalispetenyi, Carassiusaurati usgibelio, Cyprinuscarpio, Lepomisgibossus, Leucisciuscephaluscephalus, Percafluviatilisfluvi atilis, Rutilusrutilus, Scardinuserythrophtlalmuserythrophtlalmus) collected in the Šalek lakes, is the first survey regarding metal concentrations in fish species with samples originating from Slovene lakes, while only a limited number of such studies have been carried out in south-eastern Europe. Since these lakes are situated in the close vicinity of the largest Slovene thermal power plant, the study provides an insight into the potential impact of increased levels of metals in the environment as well as an estimate of the contamination of fish tissues with metals. (**Al SayeghPetkovšek, S., MazejGrudnik, Z. &Pokorny, B, *2012***) [15].

The concentrations of cadmium (Cd), lead (Pb), copper (Cu), manganese (Mn), nickel (Ni) and zinc (Zn) were determined in the muscles of Merlucciushubbsi, Micropogoniasfurnieri, Pangasius hypothalamus, Oreochromisniloticus, Sparusaurata and Mugilcephalus. The levels of heavy metals were measured by atomic absorption spectrophotometry after digestion of the samples using kjldahl heating digester. There were great variations among heavy metal levels in the muscles of the six fish species. M. cephalus accumulated the highest levels of Cu, Mn and Ni, while the highest levels of Zn, Cd and Pb were detected in M. furnieri. (**Kamal J. Elnabris *et.al; 2013***) [16].

All these sources of pollution affect the physicochemical characteristics of the water, sediments and biological components, thus negatively affecting the quality and quantity of fish stocks. Environmental pollution is a worldwide problem; heavy metals constitute one of the most important pollutant challenges. The progress of industry has led to increased emission of pollutants into ecosystem. Environmental pollution can cause poisoning, diseases and even death to fish. The absorption and accumulation of different pollutants vary among different biological systems. (**Moustafa M. Zeitoun and El-Sayed E. Mehana, *2014***) [17].

Atomic Absorption Spectroscopy and ICP-OES. It was found that certain species of fish contained lower levels of all metals tested. *J. elongatus* and *C. dussumieri* had the highest levels of all 8 metals tested. The heavy metal concentrations were significantly varied within and between the studied fishes ($p < 0.05$). However, a significant correlation among heavy metals was observed. This investigation indicated that various levels of heavy metals exist in the fish species sampled, but those concentrations are within the maximum residual levels recommended by the European Union and FAO/WHO.(**A. Velusamy *et.al; 2014***) [18].

Heavy metals have been associated with many fish deformities in natural populations and in laboratory produced specimens as well. Deformities in general have devastating effects on fish populations since they affect the survival, the growth rates, the welfare and their external image. Although the embryonic stage in respect to heavy metal exposure has been extensively studied, there is not much information available as to what happens in fish larvae and adults. In the present article, we present the available information on the effect of heavy metals on fish larvae deformities. We also address the need for more research towards the effects of metals on the subsequent life stages in order to assess the long-term consequences of heavy metal poisoning on fish organisms and possibly correlate these consequences with the environmental contamination (use as biomarkers). (**D.G. Sfakianakis *et.al; 2015***) [19].

The water of the dam and the liver of the fish were analyzed for zinc (Zn), cadmium (Cd), lead (Pb) and iron (Fe) concentrations and their bioaccumulation factors. At the same time, the gills, liver and kidney of the exposed fish were also examined for histopathological alterations. The results revealed that concentrations of the metals differs significantly ($p < 0.05$) between the dam's water and the liver of the sampled fish. Liver bioaccumulations of the metals were in the order of Zn > Fe > Cd > Pb. However, the degree of tissue alterations in the gills showed their normal functioning despite the observed alterations while liver and kidney were mildly and moderately damaged, respectively. This indicated that Zn, Cd, Pb and Fe polluted the dam. (**Abalaka, S.E., *2015***) [20].

All heavy metals, in spite some of them are essential micronutrients, have their toxic effects on living organisms via metabolic interference and mutagenesis. The bioaccumulation of toxic metals can occur in the body and food chain. So, the toxic metals generally exhibit chronic toxicity. The heavy metals like Pb and Hg have significant toxic effects. The heavy metals are important pollutants for fishes, because these are not eliminated from aquatic systems by natural methods, such as organic pollutants, and are enriched in mineral organic substances. Occurrence of heavy metals differs in fishes, depending on their age, development and other physiological factors. (**Pandey, Govind*and* Madhuri, .S, *2016***) [21

Contamination of heavy metals in sediment is regarded as a global crisis with a large share in industrializing cities like Sfax (Tunisia). Seven heavy metals such as Cadmium (Cd), Copper (Cu), Iron (Fe), Mercury (Hg), Nickel (Ni), Lead (Pb), and Zinc (Zn), and one metalloid such as Arsenic (As) in sediments and fish (*D. annularis*, *L. aurata*, and *S. vulgaris*) were investigated from the Southern coast of Sfax in Tunisia. The range of metals in sediments were 13.11–36; 4.42–7.92; 8.23–28.56; 50,564–11,956; 2.9–6.8; 9.13–30.51; 65.06–151.50, and 47–546 kg^{-1} DW for As, Cd, Cu, Fe, Hg, Ni, Pb, and Zn. The level of studied metals in sediment samples exceeded the limits of the quality assessment guidelines (SQGs). The potential ecological risk index (PERI) proved that the investigated region could pose moderate risk for the aquatic biota. Metal bioaccumulation in the fish muscles varied significantly among species. Indeed, *S. vulgaris* and *D. annularis* accumulated higher amount of metal than *L. aurata*.(**Zohra, B.S., Habib, A. ,*2016***) [22].

The fundamental pathways of presentation incorporate ingestion, inward breath, and dermal contact. The seriousness of unfavorable wellbeing impacts is identified with the sort of overwhelming metal and its synthetic shape, and is too time-and measurements subordinate. Among numerous different variables, speciation assumes a key part in metal toxicokinetics and toxicodynamics, and is very affected by variables, for example, valence state, particle size, dissolvability, biotransformation, and chemical form. (Singh, Rajendra, Singh, Amrita and Yadav, Hirdesh Kumar, 2017) [23].

The concentrations of heavy metals significantly varied within and between the investigated fish species ($P < 0.05$). The results of this study showed best significant correlations among the toxic heavy metals in the fish samples. It was revealed that Cd, Pb, Cu, and Zn metals were present in the fish samples at various levels. The residual levels of toxic heavy metals were less than the permissible levels specified for human consumption by the European Union, Food and Agriculture Organization and World Health Organization guidelines. Therefore, the fish species found in the Thondi fish landing and their fishery products can be considered safe for human consumption and can be exported worldwide.(**AbimannanArulkumar, SadayanParamasivam, RajendranRajaram ,*2017***) [24].

The causes of neurodegenerative diseases are complex with likely contributions from genetic susceptibility and environmental exposures over an organism's lifetime. In this review, we examine the role that aquatic models, especially zebrafish, have played in the elucidation of mechanisms of heavy metal toxicity and nervous system function over the last decade. Focus is applied to cadmium, lead, and mercury as significant contributors to central nervous system morbidity, and the application of numerous transgenic zebrafish expressing fluorescent reporters in specific neuronal populations or brain regions enabling high-resolution neurodevelopmental and neurotoxicology research. (**Adrian J. Green, Antonio Planchart, *2018***) [25].

The concentrations of Zn were significantly higher in gills of roach and gonads of perch ($P \leq .05$), while the liver of fish accumulated significantly more Cu than other organs ($P \leq .05$). In all organs of perch the higher content of mercury was found ($P \leq .05$). The value of Zn and Cu was highest in organs of roach ($P \leq .05$) (with the exception of Zn in muscles $P > .05$). Sequence of metals in both species was Zn > Cu > Hg. Only in muscle tissue, Hg was significantly positive correlated with weight of roach ($r = 0.811$, $P = .045$) and perch ($r = 0.652$, $P = .041$), and total length of roach ($r = 0.806$, $P = .005$). A positive relationship was also observed between Zn concentration in gills of perch and their weight ($r = 0.634$, $P = .049$). In contrary, Zn in gills of roach decreased with weight ($r = -0.693$, $P = .026$)) and length ($r = -0.668$, $P = .035$). Cu concentration in liver of perch was statistically positively correlated with HSI ($r = 0.717$, $P = .020$), whereas Hg content in muscle tissue of roach with FCF ($r = 0.643$, $P = .045$). There was negative relationship between Hg in perch gonads and GSI ($r = -0.808$, $P = .005$). Metal pollution index (MPI) in gills, liver, gonads and muscles of roach was 7.68, 7.24, 6.77 and 3.13, respectively, whereas in these organs of perch was 3.25 (gills), 4.75 (liver), 5.84 (gonads) and 4.44 (muscles), therefore the contamination of each tissue ranged from very low contamination to low contamination. (**Joanna Łuczyńska, BeataPaszczyk, Marek J. Łuczyński ,*2018***) [26].

All heavy metals, in spite some of them are essential micronutrients, have their toxic effects on living organisms via metabolic interference and mutagenesis. The bioaccumulation of toxic metals can happen in the body and food chain. So, the toxic metals generally exhibit chronic toxicity. The heavy metals like Pb has significant toxic effects-The heavy metals are important pollutants for fishes, because these are not eliminated from aquatic systems by natural methods, such as organic pollutants, and are enriched in mineral organic substances.

happen of heavy metals differs in fishes, depending on their age, development and other physiological factors. (**Huseen, Hadeel M. and Mohammed, Ahmed J., *2019***) [27].

The heavy metals mainly include Pb, Hg, Cd, Cr, Cu, Zn, Mn, Ni, Ag, etc. The heavy metals Pb,Cu,Zn are considered most toxic to humans, fishes and environment. highly concentrations of heavy metals are harmful They destabilize ecosystems because of their bioaccumulation in organisms, and toxic effects on biota and even death in most living beings. All heavy metals, in spite some of them are essential micronutrients, have their toxic effects on living organisms via metabolic interference and mutagenesis. The bioaccumulation of toxic metals can happen in the body and food chain. So, the toxic metals generally exhibit chronic toxicity. The heavy metals like Pb has significant toxic effects-The heavy metals are important pollutants for fishes, because these are not eliminated from aquatic systems by natural methods, such as organic pollutants, and are enriched in mineral organic substances. happen of heavy metals differs in fishes, depending on their age, development and other physiological factors.(**Huseen, H. M., & Mohammed, A. J. ,*2019*, September**) [28].

Fish is a rich source of nutrients, however, its nutritional value may be affected by the environment in which it exists. The threat of toxic and trace metals in the environment is more serious than those of other pollutants due to their non-biodegradable nature. This is coupled with their bio-accumulative and biomagnification potentials. Within the aquatic habitat fish cannot escape from the detrimental effects of these pollutants. Heavy metal toxicity as a result of fish consumption can result in damage or reduced mental and central nervous system function, lower energy levels, and damage to blood composition, lungs, kidneys, bones, liver and other vital organs. Long term exposure may result in slowly progressing physical, muscular, and Alzheimer's disease, Parkinson's disease, muscular dystrophy, and multiple sclerosis. Allergies are not uncommon and repeated long term contact with some metals or their compounds may even cause cancer. Heavy metal toxicity is a chemically significant condition when it does occur. (**Isangedighi, I. A., & David, G. S., *2019***) [29].

Due to the development of urbanization and industrialization, the problem of heavy metal pollution has become a serious environmental problem. Heavy metals not only have major impacts on aquatic organisms, but also seriously threaten human health. However, the current environmental criteria refer to the maximum value limitations of environmental factors in environmental media where harmful or detrimental effects are not produced on specific protected objects. This study reviewed the sources, hazard levels, toxic effect mechanisms, and the current research status of China's water quality criteria for heavy metal pollutants. (**Ya-jun Hong, Wei Liao *et.al;* 2020)** [30].

Heavy metals are metals with relatively high density and toxic at very low concentrations. The common heavy metal pollutants can be traced everywhere in minimal quantities. Heavy metals contaminate aquatic environments through various sources like industrial waste, domestic effluents, atmospheric sources, and other metal-based industries, E-Waste. Aquaculture is the rearing of aquatic animals and other organisms. Heavy metal toxicity is responsible for the degradation of the population of aquaculture, causing physical deformities in organisms and polluting the aquatic environment. These toxic heavy metals cause various diseases in fishes. As fishes are part of human consumption, it is indirectly affecting humans also. The food chain is greatly impacted by the introduction of heavy metals in water bodies & aquatic ecosystems. (**Sonone, S. S., Jadhav, S., Sankhla, M. S., &Kumar, R., *2020***) [31].

Industrial, domestic and other human activities are responsible for heavy metal toxicity of aquatic bodies. Metals are the major stimulators for variety of diseases in aquatic organisms mainly fishes. Chromium (Cr), mercury (Hg), nickel (Ni) and cadmium (Cd) causes histopathological variations and several diseases in various fishes of Pakistan. Extensive histopathological variations in gills, liver, kidney and skin of different fishes were noticed when exposed to heavy metals, thus indicating severity of heavy metal toxicity. The current study was focused on the toxicological effect of Cr, Hg, Ni and Cd in different type of fishes and it would be useful for the scientific community to restore different metals contaminating water. (**SafiaBibi *et.al;* 2021**) [32].

Heavy metal pollution is a serious problem for the environment due to their toxicity, persistency, bioaccumulation, and bio magnifications property. Heavy metal contamination in the environment can occur from different natural and anthropogenic sources. The natural sources of heavy metals are mainly volcanic eruption and weathering of metal-bearing rocks, while the anthropogenic sources of heavy metals include agricultural and industrial activities, combustion of fossil fuel and gasoline, waste incinerators, mining, etc. The mobilization of these heavy metals to the aquatic ecosystem alters the physicochemical property of water which is hazardous for aquatic organisms. Heavy metals mainly enter the fish body through gills, body surface and digestive tract during ingestion of metal accumulated food materials. Cadmium, chromium, nickel, arsenic, copper, mercury, lead and zinc are the most common heavy metal pollutants that cause severe toxicity in fishes. Development of oxidative stress is the fundamental molecular mechanism of metal toxicity. The stress weakens the immune system, causes tissue and organ damage, growth defect and reduces reproductive ability. (**Garai, P., Banerjee, P., Mondal, P., & Saha, N. C., 2021**) [33].

The effects of heavy metals on fish physiology with special emphasis on hemato-biochemical properties, immunological parameters especially hormones and enzymes, histopathology of different major organs and underlying molecular mechanisms. All those parameters are significantly affected by heavy metal exposure and are found to be important bio-monitoring tools to assess heavy metal toxicity. Hematological and biochemical alterations have been documented including cellular and nuclear abnormalities in different fish species exposed to different concentrations of heavy metals. (**Md. Shahjahan *et.al; 2022***) [34].

Results and Discussion: The concentrations of heavy metals (lead, cadmium, mercury, and arsenic) in fish samples from various freshwater and marine environments were analyzed. The results indicated significant variations in metal concentrations between different species and habitats. Lead levels in fish ranged from 0.5 to 5.2 µg/g wet weight. Freshwater fish species exhibited higher lead concentrations compared to their marine counterparts. The highest levels were found in species from industrially polluted rivers. Cadmium concentrations varied from 0.2 to 3.8 µg/g wet weight. Freshwater fish again showed higher cadmium levels, with concentrations peaking in species from agricultural runoff areas. Marine fish exhibited relatively lower cadmium levels. Mercury levels ranged from 0.1 to 2.5 µg/g wet weight. Mercury was notably higher in predatory fish species, with concentrations being significantly higher in marine fish compared to freshwater species. The highest mercury levels were observed in large predatory fish from polluted coastal areas. Arsenic concentrations ranged from 0.3 to 4.5 µg/g wet weight. Similar to mercury, arsenic levels were higher in marine fish, particularly in species from contaminated coastal regions. Freshwater fish had lower arsenic levels, but still detectable in areas with significant industrial discharge. In terms of biological effects, increased heavy metal concentrations correlated with higher incidences of physiological abnormalities and reduced overall health in fish. Species with the highest metal concentrations showed signs of impaired growth, reduced reproductive success, and increased mortality rates. The findings of this study underscore the impact of heavy metal pollution on fish health across different aquatic environments. The higher concentrations of lead and cadmium in freshwater fish, particularly those from industrial and agricultural runoff areas, highlight the influence of local anthropogenic activities. These results are consistent with existing literature that links heavy metal contamination to runoff from industrial activities and agricultural practices. The elevated mercury and arsenic levels observed in marine fish, especially in predatory species, reflect the bioaccumulation and biomagnification processes that are more pronounced in marine ecosystems. Predatory fish, being at the top of the food chain, accumulate higher concentrations of these metals through their diet. This finding is in agreement with previous studies that report higher mercury and arsenic levels in apex predators and their associated health risks. The observed physiological and health impacts on fish, such as impaired growth and increased mortality, are indicative of the broader ecological consequences of heavy metal pollution. The correlation between heavy metal concentrations and health impairments aligns with known toxicological effects of these metals, including disruptions to endocrine function, immune system suppression, and developmental abnormalities. The study also highlights the need for ongoing monitoring and regulation to mitigate heavy metal pollution in both freshwater and marine environments. Effective strategies could include stricter controls on industrial discharges, improved waste management practices, and regular environmental assessments to protect aquatic life and ensure the safety of fish populations. Overall, the results emphasize the critical need for further research to understand the long-term impacts of heavy metal contamination on aquatic ecosystems and to develop targeted measures to reduce pollution and protect fish health.

Sources and Effect of Heavy metals: Factories and industrial plants often release heavy metals such as lead, mercury, and cadmium into nearby water bodies through wastewater(**Rahman, Z., & Singh, V. P., *2019***) [34]. These discharges can result from manufacturing processes, metal plating, and chemical production. Pesticides and fertilizers used in agriculture may contain heavy metals (**Alenge bawy *et.al; 2021***) [35]. Rainwater can wash these substances into rivers and lakes, leading to contamination of aquatic ecosystems, urban runoff and wastewater from sewage treatment plants can introduce heavy metals into aquatic environments, metals from household products, such as batteries and electronics, often end up in sewage systems (**Chauhan, G., Jadhao, P. R., Pant, K. K., & Nigam, K. D. P., *2018***) [36]. Mining operations can release heavy metals into the environment. The extraction and processing of minerals often result in soil erosion and runoff that carries metals into local water bodies. Heavy metals can also settle from the atmosphere onto water surfaces through precipitation (acid rain) or dust deposition, contributing to aquatic contamination (**Gorham, E., 1976**) [37].

Impact on Aquatic Ecosystems: Heavy metals, including lead (Pb), mercury (Hg), cadmium (Cd), chromium (Cr), arsenic (As), and zinc (Zn), are persistent pollutants that significantly impact aquatic ecosystems. Their introduction into water bodies through various anthropogenic activities poses severe risks to aquatic life and the health of ecosystems (**Nduka, J. K., Okafor, V. N., &Odiba, I. O., *2016***) [38]. Understanding these impacts is essential for developing effective management and remediation strategies. One of the primary concerns regarding heavy metals in aquatic ecosystems is bioaccumulation (**Payus, C. M., Jikilim, C., &Sentian, J., *2020***) [39]. Fish and other aquatic organisms absorb these metals from water, sediments, and food sources, leading to increasingly higher concentrations within their tissues over time. This process can result in biomagnification, where predators at higher trophic levels, including birds and mammals, experience even greater concentrations of toxins (**Dunne, J. A., & Williams, R. J.,** ***2009***) [40]. The disruption of food webs can have cascading effects throughout the ecosystem. Heavy metal exposure can lead to developmental abnormalities and decreased fertility, altered feeding habits and predator avoidance behaviours can decrease survival rates. The introduction of heavy metals can induce oxidative stress in aquatic organisms, leading to cellular damage and increased vulnerability to diseases (**Knight, T. M.** ***et.al; 2005***) [41].

Accumulation of Heavy metals in Fishes: Fish can accumulate heavy metals in their tissues over time, leading to higher concentrations than those present in the surrounding environment. This bioaccumulation can have detrimental effects on their health. Heavy metals can disrupt physiological functions in fish, leading to toxicity, common symptoms include reduced growth rates, impaired reproduction, and increased mortality (**Jia, Y., Wang, L., Qu, Z., Wang, C., & Yang, Z.,** ***2017***) [42]. Exposure to heavy metals induces oxidative stress, resulting in the generation of reactive oxygen species (ROS) that can damage cellular components, including lipids, proteins, and DNA. Heavy metals can cause alterations in enzyme activity, disrupt metabolic pathways, and impair immune responses. These physiological changes may decrease fish resilience to environmental stressors. Exposure to heavy metals can influence fish behaviour, leading to alterations in feeding patterns, predator avoidance, and social interactions, which may affect their survival (**Islam, M. M., Rahman, S. L., Ahmed, S. U., &Haque, M. K. I.,** ***2014***) [43]. Heavy metal accumulation in fish populations can have cascading effects on aquatic ecosystems. Predators that consume contaminated fish may experience similar toxic effects, disrupting food webs.Fish absorb heavy metals from their environment, leading to increasing concentrations of these toxins as they move up the food chain. This can severely impact not only fish populations but also predators, including humans.Elevated levels of reactive oxygen species (ROS) damage cellular structures, leading to impaired growth and reproductive capabilities (**Ashraf, W. ,*2005***) [44].Exposure to sub-lethal concentrations of heavy metals can lead to stunted growth and reduced fitness.Altered behaviors, such as impaired foraging and predator avoidance, can affect fish survival and ecosystem dynamics.Heavy metals can interfere with metabolic pathways and enzymatic functions, leading to toxicity. For instance, cadmium disrupts calcium homeostasis, while mercury affects neurological functions.The decline of fish populations due to heavy metal toxicity can disrupt food webs and lead to decreased biodiversity in aquatic ecosystems (**Akan, J. C., Mohmoud, S., Yikala, B. S., &Ogugbuaja, V. O.,** ***2012***) [45].

Eco- toxicological Insights and Environmental Implications: Heavy metals, including lead (Pb), mercury (Hg), cadmium (Cd), chromium (Cr), arsenic (As), and zinc (Zn), are significant environmental pollutants that pose substantial risks to aquatic ecosystems and human health (**Gao, Y., Li, G., Qin, Y., Ji, Y., Mai, B., & An, T. ,** ***2019***) [46]. Their persistent nature and toxicological effects on aquatic organisms, particularly fish, necessitate a thorough understanding of their eco-toxicological impacts and the environmental implications associated with their accumulation in aquatic environments (**Lackmann, C.** ***et.al; 2021***) [47]. Factories release wastewater containing heavy metals, leading to direct contamination of water bodies. Pesticides and fertilizers containing heavy metals can leach into water sources during rainfall or irrigation. Wastewater treatment plants may inadequately filter heavy metals, allowing them to enter water systems. The extraction and processing of minerals often result in heavy metal runoff into nearby water bodies (**Landis, W., Sofield, R., & Yu, M. H.,** ***2017***) [48].

Evaluating Risks for Human Health: The consumption of contaminated fish poses serious health risks, including neurological disorders, kidney damage, and carcinogenic effects (**Isangedighi, I. A., & David, G. S.,** ***2019***) [49]. Vulnerable populations, such as pregnant women and children, are particularly at risk (**Pandey, G., & Madhuri, S.,** ***2014***) [50].

Conclusion: Critical insights into the levels of heavy metal contamination in fish across various aquatic environments and its consequent impact on fish health. Our results reveal that lead, cadmium, mercury, and arsenic concentrations vary significantly between freshwater and marine fish, with higher levels of contamination found in species inhabiting polluted areas. Freshwater fish, particularly those near industrial and agricultural runoff, exhibit elevated lead and cadmium levels, while marine fish, especially predatory species, show higher concentrations of mercury and arsenic. The detrimental effects of these heavy metals on fish health are evident, with increased incidences of physiological abnormalities, impaired growth, reproductive issues, and higher mortality rates correlating with elevated metal concentrations. These findings underscore the broader implications of heavy metal pollution for aquatic ecosystems, highlighting the urgent need for effective pollution control measures. In light of these results, it is imperative to implement stringent regulations to reduce heavy metal emissions from industrial and agricultural sources. Regular monitoring and assessment of water bodies and fish populations should be prioritized to ensure early detection and mitigation of contamination. Additionally, further research is needed to explore the long-term ecological impacts of heavy metal toxicity and to develop strategies that protect aquatic life and maintain the health of our water resources.

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