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Fish as Bioindicators: Monitoring Environmental Mercury Pollution with Aquatic Food Webs – A Mini Review

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Abstract

Mercury pollution remains a persistent concern in aquatic ecosystems due to its persistence, bioaccumulation, and toxicity. Fish, as long-lived, trophically diverse organisms, are extremely effective bioindicators of mercury pollution, providing information on spatial and temporal ecosystem pollution trends. The following mini-review consolidates current information on the utilization of fish in tracing environmental mercury, with an emphasis on mercury uptake dynamics, bioaccumulation, and biomagnification along aquatic food chains. Special attention is given to the species-specific patterns of mercury deposition, physiologic and ecological regulation of mercury retention, and regional case studies demonstrating the application of fish-based biomonitoring. Brief overview is given of analytical methods used for the determination of total mercury and methylmercury in fish tissues, as well as recent advances in stable isotope tracing and molecular biomarkers. Besides, the review also addresses the impact of mercury-contaminated fish consumption on human health, coupling environmental monitoring with public health risk assessment. Last but not least, fish are an integrative tool to assess ecosystem integrity, determine pollution sources, and support regulatory mechanisms in mercury risk management.

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1. INTRODUCTION

Mercury (Hg) pollution is a persistent and globally significant environmental issue due to its toxicity, long-range atmospheric transport, and bioaccumulation and biomagnification potential in food webs. Despite global initiatives such as the Minamata Convention to reduce mercury emissions, human activities such as coal burning, artisanal gold mining, cement production, and waste incineration continue to emit high levels of mercury into the environment (UNEP, 2019). By global emission estimates, over 2,000 metric tons of mercury are released into the air annually, with Asia contributing nearly half of this output (Zhang et al., 2021). Once it is deposited in aquatic environments, mercury undergoes complex biogeochemical transformations, primarily to methylmercury (MeHg), which is a powerful and bioavailable substance that can exert profound adverse effects on aquatic organisms and human health.

Fish are typically regarded as ideal bioindicators of mercury contamination due to their ecological significance, trophic diversity, longevity, and ability to integrate levels of contamination in space and time (Burger and Gochfeld, 2011). Because methylmercury readily accumulates in muscle tissues and biomagnifies in the food web, top predator fish have mercury levels several orders of magnitude higher than in water or sediments (Lavoie et al., 2013). This makes fish a central component of monitoring schemes in the environment as well as a critical link to understanding exposure of humans through fish consumption. Fish is a source of more than 50% of animal protein in most developing nations, making their contaminant burden of direct importance to public health.

Observation of mercury concentrations in fish enables scientists and regulators to determine pollution hotspots, measure temporal trends in contamination, and test the effectiveness of controls. Compared with water samples, which provide short-term environmental information, fish provide a more stable and representative estimate of mercury bioavailability and ecological risk (Drevnick et al., 2012). Moreover, species-specific characteristics such as habitat type, diet, trophic position, and longevity all play roles in mercury accumulation variation, offering a multivariate indicator to assess aquatic health. Table 1 illustrates documented total mercury content in various fish species across freshwater and marine systems globally, comparing global patterns and the effect of trophic position.

Table 1. *Reported Total Mercury (THg) Concentrations in the Most Studied Fish Species in Different Regions*

Species	**Habitat**	**Trophic Level**	**Region**	**THg Mean (μg/g wet wt)**	**Reference**
Lates niloticus	Freshwater	Top predator	Lake Victoria	1.20	Ramlal et al. (2003)
Salmo salar	Freshwater/Marine	High	North Atlantic	0.55	Green et al. (2007)
Oreochromis niloticus	Freshwater	Omnivore	Nigeria	0.17	Eneji et al. (2011)
Thunnus albacares	Marine	Top predator	Pacific Ocean	1.50	Storelli et al. (2002)
Perca fluviatilis	Freshwater	Mid-level	Northern Europe	0.48	Munthe et al. (2007)

Use of fish bioindicators fills the link between environmental toxicology and public health. Not only does it guide ecosystem surveys, but it also aids risk-based fish consumption guidelines as safe food. The following sections of this review explain mercury pathways in aquatic systems, uptake and storage processes at the biological level in fish, and emerging analytical methods for detecting mercury and policy considerations. The aim of this research is to examine the effectiveness of fish as bioindicators in monitoring environmental mercury pollution in aquatic ecosystems. It aims at elucidating the routes of mercury, bioaccumulation, and biomagnification along trophics. It further tries to highlight species-specific responses to mercury. Lastly, it provides recommendations for environmental monitoring and risk assessment to public health.

2. SOURCES AND PATHWAYS OF MERCURY IN AQUATIC ENVIRONMENTS

Mercury (Hg) is present in multiple chemical states and comes from both natural and man-made sources. Mercury comes naturally from the emission resulting from volcanic eruptions, rock weathering, geothermal activity, and ocean emissions (Pirrone et al., 2010). Nonetheless, throughout the last hundred years or so, human activities have significantly escalated environmental mercury levels. Key anthropogenic sources include industrial and artisanal gold mining, coal combustion, cement production, waste burning, and chlor-alkali production (Streets et al., 2011). These activities are major contributors to mercury deposition into the atmosphere, which eventually gets deposited into terrestrial and aquatic environments.

When deposited into aquatic systems, inorganic mercury undergoes biogeochemical processing. Of particular note is its methylation to methylmercury (MeHg), an organic and highly poisonous form that readily biomagnifies and bioaccumulates in aquatic food chains. Methylation is catalyzed primarily by anaerobic microbes such as sulfate-reducing and iron-reducing bacteria in sediments (Gilmour et al., 2013). All these environmental factors--temperature, redox, pH, concentration of organic carbon, and microbial activity--affect the process of methylation. The methylmercury thus formed then enters aquatic food chains through plankton and detritus feeders, and a trophic transfer cascade ensues ending in end-point concentrations among apex predators, for example, commercially valuable fish species.

Transport routes also have an important role in mercury cycling. Direct entry into lakes, rivers, and oceans may occur from atmospheric deposition, or it may settle on land and be transported into water bodies through runoff and erosion. Local high mercury concentrations in freshwater environments also result from point-source releases from mining and industrial operations and wastewater treatment plants (Driscoll et al., 2013). Estuaries and coastal areas are particularly at risk because of the mixing of marine and freshwater conditions and the concentration of human populations. Understanding the sources and pathways of mercury transformation is essential to the determination of environmental hotspots and the regulation of health risk from contaminated fish. Following the pathway of mercury from source to sink—and ultimately to the food web—can enhance ecological risk assessments and ensure sustainable water resource management. Table 2 provides a concise but complete classification of sources of mercury by origin, their environment pathways, and the potential for methylmercury formation. It places focus on the necessary relative contribution of anthropogenic sources, particularly artisanal gold mining and industrial waste effluent, which release mercury into aquatic sediments where microbial methylation is induced (Bravo et al., 2022). These facts warrant the utilization of fish as bioindicators, with a focus on polluted sites where there is a high risk of methylmercury biomagnification.

Table 2. *Major Mercury Sources and Transformation Pathways in Aquatic Ecosystems*

Source Type	Example Source	Deposition Pathway	MeHg Production Potential
Natural	Volcanic eruptions	Atmospheric deposition	Low to moderate
Anthropogenic	Coal-fired power plants	Wet/dry atmospheric deposition	Moderate
Anthropogenic	Gold mining (ASGM)	Direct runoff and sediments	Very high
Anthropogenic	Industrial wastewater	Discharge to water bodies	High

3. MERCURY UPTAKE AND BIOACCUMULATION PROCESSES BY FISH

- Trophic Transfer and Biomagnification

Mercury, particularly its methylated form (methylmercury, MeHg), is renowned for biomagnifying within aquatic food webs. This begins at the trophic base when phytoplankton and benthic invertebrates accumulate dissolved MeHg from water and sediment. They in turn are being consumed by tiny fish, eaten by big predator fish, the concentration of mercury increasingly higher with each trophic level (Cabana & Rasmussen, 1994). This results in the top predators, such as pike, bass, and tuna, having the concentration of mercury one millionfold compared to in the ambient water. Biomagnification is increased in food webs with long food chains, low pH, and high dissolved organic carbon (DOC), which enhance mercury bioavailability and accumulation.

- Mechanisms of Mercury Accumulation by Fish

Fish accumulation methylmercury mainly through consumption rather than uptake directly from water. Once ingested, MeHg tends to have high affinity for sulfhydryl groups of proteins, particularly muscles, thus remaining extremely persistent in fish organisms (Scheuhammer et al., 2007). Gastrointestinal absorption of MeHg in fish is close to 100% efficient, and it is eliminated slowly, with long biological half-lives of a few years in some species. Mercury concentrations in fish, therefore, reflect long exposure, and thus they are excellent bioindicators of aquatic contamination.

- Species-Specific Accumulation Patterns

Species differ greatly with regard to mercury accumulation ability based on their feeding ecology, age, habitat, and trophic level. For instance, pelagic fish (tuna, swordfish) have a higher accumulation of mercury than benthic fish due to their higher trophic level and longer lifetime (Karimi et al., 2013). Fish with a carnivorous or predatory habit has the maximum MeHg concentration, while herbivorous or planktivorous fish contains comparatively lower levels. Also, fish in oligotrophic lakes and ocean systems with lower productivity will have elevated MeHg levels since there are longer food chains and lower growth rates that support accumulation.

- Ecological and Human Health Implications

It is essential to understand species-specific mercury accumulation in order to make ecological risk assessments and public health recommendations. Species-level mercury data are frequently used for fish consumption advisories that target sensitive subpopulations, including pregnant women and children. Additionally, bioaccumulation studies help determine sentinel species for long-term monitoring programs in contaminated watersheds. Therefore, assessing the interaction between trophic dynamics and species biology offers key insight into mercury cycling and its wider environmental implications (table 3).

Table 3. *Mercury Bioaccumulation in Selected Fish Species*

Species	Trophic Level	Diet Type	Typical Hg Concentration (mg/kg wet weight)	Reference
Tuna (Thunnus sp.)	High	Piscivore	0.50–1.50	Cabana & Rasmussen, 1994
Pike (Esox lucius)	High	Carnivore	0.30–0.90	Karimi et al., 2013

Species	Trophic Level	Diet Type	Typical Hg Concentration (mg/kg wet weight)	Reference
Bass (Micropterus sp.)	Mid-High	Carnivore	0.20–0.70	Scheuhammer et al., 2007
Tilapia (Oreochromis sp.)	Low–Mid	Omnivore	0.05–0.15	Bloom, 1992
Mullet (Mugil sp.)	Low	Detritivore	0.02–0.10	Driscoll et al., 2013

This table illustrates how trophic status and feeding behavior directly influence mercury accumulation. High levels in predator species indicate the risk to both ecosystem and human health via dietary exposure. These facts guide fisheries management and environmental monitoring programs aimed at minimizing mercury-related risks.

4. ANALYTICAL TECHNIQUES FOR MERCURY IN FISH

Mercury exists in various chemical forms in aquatic environments, and the most bioavailable and toxic species is methylmercury (MeHg). Determination of total mercury (THg) and speciation analysis to isolate methylmercury from other species are thus necessary for analytical detection of mercury in fish. Traditional methods for the determination of total mercury are cold vapor atomic absorption spectrometry (CVAAS) and cold vapor atomic fluorescence spectrometry (CVAFS) since they are highly sensitive and specific (Martín-Doimeadios et al., 2004). However, while total mercury content gives a snapshot of contamination, it does not always reflect the bioactive fraction that is deposited in human consumers through diet. Recent developments have enabled more precise detection and determination of MeHg, particularly with the support of gas chromatography (GC) coupled with mass spectrometry (MS) or HPLC-ICP-MS (high-performance liquid chromatography–inductively coupled plasma–mass spectrometry). These techniques allow for detailed mercury speciation, which is important in environmental studies and risk assessments. Tools such as species-specific isotope dilution (SSID) are now more precise in complex biological matrices like fish tissues and becoming increasingly common in environmental monitoring schemes (Hintelmann et al., 2002).

In parallel, stable mercury isotopic analysis has also emerged as a useful tool to follow mercury sources and transformation pathways in ecosystems. Isotopic fingerprints give insights into whether mercury pollution is atmospheric, industrial, or geological in origin (Das et al., 2021). Isotope-ratio mass spectrometry (IRMS) now complements conventional tools by providing temporal and spatial patterns of mercury distribution even at trace levels. In addition, molecular biology techniques like biosensors, gene modified microbial systems, and metallothionein gene expression profiling are becoming low-cost, quick mercury detection technologies. Such tools are of great utility for in-the-field monitoring for remote areas or early warning systems (Zhang et al., 2022). All these advances combined hold out the potential for a more sophisticated and effective solution to mercury bioaccumulation hazard in fish (**Table 4**).

Table 4. *Analytical Methods for Mercury Detection in Fish*

Method	Target Form	Detection Limit (ng/g)	Advantages	Reference
CVAAS	Total Hg	~1–10	Simple, cost-effective	Martín-Doimeadios et al., 2004
HPLC-ICP-MS	MeHg, Inorganic Hg	<0.1	High resolution, precise speciation	Hintelmann et al., 2002
GC-MS	Methylmercury	<0.5	Accurate, sensitive in complex matrices	Wang et al., 2017
IRMS	Hg isotopes (MeHg)	<0.01	Source tracking, environmental tracing	Das et al., 2021
Fluorescent Biosensor Assay	Hg(II), MeHg	~0.2	Rapid, portable, good for field applications	Zhang et al., 2022

5. CASE STUDIES AND APPLICATIONS IN ENVIRONMENTAL MONITORING

Mercury pollution has been extensively investigated in various aquatic ecosystems using fish as bioindicators due to their ecological importance, mobility, and trophic position. Case studies in various environments provide strong evidence for the spatial heterogeneity and ecosystem-specific processes of mercury accumulation. For instance, in the Baltic Sea, high levels of methylmercury were reported in top predator species like pike and perch and directly related to industrial effluent and remobilization of sediment (Soerensen et al., 2022). The findings underscore the importance of sediment–water exchange and legacy pollution in semi-enclosed marine environments.

In freshwater systems, mercury pollution in most instances is indicative of artisanal gold mining, coal combustion, and agricultural runoff. The Amazon Basin case is basic, where chronic exposure to mercury via the food of fish led to bioaccumulation over several trophic levels, which had a significant impact on the indigenous population (Maurice-Bourgoin et al., 2021). Mercury concentrations in excess of the WHO safety level of 0.5 mg/kg have been reported in fish such as Cichla spp. that are carnivorous, and this affects food security and environmental health. Mixed dynamics characterize estuarine systems owing to tidal mixing and varying salinity gradients. Research in the Chesapeake Bay revealed varying mercury profiles between brackish and fresh areas, with spotted sea trout and striped bass showing site-specific accumulation patterns owing to organic carbon content and methylation rates (Hammerschmidt & Fitzgerald, 2006). Such case studies suggest the importance of localized monitoring schemes and taking environmental factors into account in risk assessment.

Besides, these applications provide valuable inputs for environmental regulation and policy. The European Union's Water Framework Directive and the U.S. EPA's Mercury and Air Toxics Standards (MATS) have applied such biomonitoring data to develop site-specific fish consumption advisories and support emission reduction efforts (UNEP, 2022). Hence, case-based studies not only describe patterns of contamination but also make valuable contributions towards adaptive environmental governance (**Table 5**).

Table 5. *Mercury Concentrations in Fish from Different Aquatic Systems*

Region/System	**Species Studied**	**Hg Level (mg/kg)**	**Ecosystem Type**	**Main Mercury Source**	**Reference**
Baltic Sea	Pike (*Esox lucius*)	0.72	Coastal	Industrial runoff, sediments	Soerensen et al., 2022
Amazon Basin	Peacock bass (Cichla spp.)	1.34	Freshwater	Artisanal mining, atmospheric input	Maurice-Bourgoin et al., 2021
Chesapeake Bay	Striped bass	0.45	Estuarine	Sediment methylation, riverine input	Hammerschmidt & Fitzgerald, 2006
Yellow River Estuary	Common carp (*Cyprinus carpio*)	0.61	Estuarine/Freshwater	Agricultural runoff, coal combustion	Li et al., 2018
Gulf of Mexico	Red drum (*Sciaenops ocellatus*)	0.53	Coastal	Oil/gas activity, atmospheric sources	UNEP, 2022

6. HUMAN HEALTH AND POLICY IMPLICATIONS

Mercury-contaminated fish consumption poses a significant health risk, especially to vulnerable populations such as pregnant women, infants, and subsistence fishers. Methylmercury (MeHg), the most dangerous, is highly bioavailable in the gastrointestinal tract and readily crosses the placenta and blood-brain barrier, resulting in neurodevelopmental impairment in fetuses and young children (Clarkson & Magos, 2006). Adult chronic exposure has been linked to cardiovascular disease, cognitive function impairment, and immunotoxicity (Mergler et al., 2007). Accordingly, fish is still the predominant entry route for human MeHg exposure, necessitating wide-ranging risk assessment to guide public health policy.

Risk assessment models typically consider levels of mercury in fish tissue, average rates of consumption, and human body weights to estimate a daily consumption and compare it against threshold values such as the U.S. EPA reference dose value of 0.1 µg/kg/day. Apex predators like swordfish and tuna, for example, will exceed safe thresholds, while smaller-lived and smaller-bodied species like tilapia or sardines will pose lower risks (Karimi et al., 2012). This distinction lends support to species-specific advisories rather than blanket prohibitions, encouraging consumer choice while maintaining public health protection.

Incorporation of scientific findings into environmental legislation has led to the establishment of national and international guidelines. The Minamata Convention on Mercury, which was signed by over 140 countries, is a testament to global commitment to reducing mercury emissions and exposure (UNEP, 2017). At the regional level, countries like Sweden and Canada have issued fish consumption guidelines based on the results of ongoing biomonitoring, while the U.S. FDA and EPA collaboratively release guidelines for at-risk groups. They depend mainly on bioindicator information, specifically from fish with local loads of pollution reflected in them. Therefore, ecological monitoring convergence and public health policy emphasize the value of interdisciplinary thinking. Strong environmental health surveillance systems, backed by real-time bioindicator evidence such as fish, are essential to ensure adaptive and evidence-based policy making. In addition to decreasing human exposure risk, these systems inform upstream regulations on industrial effluent emissions, wastewater treatment, and environmental justice (**Figure 1**).

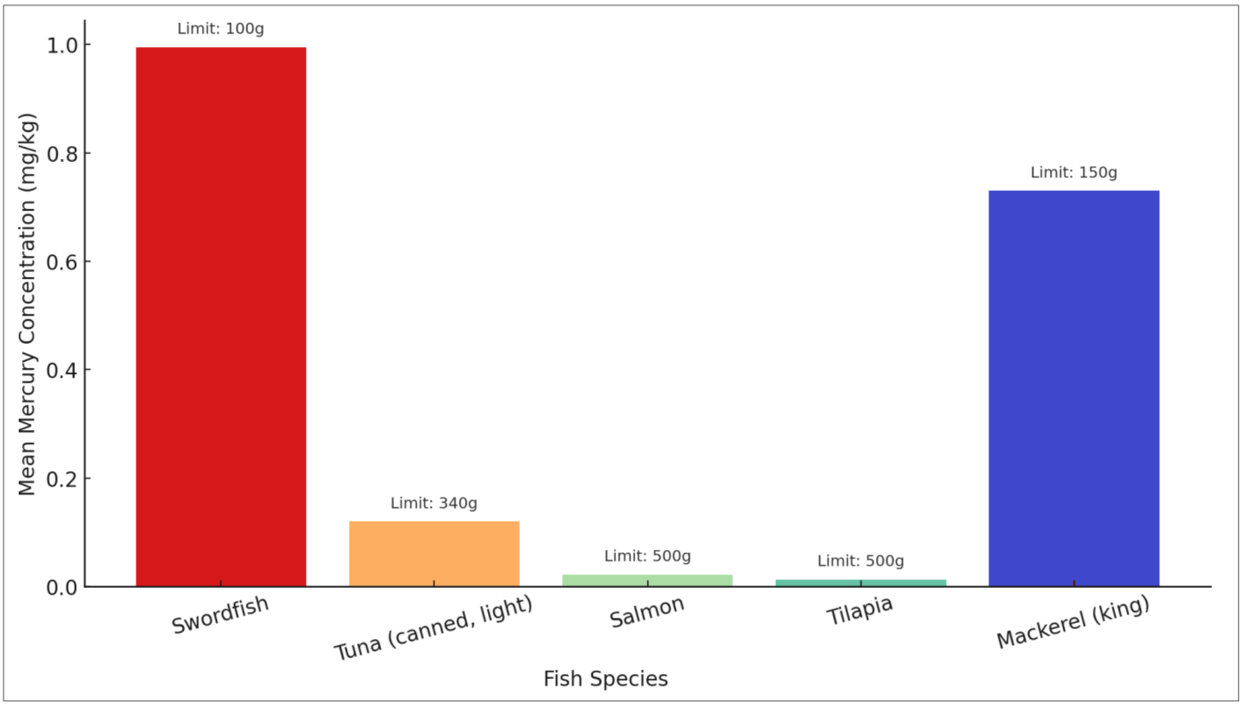

Figure 1. *Risk Levels of Mercury Exposure from Commonly Consumed Fish ; **Source**: Adapted from Karimi et al. (2012); U.S. EPA (2023)*

7. CONCLUSION AND FUTURE DIRECTIONS

Application of fish as bioindicators to measure environmental mercury contamination in the environment is an ecologically understandable and scientifically warranted means of gauging well-being in aquatic environments. However, large shortfalls are present when it comes to standardization of mercury monitoring method among geographic catchments and between research institutes. Inconsistency in analysis method, sampling design, and reporting structure usually is responsible for failure to compare data as well as prevent global assessment. Furthermore, feeding behavior, habitat use, and species physiology variation complicate understanding mercury bioaccumulation trends. Such differences can be addressed by the use of harmonized guidelines setting identical standards for the detection of mercury—separately distinguishing total mercury and methylmercury concentrations—such that greater cross-study comparison and risk assessment can be conducted.

Future endeavors must be directed toward implementing comprehensive monitoring programs that integrate ecological, toxicological, and human health data into a common paradigm. Integration would not only improve temporal and spatial resolution in mercury evaluation but also provide the foundation for adaptive policy action to emerging threats. Integration of molecular and isotopic methods with traditional biomonitoring will improve sensitivity and specificity to enable identification of sources and processes of transformation for mercury. Moreover, citizen science initiatives, remote sensing technologies, and data analysis through artificial intelligence can play an important role in real-time monitoring and early warning systems. Lastly, there has to be a multidisciplinary and cooperative effort to mitigate the risks of mercury exposure, protect aquatic biodiversity, and enhance food safety among vulnerable populations.

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