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Contaminated Waters: A Comprehensive Review of Heavy Metal Pollution in Marine Fish and Its Health Risks

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Abstract. Marine fish are crucial for the global food supply, providing essential nutrients to millions of people throughout the world. However, the presence of high levels of heavy metals in marine fish has become a significant risk to both human health and the sustainability of the fishing industry. This article is to provide a concise overview of recent scientific studies on the presence of heavy metals in marine fish products and the potential consequences for human health. The examination encompasses a range of frequently encountered heavy metals, along with the factors that affect the levels of pollution. This review also explores the geographical distribution of contaminated fish, pinpointing areas with high levels of contamination that necessitate focused attention. This study utilizes an comprehensive literature search technique by searching databases with the inclusion criteria of comprising relevant and recently published studies. The extracted data comprises information on the degrees of contamination, the fish species that are affected, and the health consequences that arise from consuming infected fish. This article also emphasizes the necessity for further research to address existing knowledge gaps and develop more efficient technologies and policies for managing heavy metal contamination in marine environments.

1 Introduction

Marine fish are a crucial component of the global food supply, providing a rich source of high-quality protein, essential fatty acids, vitamins, and minerals [1]. The consumption of marine fish is associated with numerous health benefits, including improved cardiovascular health, enhanced brain function, and reduced risk of certain chronic diseases [2]. These

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benefits are largely attributed to the high content of omega-3 fatty acids, vitamin D, selenium, and other essential nutrients found in fish [3,4]. Globally, the trade of fish and fishery products contributes substantially to national economies, with the export of fish products generating significant revenue for many countries [5].

However, the issue of heavy metal contamination in marine fish poses a serious threat to both human health and the sustainability of the fishing industry [6]. Heavy metals such as mercury, lead, cadmium, and arsenic are persistent environmental pollutants that can accumulate in marine ecosystems through both natural processes and human activities [7]. Industrial discharge, agricultural runoff, mining, and waste disposal are among the major anthropogenic sources of these contaminants [8]. Once in the marine environment, heavy metals can be taken up by aquatic organisms and biomagnified through the food chain, leading to high concentrations in predatory fish species commonly consumed by humans [9].

The consumption of fish contaminated with heavy metals can have severe health implications. Heavy metals are known to be toxic, with potential effects including neurotoxicity, carcinogenicity, and damage to various organs and systems in the body [10] For instance, mercury exposure is particularly harmful to the developing brains of fetuses and young children, while cadmium and lead exposure are linked to kidney damage and hypertension [11]. Arsenic exposure has been associated with skin lesions, cancer, and cardiovascular diseases [12]. Given these risks, understanding the extent of heavy metal contamination in marine fish and its impact on human health is of paramount importance [6]

The primary aim of this literature review is to compile and analyze recent studies on heavy metal contamination in marine fish and its impacts on human health. This review seeks to provide a comprehensive overview of the types and levels of heavy metals found in different marine fish species, the sources and pathways of contamination, and the geographical distribution of contaminated fish. Additionally, the review will examine the toxicological effects of heavy metals, summarize epidemiological evidence linking fish consumption to health outcomes, and discuss risk assessments conducted in recent studies. By synthesizing the findings from a wide range of research, this review aims to highlight current knowledge gaps, identify areas requiring further investigation, and provide evidence-based recommendations for public health policies and consumer guidelines.

Finally, the findings of this review are highly relevant for informing public health policies aimed at mitigating the risks associated with heavy metal contamination in marine fish. Policymakers can use the insights gained from this review to develop and implement regulations and guidelines that limit the levels of heavy metals in seafood, ensuring safer consumption for the public. This is particularly important for vulnerable populations such as pregnant women, young children, and communities with high fish consumption rates.

2 Types of heavy metals found in marine fish

Heavy metals, defined by their high atomic weights and densities, are elements that can be harmful even in minute quantities [13]. These metals are persistent environmental pollutants, and their toxic effects pose significant threats to both marine ecosystems and human health [14]. In marine fish, several heavy metals have been identified as key pollutants of concern. The most prevalent and hazardous among these are mercury (Hg), lead (Pb), cadmium (Cd), arsenic (As), and chromium (Cr) [15, 16].

2.1 Mercury (Hg)

Mercury is one of the most dangerous heavy metals commonly found in marine fish, particularly in its organic form, methylmercury [17]. Methylmercury is highly toxic and can easily bioaccumulate in organisms higher up the food chain, including large predatory fish such as tuna and swordfish [18]. This bioaccumulation process results in higher concentrations of mercury in these species, which, when consumed by humans, can lead to severe health issues [19]. The most concerning effects of mercury exposure include damage to the nervous system, particularly in developing fetuses, making it a significant concern for pregnant women and young children [20].

2.2 Lead (Pb)

Lead contamination in marine environments is predominantly a result of industrial activities, urban runoff, and atmospheric deposition [21]. In fish, lead tends to accumulate in the gills, liver, and bones, though muscle tissues can also harbor residues [22]. The presence of lead in marine fish is alarming due to its potential to cause chronic health issues in humans who consume contaminated seafood. Long-term exposure to lead is known to result in neurotoxicity, affecting cognitive functions, as well as kidney damage and cardiovascular complications [23].

2.3 Cadmium (Cd)

Cadmium is another highly toxic metal frequently detected in marine fish. Its presence is mainly attributed to industrial processes such as mining, metal refining, and the application of phosphate fertilizers in agriculture [24]. Once released into the marine environment, cadmium is absorbed by aquatic organisms and tends to accumulate in the kidneys and liver of fish [25]. The consumption of cadmium-contaminated fish can lead to serious health issues in humans, including renal dysfunction, bone demineralization, and an increased risk of developing cancer [26].

2.4 Arsenic (As)

Arsenic occurs in both organic and inorganic forms in marine environments. While marine fish predominantly contain organic arsenic, which is less harmful, certain species can accumulate inorganic arsenic, which is far more [27]. Chronic exposure to inorganic arsenic through the consumption of contaminated fish can lead to severe health problems, including skin lesions, developmental effects, cardiovascular disease, and an elevated risk of cancer. This makes monitoring arsenic levels in marine fish critical for ensuring food safety [12, 28].

2.5 Chromium (Cr)

Chromium in marine environments exists primarily in two oxidation states: trivalent chromium (Cr III), which is less toxic, and hexavalent chromium (Cr VI), which is highly toxic [29]. Chromium contamination in marine fish often stems from industrial activities such as tanning, electroplating, and the production of stainless steel [30]. The ingestion of fish contaminated with hexavalent chromium can lead to various health issues, including gastrointestinal distress, liver and kidney damage, and a heightened risk of cancer [31]. The toxicological impacts of chromium underscore the importance of regulating industrial discharges to protect marine life and human consumers [32].

3 Sources and factors influencing heavy metal contamination

The contamination of marine fish by heavy metals arises from various sources, both natural and anthropogenic, with several factors influencing the extent and distribution of these pollutants in marine ecosystems [6]. The sources of heavy metal contamination in marine fish are explained in detail in Fig. 1.

3.1 Natural sources

Natural occurrences such as volcanic eruptions, weathering of metal-rich rocks, and oceanic hydrothermal vents contribute to the background levels of heavy metals in marine environments. However, these natural sources are often overshadowed by anthropogenic activities [33, 34].

3.2 Industrial discharges

One of the primary sources of heavy metal contamination in marine environments is the discharge of industrial effluents. Industries such as mining, metal processing, and chemical manufacturing release heavy metals like mercury, lead, and cadmium into nearby water bodies. These metals can travel long distances in the water column and accumulate in sediments, eventually being absorbed by marine organisms [35, 36].

3.3 Agricultural runoff

The use of phosphate fertilizers, pesticides, and fungicides in agriculture can lead to the runoff of heavy metals like cadmium and arsenic into marine ecosystems. This runoff is particularly concerning in coastal areas where agricultural activities are prevalent, leading to localized contamination hotspots [37,38].

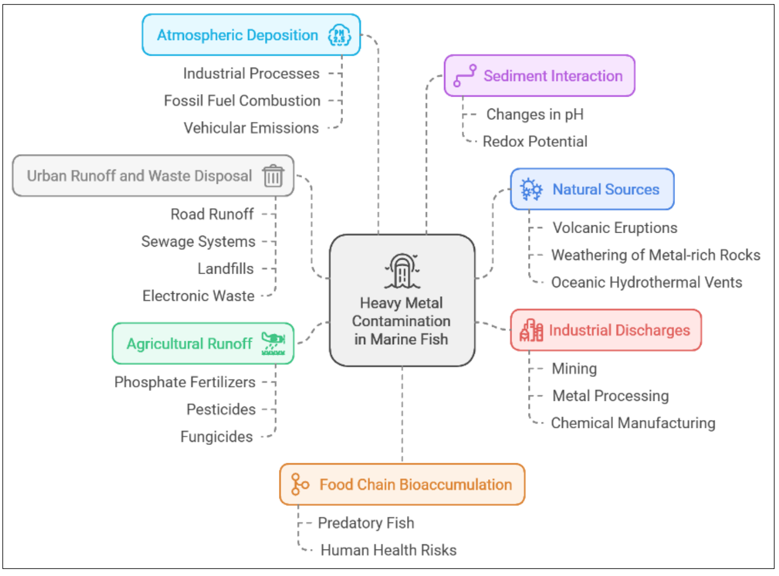

Fig. 1. Heavy metal contamination in marine fish

3.4 Urban runoff and waste disposal

Urbanization and improper waste disposal practices contribute significantly to the heavy metal load in marine environments. Runoff from roads, sewage systems, and landfills often contains lead, chromium, and other metals, which can find their way into the ocean. Additionally, improper disposal of electronic waste can release various heavy metals, including mercury and lead, into the marine ecosystem [39, 40].

3.5 Atmospheric deposition

Atmospheric deposition of heavy metals occurs through the fallout of airborne particles emitted from industrial processes, fossil fuel combustion, and vehicular emissions. These particles can travel long distances before settling into marine environments, introducing heavy metals like mercury and lead into the water [41, 42].

3.6 Sediment interaction

The interaction between heavy metals and marine sediments plays a crucial role in determining the availability and mobility of these pollutants. Metals bound to sediments can be remobilized under certain environmental conditions, such as changes in pH or redox potential, leading to increased bioavailability and uptake by marine organisms [43, 44].

3.7 Food chain bioaccumulation

The process of bioaccumulation, where heavy metals accumulate in the tissues of organisms at each trophic level, is a significant factor in determining the concentration of heavy metals in marine fish. Predatory fish at the top of the food chain tend to have higher concentrations of heavy metals, posing greater health risks to humans who consume them [9, 45].

4 Geographical distribution of contaminated fish

Mercury accumulation in marine fish varies based on species, age, size, and feeding habits. Larger, long-lived predatory fish tend to have higher mercury concentrations due to biomagnification [46]. Key species affected include (1) tuna, which is known for high mercury levels due to their position at the top of the marine food chain, (2) swordfish, another top predator with significant mercury accumulation, (3) sharks: Large, long-lived species like sharks exhibit high mercury concentrations, and (4) mackerel and king mackerel, species with notable mercury levels due to their diet and longevity [47].

Recent studies provide valuable insights into the current levels of mercury contamination in marine fish was presented in Table 1 [46, 47].

Table 1. Geographical distribution of mercury contaminated fish in different oceans and seas

No	Area	Fish Species	Level	Source
1	Marano and Grado Lagoon, Northern Adriatic Sea, Italy	Grass Goby (*Zosterisessor ophiocephalus*)	0.61 - 0.74 mg/kg ww	[48]
2	Marano and Grado Lagoon, Northern Adriatic Sea, Italy	Peacock Blenny (*Salaria pavo*)	1.6 - 1.7 mg/kg ww	[48]

3	Marano and Grado Lagoon, Northern Adriatic Sea, Italy	Mediterranean Banded Killifish (*Aphanius fasciatus*)	0.49 - 1.7 mg/kg ww	[48]
4	Gomataon and Sinangoé, Ecuadorian Amazon	Multiple species including Piscivores and Omnivores	Exceeded international limits	[49]
5	Vaal Dam, South Africa	Various fish species including *Labeobarbus kimberleyensis*	0.101 mg/kg (in one species)	[50]
6	Noakhali, Bangladesh (Meghna River Estuary)	15 fish species sampled, which is widely consumed in Bangladesh	Mercury levels measured (values not provided)	[51]
7	Coastal Mediterranean (Location unspecified)	*Umbrina cirrosa* and *Sciaena umbra*	0.18 - 0.19 ug/g ww	[52]

Lead contamination varies among fish species due to differences in habitat, feeding habits, and trophic levels. Generally, bottom-dwelling fish and species that feed on benthic organisms tend to have higher lead concentrations. Recent studies provide insights into the levels of lead contamination in various marine fish species across different regions. Summary of the latest research on lead contamination levels in marine fish was presented in Table 2.

Table 2. Geographical distribution of lead contaminated fish in different oceans and seas.

No	Area	Fish species	Level	Source
1	Bandung Raya, Indonesia	Tuna, tilapia, catfish	0.152 - 0.285 mg/kg	[53]
2	Maninjau Lake, West Sumatra	*R. argyrotaenia*, tilapia	exceeds 0.03 mg/L threshold.	[54]
3	Donan River, Cilacap, Central Java	Whiting fish (*Sillago sihama*)	ranging from 1.24 to 9.19 ppm (exceeding safety limits)	[55]
4	Lamat River, Magelang, Central Java	Unspecified fish species	values between 0.3807-0.7268 µg/g (exceed SNI)	[56]
5	Banjir Kanal Timur, Semarang	Unspecified fish species	up to 31.35 ppm	[57]
6	Mellat Lake, Iran	Common carp	0.487 - 8.107 mg/kg	[58]
7	Lahore, Pakistan	*Labeo rohita*	0.83 - 5.73 ug/g in muscle	[59]
8	Marano, Lagoon, Italy	*U. cirrosa*, *S. umbra*	0.10 - 0.12 ug/g	[52]
9	Mediterranean Sea	Bony fish species	0.01 – 0.67 ppm	[60]

Marine fish accumulate arsenic primarily through the food they consume and to a lesser extent through direct absorption from water. Arsenic in marine environments exists in various forms, with organic arsenic compounds (e.g., arsenobetaine) being predominant in marine organisms. These organic forms are generally less toxic than inorganic arsenic, but concerns remain due to potential conversion between forms. Recent studies have highlighted varying levels of arsenic contamination in marine fish across different regions, which is presented in Table 3.

Table 3. Geographical distribution of arsenic contaminated fish in different oceans and seas.

No	Area	Fish Species	Level	Source
1	Aiba Reservoir, Iwo, Nigeria	Various species including *Oreochromis niloticus*, *Tilapia zillii*, *Channa obscura*	1.46 - 49.95 ppb (varied by tissue type)	[61]
2	Polish Market (Multiple Locations)	Various fish species (general market samples)	Total As: 0.46 mg/kg, Inorganic As: ND (<0.025 mg/kg)	[62]
3	East Kolkata Wetlands, India	*Channa punctata, Anabas testudineus, Heteropneustes fossilis*	0.14 - 0.67 mg/kg	[63]
4	Nile River, Egypt	Nile Tilapia (*Oreochromis niloticus*)	1.33 mg/kg (in muscle tissue)	[64]
5	Ganges River, India	*Labeo rohita, Cirrhinus mrigala*	0.32 - 1.50 mg/kg (in muscle tissue)	[65]

Marine fish can accumulate cadmium through several routes, primarily through their diet and, to a lesser extent, through direct absorption from the water. Recent studies have documented varying levels of cadmium contamination in marine fish across different regions. Below are some examples from recent research, presented in Table 4.

Table 4. Geographical distribution of cadmium contaminated fish in different oceans and seas.

No	Area	Fish Species	Level	Source
1	Nanded, Maharashtra, India	Ophiocephalus striatus (*Channa striatus*)	0.58 - 0.63 mg/L (LC50 at 96 hours)	[66]
2	Kolkata, West Bengal, India	*Labeo rohita, Catla catla*	Detected in market samples, values not specified	[67]
3	Egypt (General Area)	*Oreochromis niloticus* (nile tilapia)	0.12 - 1.46 mg/kg in muscle tissue	[68]
4	China (Yellow River Area)	*Cyprinus carpio* (Common Carp)	0.05 - 0.28 mg/kg	[25]

5 Health impacts of consuming contaminated fish

The consumption of fish contaminated with heavy metals such as mercury, lead, cadmium, and arsenic poses significant risks to human health [7]. This subchapter explores the toxicological effects of these metals, reviews epidemiological evidence linking fish consumption to adverse health outcomes, and discusses risk assessment findings related to safe consumption levels.

5.1 Toxicological effects of heavy metals

Heavy metals present in contaminated fish can have a range of toxicological effects on human health, depending on the metal involved and the level of exposure.

5.1.1 Mercury

Mercury, particularly in its methylmercury form, is one of the most toxic heavy metals found in fish. Methylmercury is highly neurotoxic and can cross the blood-brain barrier, leading to neurological impairments [69]. Chronic exposure to methylmercury, even at low levels, can cause cognitive deficits, motor dysfunction, and developmental delays, especially in fetuses and young children. Additionally, mercury exposure has been linked to cardiovascular diseases and immune system dysfunction in adults [70].

5.1.2 Lead

Lead is another toxic metal that can accumulate in the human body through the consumption of contaminated fish [71]. Lead exposure is particularly harmful to the nervous system, causing neurotoxicity that can manifest as cognitive impairments, behavioral changes, and developmental delays in children [71, 72]. Long-term exposure to lead has also been associated with kidney damage, hypertension, and reproductive toxicity in adults [73, 74].

5.1.3 Cadmium

Cadmium exposure through fish consumption primarily affects the kidneys and bones. Cadmium is a known nephrotoxin, leading to renal dysfunction and increased risk of chronic kidney disease [75, 76]. It also disrupts calcium metabolism, resulting in bone demineralization and an increased risk of fractures [77, 78]. Furthermore, cadmium is classified as a human carcinogen, with links to lung and prostate cancers. [76, 79].

5.1.4 Arsenic

Arsenic exposure, particularly from inorganic arsenic in contaminated fish, can lead to severe health consequences. Chronic arsenic exposure is associated with skin lesions, cardiovascular disease, and neurotoxicity. Arsenic is also a well-established carcinogen, with strong evidence linking it to skin, lung, and bladder cancers. The consumption of arsenic-contaminated fish can significantly increase the risk of these health outcomes fish [12].

5.2 Epidemiological evidence

A growing body of epidemiological research has established links between fish consumption and adverse health outcomes due to heavy metal contamination.

5.2.1 Mercury and neurodevelopmental disorders

Several epidemiological studies have demonstrated a clear association between prenatal exposure to methylmercury from fish consumption and neurodevelopmental disorders in children. For example, research conducted in the Faroe Islands found that children exposed to higher levels of methylmercury in utero had lower scores on cognitive tests and delayed motor skills development [70, 80].

5.2.2 Lead and cardiovascular disease

Epidemiological studies have also linked lead exposure from fish consumption to an increased risk of cardiovascular diseases [81]. Lamas [82] and Collin [83] found that individuals with higher blood lead levels, likely due to contaminated fish consumption, had a significantly higher risk of developing hypertension and coronary artery disease.

5.2.3 Cadmium and renal dysfunction

The toxic effects of cadmium on the kidneys have been well-documented in epidemiological studies. Research in populations with high fish consumption has shown a higher prevalence of chronic kidney disease and other renal dysfunctions among those with elevated cadmium levels [84].

5.2.4 Arsenic and cancer risk

Epidemiological evidence strongly supports the link between arsenic exposure and cancer. Studies in regions with high arsenic contamination have reported significantly higher rates of skin, lung, and bladder cancers in populations with high fish consumption [85].

5.3 Risk assessment

Risk assessment studies aim to determine safe consumption levels for fish to minimize the health risks associated with heavy metal contamination. These studies often consider factors such as the metal concentration in fish, the frequency and quantity of fish consumption, and the vulnerability of specific populations.

5.3.1 Mercury

The U.S. Environmental Protection Agency (EPA) has set a reference dose (RfD) for methylmercury at 0.1 micrograms per kilogram of body weight per day, which is intended to protect against neurodevelopmental effects in children [86]. However, studies suggest that even lower levels of mercury exposure can be harmful, particularly for pregnant women and young children, and necessitating stricter consumption guidelines.

5.3.2 Lead

For lead, there is no safe level of exposure, as even low levels can cause significant health effects. The Centers for Disease Control and Prevention (CDC) recommends minimizing lead exposure as much as possible, especially in vulnerable populations like children and pregnant women [87].

5.3.3 Cadmium

The European Food Safety Authority (EFSA) has established a tolerable weekly intake (TWI) for cadmium at 2.5 micrograms per kilogram of body weight, based on its nephrotoxic effects [88]. However, risk assessments indicate that populations with high fish consumption may exceed this TWI, highlighting the need for targeted public health interventions in these regions.

5.3.4 Arsenic

For arsenic, risk assessments focus on minimizing exposure to inorganic forms, as these are the most toxic. The World Health Organization (WHO) recommends a provisional tolerable weekly intake (PTWI) of 15 micrograms per kilogram of body weight for inorganic arsenic, although recent studies suggest that even lower levels of exposure may increase cancer risk [89]. These findings support the need for ongoing monitoring and regulation of arsenic levels in seafood.

6 Mitigation strategies and recommendations

Heavy metal contamination in marine fish is a significant public health and environmental concern. Effective strategies are necessary to control contamination, ensure seafood safety, and protect human health.

6.1 Regulatory measures

International and national regulations limit heavy metals in seafood. Organizations like the WHO and FAO set global standards for contaminants like mercury and lead in fish, protecting consumers and supporting safe trade [90]. National agencies, such as the EPA in the U.S. and EFSA in Europe, enforce these limits and may add measures based on local needs [91, 92].

6.2 Monitoring and assessment

Monitoring is essential for tracking heavy metal levels and ensuring seafood safety. Agencies collect samples from water, sediments, and marine life, using advanced technologies like atomic absorption spectrometry (AAS) and inductively coupled plasma mass spectrometry (ICP-MS) to detect contamination [93]. Innovations like portable sensors and satellite-based monitoring enhance real-time detection and identification of contamination hotspots.

6.3 Public health recommendations

Health authorities provide guidelines to minimize exposure to heavy metals. For example, the U.S. FDA advises pregnant women and children to avoid high-mercury fish and choose safer options like salmon. Public health campaigns play a crucial role in educating consumers about the risks and promoting safer seafood choices.

6.4 Future research

Ongoing research aims to improve understanding of metal accumulation, develop removal technologies, and assess long-term health impacts, with global collaboration key to tackling marine pollution [94].

7 Conclusion

This review underscores the serious health risks of heavy metal contamination in marine fish, emphasizing the need for stricter regulations, ongoing monitoring, and public awareness to protect vulnerable populations. It highlights the importance of further research to develop better strategies for managing contamination and ensuring the safety of marine resources.

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