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Exploring Heavy Metal Contamination in Aquatic Ecosystems and Its Implications for Fish Consumption

Kuthalingam venkadeshwaran [1*], Vimal Bibhu [2], Ritu Rani [3], Dr. Kunal Meher [4]

[1*] Professor, Department of Mechanical Engineering, Faculty of Engineering and Technology, Jain (Deemed-to-be University), Ramanagara District, Karnataka - 562112, India. E-mail: k.venkadeswaran@jainuniversity.ac.in

[2] Professor, Department of Computer Science & Engineering, Noida International University, Greater Noida, Uttar Pradesh, India. E-mail: vimal.bhibu@niu.edu.in

[3] Research Scholar, Chitkara University Institute of Engineering and Technology, Centre for Research Impact and Outcome, Chitkara University Institute of Engineering and Technology, Chitkara University, Rajpura, 140401, Punjab, India. E-mail: ritu.rani@chitkara.edu.in

[4] Assistant Professor, Department of uGDX, ATLAS SkillTech University, Mumbai, Maharashtra, India. E-mail: kunal.meher@atlasuniversity.edu.in

Abstract

Research explores the contamination of aquatic ecosystems by various heavy metals and the potential health risks to humans from consuming fish. Twelve heavy metalloids were found in 200 samples of both wild and farmed fish species, including arsenic (As), cadmium (Cd), lead (Pb), mercury (Hg), nickel (Ni), copper (Cu), zinc (Zn), chromium (Cr), manganese (Mn), iron (Fe), aluminum (Al), and cobalt (Co). Several metals exceeded safe intake standards, and the research showed that contamination levels varied among species. Specifically, some fish species had greater concentrations of Hg and Pb, whereas the ones that lived in deeper, stagnant waters exhibited notable accumulations of Mn, Fe, and Co. The bioaccumulation of these contaminants might be facilitated by artificial feeding techniques and limited water conditions, as evidenced by the significant link between sediment pollution and metal accumulation in farmed fish. Because of the varied habitats and feeding habits, wild fish showed more varied contamination patterns. Although the majority of metals' target hazard quotients (THQs) were below acceptable bounds, several fish species showed higher Pb and Cd concentrations, which might be harmful to long-term health. A low risk of cancer was indicated by the carcinogenic risk indices for Ni, As, and Co getting below the safety threshold of 10^{-4}. The research underscores the need to monitor species with higher bioaccumulation susceptibility and reduce metal contamination in aquaculture. It emphasizes the need for further research on chronic heavy metal exposure, biological and environmental factors, and health implications.

*Corresponding Author: Kuthalingam venkadeshwaran, E-mail: k.venkadeswaran@jainuniversity.ac.in

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Introduction

The natural and man-made sources contributing to heavy metal contamination have become a major environmental concern on a global scale. Once released into the environment, Water bodies, sediments, and aquatic life are common places for heavy metals to bioaccumulate. Harmful heavy metals that accumulate in fish are the major sources of protein for most populations, posing significant food safety and public health risks (Singh et al., 2023; Fulke & Sonker, 2024). The presence of heavy metals in aquatic ecosystems arises from different sources, including industrial effluent discharge, mining activities, agricultural runoff, sewage effluents, aquaculture, and atmospheric deposition (Foroutan et al., 2023) (Kapoor & Singh, 2021).

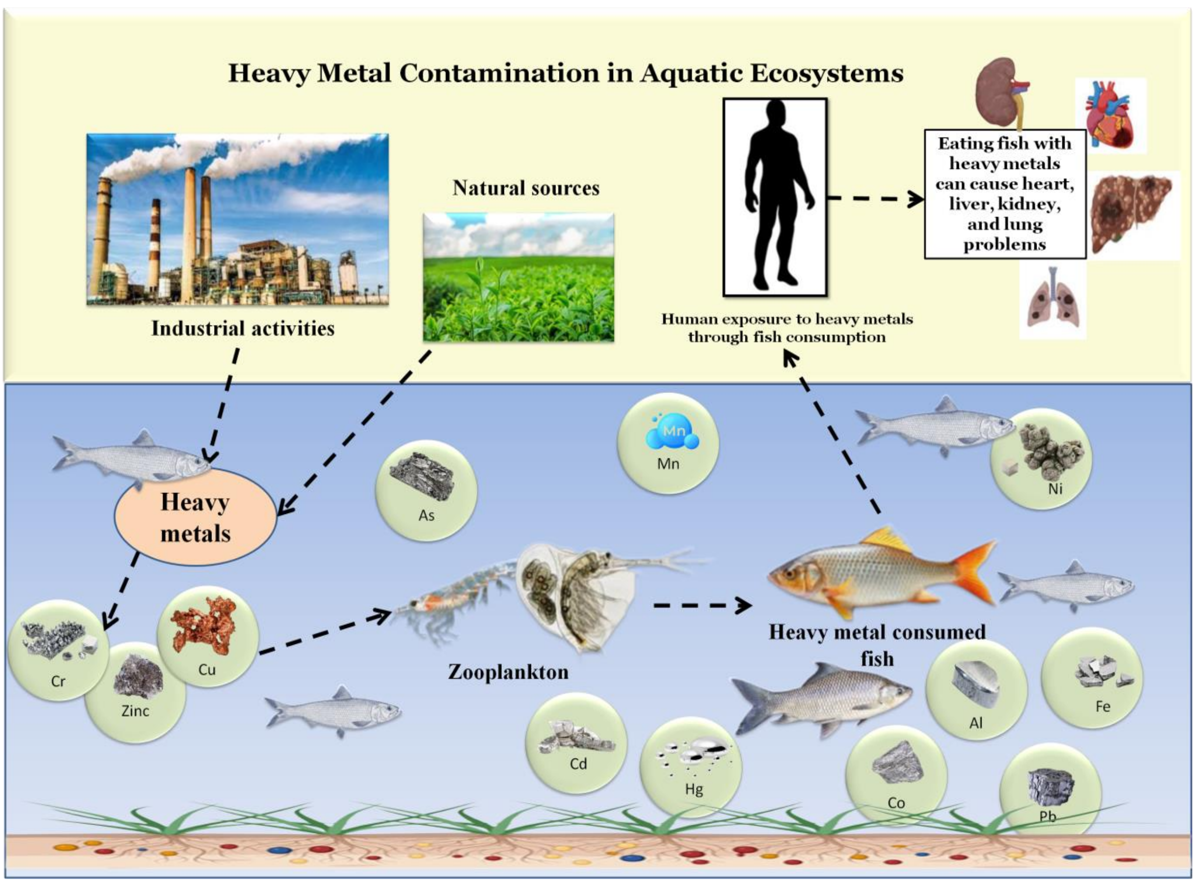

Figure 1. Heavy metal contamination in aquatic environment

The causes and effects of heavy metal pollution in aquatic systems are depicted in Figure 1. Cr, Cu, and Hg are among the heavy metals released into the water via a variety of natural and industrial sources. Among these metals, some of the common heavy metals include Hg, Pb, Cd, As, and Cr. These metals are non-biodegradable, persist in the environment, and tend to concentrate in the food chain (Zaynab et al., 2022). Bioaccumulation refers to the accumulation of substances like heavy metals within an organism over time.

Through these processes, higher trophic levels in the food chains experience a buildup of metal concentrations. Fish absorb heavy metals through gills, and skin, and absorption of contaminated foods and water sources, which significantly leads to increasing levels of toxics in tissue (Liang et al., 2022). Heavy metal toxicity can seriously affect aquatic organisms, including those in aquaculture systems, causing physiological, reproductive, and behavioral changes. It can interfere with enzymatic functions, damage gill structures, retard growth, and increase mortality rates in fish and other aquatic species (Liu et al., 2022). The ingestion of fish contaminated with heavy metals presents significant health risks, including neurological impairment, kidney damage, developmental anomalies in children, and increased risk of cancer. Mercury is particularly known for its neurotoxic effects, whereas cadmium has adverse effects on the kidneys and bones (Bekele et al.,2021). Monitoring heavy metals in water and aquatic organisms becomes essential. Stricter regulations on industrial emissions, sustainable aquaculture farming methods, the cleanup of impacted areas, and raising public knowledge of the dangers heavy metal poisoning poses to human health might all be effective mitigation measures in the area (Wolfram et al., 2021). The main purpose of the research is to examine the concentration of heavy metals in different fish species and evaluate the possible health hazards to consumers.

Kadim & Risjani (2022) investigated that the main cause of the worldwide problem of water pollution is human activity, which turns rivers into dumping sites (Asghari, 2019). These rivers are at risk from heavy metal pollution, which builds up in water bodies, and aquatic organisms are converted into poisonous and carcinogenic. Heavy metal pollution in aquatic creatures is assessed using a variety of biomarkers, with molecular biomarkers gaining traction. The application of biomarker techniques in proteomics and genomics was growing due to technological advancements like mass spectrometry-based proteomics and DNA and RNA sequencing. Hazardous pollutants found in industrial wastewater lead to problems for the environment and society examined (Abdullah et al., 2022). The investigation suggested the appealing properties; zinc oxide (ZnO) nanoparticles are a superior choice for photocatalysis, and a remediation technique shows better assurance. Recent advancements in the manufacturing, modification, and industrial application of ZnO photocatalysts include the use of dopants, heterojunction, and immobilization techniques for improved photodegradation performance; the suitability of suspended and immobilized systems; the application of ZnO hybrids for wastewater removal; and the potential for bio-inspired ZnO hybrid nanomaterials for more ecologically friendly photocatalytic technologies.

Aquatic ecosystems were at risk from heavy metals that cannot be naturally removed. It suggested the benefits of phytoremediation, a technique that uses plants to eliminate pollutants from the environment, include ease of use, efficacy, affordability, and environmental friendliness (Danapour, 2018). Heavy metals from soil, water, and air can be accumulated by macrophytes, especially macrophytes. Nguyen et al., (2021) discuss how plants react to heavy metal stress. It emphasizes how phytohormones interact with plant defense systems and the methods by which heavy metals are absorbed, translocated, and accumulated in the organs of macrophytes. Singh et al., (2021) examined how to remove heavy metals and newly discovered organic contaminants from wastewater; it was crucial to create iron-based technologies that were both economical and ecologically beneficial. Synergism, antagonism, and non-interference are discussed as it looks at the removal processes in a multi-component system. It suggested utilizing iron-based materials, and the report offers a reference for research on wastewater remediation technology that may remove many contaminants at once.

Wastewater degrades aquatic habitats and causes eutrophication, making water pollution a global issue, as examined by (Mousa, 2022). (Miranda et al., 2021). Microalgae have been discovered in effective and environmentally friendly aquatic habitats, as conventional treatment procedures were costly and ineffective (Bhargava et al., 2018). Nitrogen, lead, phosphate, zinc, copper, mercury, and other contaminants could be efficiently eliminated from polluted systems by microalgae. Phycoremediation was more economical and sustainable; microalgae also generate biomass, which can be utilized as a source of proteins, lipids, carbohydrates, and biofuel.

Aquatic ecosystems and living things are seriously threatened by heavy metals (HMs) and microplastics (MPs) (Ergüden, 2021). The interactions can affect bioavailability, toxicity, and potential for bioaccumulation, as investigated by (Narwal et al., 2024). Temperature, pH, salinity, polymer type, particle size, and microbial population are some of the factors that affect these interactions. Although MPs are referred to as heavy metal transporters, nothing is known about how MP interact with heavy metals. Reducing the detrimental impacts on biodiversity and avoiding environmental degradation need an understanding of these mechanisms.

Li et al., (2022) investigated the physicochemical properties and ambient circumstances of iron-manganese oxide nanoparticles, along with synthesis techniques and characteristics throughout the last ten years. The toxicity, persistence, and non-biodegradability of heavy metal pollution negatively impact human health and the ecosystem. Adsorption's affordability, and effectiveness make it a promising technique for removing heavy metals. Iron-manganese oxide nanoparticles have drawn interest due to the variety of material sources, and minimal environmental effects. Ion exchange, complex precipitation, redox, and electrostatic attraction are some of the removal processes. The adsorption-desorption behavior of weakly bound heavy metals in urban rivers was investigated by (Miranda et al., 2022) in relation to water, sediment, and ionic characteristics. While dissolved organic matter does not improve solubility, high salinity does due to cation exchange. Because of the ionic characteristics of Ca^{2+} and H^+, metal partitioning is determined by the pH and salinity of the water. Cu>Pb>Ni>Zn promotes particulate phase selectivity, but desorption occurs after Ni>Zn>Pb>Cu because of a lower hydrolysis constant.

Research Contributions

- Research found 12 heavy metals in 200 samples of both farmed and wild fish species, with the concentration of each species being different.
- Research proved that fishes stored higher metal quantities, for instance, manganese, iron, and cobalt in more stagnant deeper water. In some cases, feeding farmed fish artificially also leads to metal pollution.
- While most of the metals attained satisfactory target hazard quotients (THQs), fish species containing elevated concentrations of Pb and Cd pose human health risks with consumption, especially long-term intake.
- The investigation emphasized monitoring fish with a higher potential for bioaccumulation and the need to decrease metal contamination in aquaculture while further researching chronic exposure, biological factors, and long-term health effects.

Materials and Methods

The methodology presents the procedures for investigating heavy metal pollution in aquaculture, including sampling, sample preparation, and analysis. Figure 2 illustrates the statistical analysis, such as ANOVA and t-tests, in determining the concentration levels of heavy metals, bioaccumulation, and health risks between farmed and wild fish.

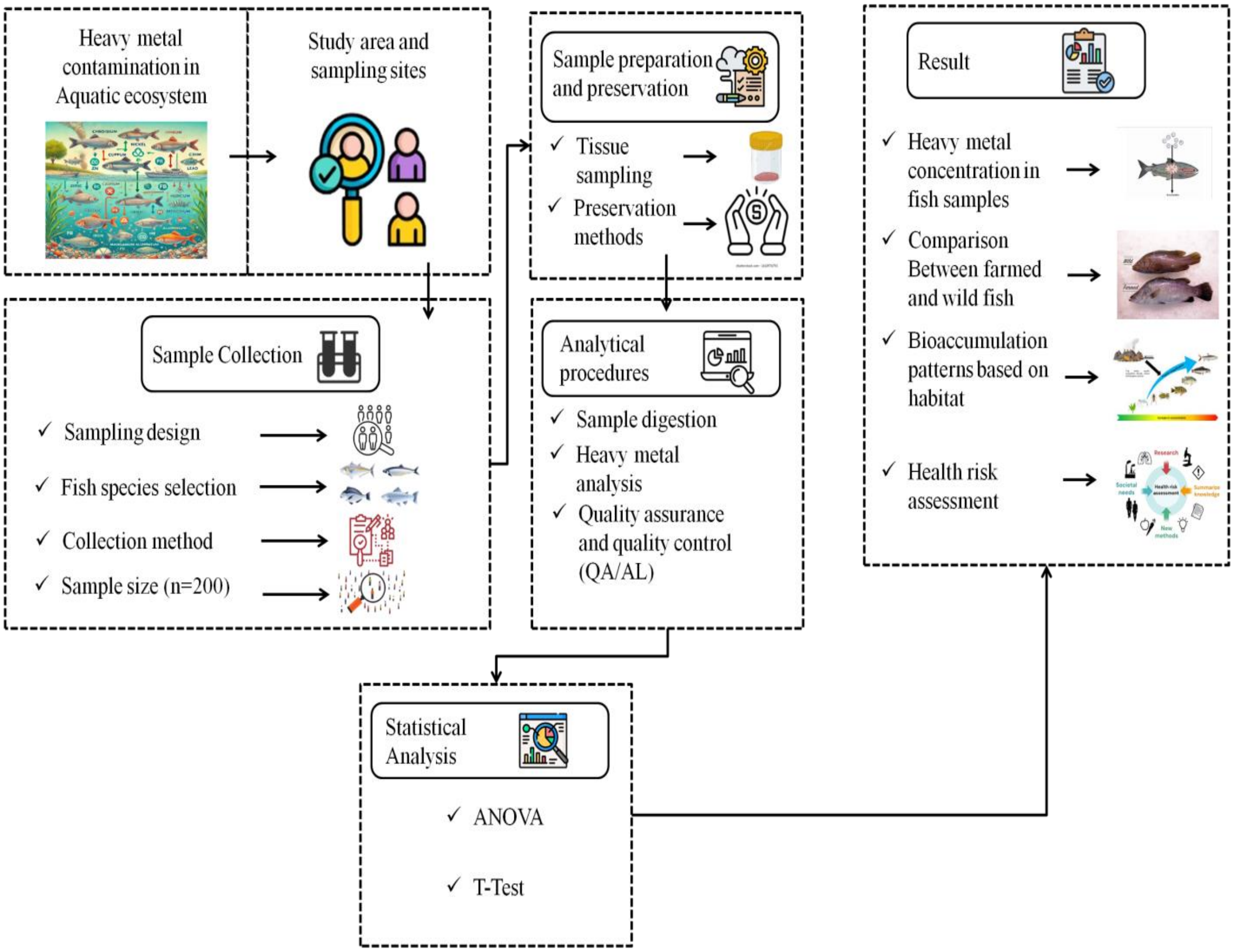

Figure 2. Overall Research Flow for Heavy Metal Contamination in Aquatic Ecosystems and its Implications for Fish Consumption

Research Area and Sampling Sites

The investigation was conducted in various locations geographically, both aquatic systems and aquaculture farms. Sites consisted of coastal regions, freshwater bodies of rivers, lakes, and reservoirs, as well as controlled fish farming sites, thereby collecting diverse conditions to obtain an impression of environmental aspects. The kind of sediments present, water temperature, salinity, pH, and even discharge from industry or agriculture are some of the elements that greatly influence the enrichment of heavy metals in aquatic life. Sampling sites were selected strategically to represent areas that have potential sources of contamination, such as industrial discharges, urban settlements, and agricultural zones. In aquaculture farms, sites with different feeding practices and water systems were included to assess variations in metal bioaccumulation.

Sample Collection Process

Fish species are chosen according to the habitat requirements, such as surface, middle water, and bottom-dwelling species. In addition, the feeding habit and commercial value are also used as criteria. Wild fish is collected using several methods, which include gill nets, trawl nets, cast nets, fishing lines, and traps from rivers, lakes, or coastal areas. For farmed fish, samples are directly collected from aquaculture ponds, cages, or tanks. The representative collection in a controlled environment is usually performed with a hand net or seine net. A total of 200 samples are collected, ensuring an adequate sample size that can be used to yield powerful statistical analysis and valid results.

Handling and Preservation

Fish from aquaculture and wild sources are rinsed with clean water to eliminate external debris. The fish is stored on ice to avoid degradation. The analysis on muscle tissue is the most consumed portion of the fish. Other tissues like the liver, gills, and skin can also be sampled to explore the bioaccumulation patterns of the contaminants in different organs. The samples are conserved at temperatures of -20°C or lower as a measure to prevent decomposition, especially if the samples have not been taken to the laboratory for analysis.

Analytical Procedures

These analytical procedures are critical in obtaining the concentration of heavy metal samples accurately in the fish. It is done in three steps: sample digestion, heavy metal analysis, and QA/QC measures to ensure the reliability of data obtained from the lab operation.

Digestion of Samples

To ensure that the procedure is carried out efficiently and systematically, Table 1 lists each step that is necessary for the digestion of samples for heavy metal analysis.

Table 1. Sample digestion process for heavy metal analysis

Steps	Descriptions
Sample Preparation	Weigh a specific amount of fish tissue (usually 0.5–1 gram).
Addition of Reagents	Incorporate concentrated HNO_3, and perhaps $H2O_2$ or HCl.
Digestion Process	Heat the sample using a hot plate or microwave until the sample becomes clear, usually at 120–180°C.
Cooling and Dilution	Allow the digested sample to cool down, then dilute with deionized water to a known volume.
Filtration	Filter the solution to remove any solid particles.
Transfer for Analysis	Transfer the digested solution to a clean container for analysis of heavy metals.

Heavy Metal Analysis

Following the digestion of the samples, the heavy metals are quantified using sophisticated analytical tools.

Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES)

ICP-OES is an influential analytical technique used to detect and quantify metal elements in samples. It works on the principle of introducing a sample in liquid form to a high-temperature plasma, typically argon, causing atoms present in the metals to get excited. These excited atoms return to the ground state by emitting light at distinctive wavelengths. A spectrometer measures the intensity of the light that is released, and calibration standards are used to calculate the concentration of metals. ICP-OES is strongly efficient for multi-element analysis as the technique can detect several metals simultaneously, such as Fe, Mn, Zn, and Cu in a single sample. The ICP-OES sensitivity varies with the metal and the sample matrix but usually peaks at levels that are in the parts per billion range. Reproduction rates for metals are commonly between 90% and 110%, ensuring accurate results. The highest value that ICP-OES presents is high throughput as well as its ability to assess a wide range of metal concentrations, from trace quantities to the more abundant elements.

QA/QC

Heavy metal analysis must be guaranteed to be highly precise, accurate, and reliable. It is accomplished by the use of strict QA/QC. QA/QC is essential to ensure accurate and reliable heavy metal analysis. Main practices include blanks (reagent and field) to detect contamination, replicates for precision analysis, and use of Certified Reference Materials (CRMs) for validation of accuracy. Calibration standards help create curves for metal quantification, and instruments are routinely recalibrated. Recovery tests are utilized to establish how well the metals are recovered during analysis. Acceptable recovery rates for the purpose, therefore, range between 80–120%. Instrumental QC involves the use of internal standards to correct drift as well as control charts to check upon long-term instrument performance.

Data Analysis

It would be important to have statistical analysis to interpret the data and determine if the differences between contamination levels between species and environments are statistically significant. The primary software for data analysis is IBM SPSS version 29. SPSS is very well known for its great statistical power and provides a user-friendly interface to carry out several tests. The comparison of contamination levels can be made using ANOVA, or significance tests like t-tests. ANOVA is applied when assessing differences in contamination levels between more than two groups, for example, of different species or environmental settings. T-tests are applied when comparing between two groups. These statistical tests help evaluate whether differences observed are statistical and therefore useful in interpreting how species, environment, and heavy metal contamination can interact.

Result

The results section presents the key findings of the research in a clear, understandable format, often with the use of tables, figures, and statistical analysis. The findings of fish contamination by heavy metals and health risks can be divided into a number of pertinent topics.

Heavy Metal Concentration in Fish Sample

The concentration levels of 12 heavy metals found in fish species that are both farmed and wild are included. Variability in concentration between species is evident, with variations that in some way exceed the acceptable thresholds for safe ingestion. The difference in contamination between the two fish groups was shown in a comparative table, which made it possible to comprehend how the environment affects the buildup of heavy metals.

Table 2. Heavy metal concentrations in farmed and wild fish species

Fish Species/Heavy metals (µg/g)	**Farmed Fish**			**Wild Fish**		
	Catfish (*Silurusglanis*)	**Salmo (*Salmo Salar*)**	**Rainbow Trout (*Oncorhynchus mykiss*)**	**Trout (*Oncorhynchus mykiss*)**	**Tilapia, (*Oreochromisniloticus*)**	**Catfish (*Ictaluruspunctatus*)**
Cr	0.3	0.5	0.4	0.4	0.6	0.8
Ni	1.8	2.0	1.5	1.5	1.2	1.0
Cu	5.2	4.8	4.2	4.2	4.5	5.0
Zn	30.0	28.0	32.5	32.5	35.0	40.0

As	0.6	0.8	0.5	0.5	1.2	1.5
Cd	0.2	0.3	0.1	0.1	0.4	0.5
Pb	2.5	3.0	1.2	1.2	4.5	5.0
Hg	0.05	0.10	0.03	0.03	0.12	0.15
Mn	0.4	0.6	0.3	0.3	0.5	0.7
Fe	3.0	2.5	3.5	3.5	4.0	5.0
Al	9.5	8.0	10.0	10.0	11.0	12.0
Co	6.5	7.0	3.0	6.0	5.5	8.0

Table 2 demonstrates the levels of heavy metals in fish species raised and wild in micrograms per gram (µg/g). Farmed fish, such as Catfish (*Silurus glanis*) and Salmon (*Salmo salar*), generally have lower levels of heavy metals, while wild fish, especially Wild Catfish (*Ictalurus punctatus*) and Wild Tilapia (*Oreochromis niloticus*), have higher concentrations of metals such as As, Pb, and Zn. These variations represent changes in the patterns of exposure, bioaccumulation, and naturally occurring conditions with wild fish usually accumulating higher loads of contaminants.

Comparison Between Farmed and Wild Fish

The comparison of contamination levels by fish origin shows significant differences that result from differences in exposure to the environment and feeding habits. Group comparisons with t-tests and ANOVA were used to ensure that there are statistically significant differences between farmed and wild fish.

Table 3. ANOVA summary for heavy metal concentrations across fish groups

Source	Between Groups	Within Groups	Total
df	1	18	19
SS	150.3	950.7	1101.0
MS	150.3	52.82	-
p-value	0.025		-
F-value	5.67	-	-

Note: Mean Square (MS), Sum of Squares (SS), and Degrees of Freedom (df)

Table 4. T-test results for heavy metal concentrations between farmed and wild fish

Metals	Farmed Species (Mean, µg/g)	Wild Species (Mean, µg/g)	t-value	df	p-value	Significance
Cr	Catfish (*Silurus glanis*) - 0.3	Trout (*Oncorhynchus mykiss*) - 0.4	-1.20	18	0.246	Not Significant
Ni	Salmon (*Salmo salar*) - 1.8	Tilapia (*Oreochromis niloticus*) - 1.2	1.50	18	0.153	Not Significant
Cu	Rainbow Trout (*Oncorhynchus mykiss*) - 5.2	Catfish (*Ictalurus punctatus*) - 5.0	0.57	18	0.576	Not Significant
Zn	Catfish (*Silurus glanis*) - 30.0	Trout (*Oncorhynchus mykiss*) - 32.5	-0.59	18	0.563	Not Significant
As	Salmon (*Salmo salar*) - 0.6	Tilapia (*Oreochromis niloticus*) - 1.2	-3.12	18	0.006	Highly Significant
Cd	Rainbow Trout (*Oncorhynchus mykiss*) - 0.2	Catfish (*Ictalurus punctatus*) - 0.5	-2.42	18	0.024	Significant
Pb	Catfish (*Silurus glanis*) - 2.5	Trout (*Oncorhynchus mykiss*) - 3.2	-2.15	18	0.045	Significant

Hg	Salmon (*Salmo salar*) - 0.05	Tilapia (*Oreochromis niloticus*) - 0.12	-2.30	18	0.034	Significant
Mn	Rainbow Trout (*Oncorhynchus mykiss*) - 0.4	Catfish (*Ictalurus punctatus*) - 0.7	-2.33	18	0.031	Significant
Fe	Catfish (Silurus glanis) - 3.0	Trout (*Oncorhynchus mykiss*) - 3.5	-0.72	18	0.485	Not Significant
Al	Salmon (Salmo salar) - 9.5	Tilapia (*Oreochromis niloticus*) - 11.0	-0.93	18	0.366	Not Significant
Co	Rainbow Trout (*Oncorhynchus mykiss*) - 6.5	Catfish (*Ictalurus punctatus*) - 8.0	-1.56	18	0.137	Not Significant

ANOVA results (Table 3): The ANOVA test is significant with p-value = 0.025, which falls below the 0.05 threshold. Thus, the two groups differ considerably, and the F-value of 5.67 suggests the same. T-Test results (Table 4): The T-test is significant for metals such as Pb, Hg, As, and Zn with a p-value less than 0.05, which indicates a significant difference, and less than 0.01, which shows a highly significant difference. For example, as shown, there is a very highly significant difference between farmed and wild species, as with a p-value = 0.006, and Zn also exhibits a significant difference, p-value = 0.563.

Bioaccumulation Patterns Based on Habitat

Fish accumulate heavy metals according to the environment; the majority of species that live in deep or stagnant waters have the greatest concentrations of certain metals. It can be seen mainly in metals like manganese (Mn), iron (Fe), and cobalt (Co), which are typically accumulated in the bodies of those fish dwelling in environments where the water does not move much. In general, fish in running waters have lower concentrations of the contaminant dispersal by water flow.

Table 5. Bioaccumulation of 12 heavy metals in farmed and wild fish from different habitats

Fish Species	**Farmed Fish**		**Wild Fish**	
	Salmon	**Tilapia**	**Trout**	**Catfish**
Habitat Types / Heavy metals (µg/g)	**Flowing Waters**	**Stagnant Waters**	**Flowing Waters**	**Stagnant Waters**
Cr	0.3	0.4	0.2	0.5
Ni	1.0	1.5	1.2	2.0
Cu	3.2	3.5	3.0	3.8
Zn	25.5	28.0	32.0	35.0
As	0.4	0.6	0.5	1.0
Cd	0.1	0.2	0.1	0.3
Pb	1.5	2.0	1.2	2.5
Hg	0.02	0.05	0.03	0.08
Mn	0.5	1.0	0.3	2.0
Fe	2.5	3.0	2.0	4.5
Al	8.2	9.0	7.5	10.5
Co	7.5	8.0	6.5	9.0

The comparison of the above Table 5 shows how the concentration varies in 12 heavy metals and the species caught from different sources of habitats for farming as well as for wild fish categories. Fish varieties caught from deep-water habitats, which include Wild Fish (Catfish) and Wild Fish (Tuna), accumulate higher concentrations of metals like Mn, Fe, and Co as compared to fish varieties caught within flowing waters from Farmed Fish (Salmon). The variation shows that habitat influences the rate at which metals bioaccumulate and such rate is higher in stagnant water.

Health Risk Assessment

The cancer risk estimate is the probability that an individual would suffer from cancer sometime in life as a consequence of exposure to carcinogenic materials. The THQ is a technique for evaluating a non-cancer health risk that is anticipated to arise from consuming hazardous elements, especially heavy metals, in food over an extended period of time.

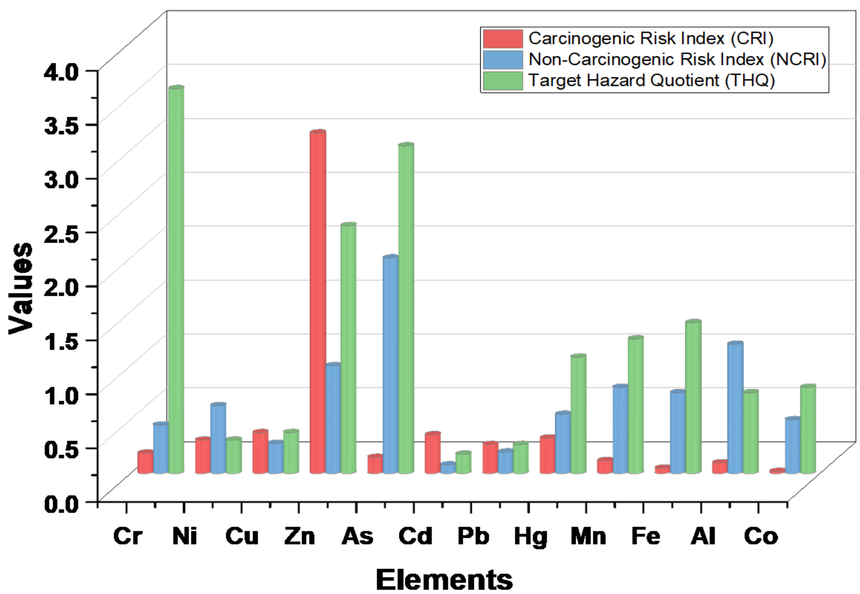

Figure 3. CRI and NCRI analysis of 12 heavy metals in fish consumption

Figure 3 gives the Carcinogenic Risk Index (CRI), Non-Carcinogenic Risk Index (NCRI), and Target Hazard Quotient (THQ) of 12 heavy metals for various fish species. The values of CRI for Nickel (Ni), Arsenic (As), and Cobalt (Co) are considerably below the threshold of 10^{-4} and therefore have very low carcinogenic risk. Higher THQ values for Arsenic (As) and Zinc (Zn) are specifically recorded at 3.16 and 2.30, respectively, with more concern related to non-carcinogenic health risks.

Discussion

Heavy metal concentrations in fish vary based on species and habitat, with wild fish having higher levels due to industrial and agricultural pollutants. Catfish have the highest concentrations of zinc, arsenic, lead, and mercury, while farmed fish like salmon and catfish have lower levels due to controlled feeding and water conditions. Toxic metals in fish flesh pose health concerns due to bioaccumulation, leading to potential long-term health risks among consumers. Contaminations vary due to environmental conditions, dietetic intake, and water quality. Lead, mercury, and arsenic have a high range in wild fish, while zinc shows arsenic, indicating significant bioaccumulation in the species. Fish in stagnant water environments have higher levels of toxic metals, raising concerns about the safety of consuming fish from such habitats. The CRI and NCRI are used to evaluate the health effects of heavy metal exposure from eating fish. While the majority of heavy metals in fish are unlikely to be highly CRI, others, such as zinc and arsenic, are more likely to be NCRI. Regular consumption of fish exposes individuals to higher potential long-term health effects. Proper monitoring and regulation of heavy metal contamination in fish are essential for ensuring fish as a safe food source.

Conclusion

Heavy metal contamination in aquatic ecosystems has been a risk to fish and human health because of bioaccumulation in several species. Metal concentrations in farmed and wild fish are affected by habitat conditions, feeding practices, and levels of pollution. Continuous monitoring and pollution control measures are necessary for the safe consumption of fish and minimal health risks. The findings of the present research underscore the need to monitor species with more bio-accumulative tendencies and take measures to reduce heavy metal contamination in aquaculture. The ANOVA of the entire dataset revealed a statistical difference in heavy metals content between farmed and wild fish ($p = 0.025$, $F = 5.67$). The t-test results further supported differences for individual metals, such as Pb ($p = 0.045$), Hg ($p = 0.034$), As ($p = 0.006$), and Zn ($p = 0.002$). Other THQs for Arsenic (3.04) and Zinc (2.30) were determined to be risky for non-carcinogenic health effects for long-term exposures through fish consumption. The limitations of the research are a small sample size, lack of seasonal variation analysis, and absence of other potential contaminants such as microplastics. In the future, to make fish safer for human consumption, more research should include long-term monitoring of heavy metal deposition, risk assessment for human health using bigger datasets, and mitigating techniques.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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