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Research article

Global and Local Perspectives on Heavy Metal Contamination and Associated Human

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Abstract
Heavy metal contamination of ecosystems represents a significant global threat to both environmental integrity and human health. This comprehensive review synthesizes evidence from 205 scientific studies to analyse the global panorama and a detailed Nigerian case study on heavy metal bioaccumulation in fish and the associated human health risks. The analysis reveals severe and widespread contamination, with South Asia and specific African regions, particularly Nigeria's Niger Delta, identified as critical hotspots. Heavy metals such as lead, cadmium, mercury, and arsenic remain highly prevalent across aquatic and terrestrial food chains, frequently exceeding international limits and demonstrating strong tissue-specific bioaccumulation particularly in liver, kidney, and fatty tissues. Furthermore, carcinogenic risks from arsenic and other metals often surpass acceptable limits, indicating a long-term cancer threat to regular consumers. The Nigerian context underscores unique exacerbating factors, including extreme pollution from petroleum activities and the alarming role of traditional smoke drying, which can concentrate toxic metals in fish by over 100%, dramatically amplifying consumer exposure. This review identifies major gaps in current research and surveillance, including inconsistent risk assessment methods, limited contaminant speciation, underrepresentation of modern pesticides, a lack of data on metal mixtures and human biomarkers, and insufficient cumulative risk assessment for multi-chemical exposures. To address this silent public health crisis, the conclusion proposes an integrated framework of actions, including the urgent standardization of monitoring, stringent enforcement of industrial pollution controls, targeted consumer safety advisories, and the promotion of safer food processing technologies and sustainable aquaculture.

Keywords: Heavy metals, Bioaccumulation, Fish consumption, Health risk assessment, Target Hazard Quotient, Carcinogenic risk, Nigeria, Global review, Aquatic pollution

INTRODUCTION

Fish represent a vital source of high-quality protein, essential omega-3 fatty acids, vitamins, and minerals for billions of people worldwide, particularly in coastal regions and developing nations. For instance, in Nigeria and many similar countries, fish consumption constitutes a cornerstone of food security, providing over 60% of the animal protein intake for the population (Abalaka *et al.,* 2020; FAO, 2022). This dietary reliance underscores the critical public health and nutritional importance of safe and uncontaminated fish supplies.

However, the integrity of this crucial food resource is increasingly compromised by pervasive anthropogenic pollution. Aquatic ecosystems globally serve as the ultimate sink for contaminants from industrial effluents, agricultural runoff laden with pesticides and fertilizers, mining operations, municipal waste, and fossil fuel extraction (Ahmed *et al.,* 2015). Among these pollutants, heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), and nickel (Ni) are of paramount concern due to their toxicity, persistence, and bio-accumulative potential. Unlike organic pollutants, metals are non-biodegradable and can accumulate in sediments, acting as long-term sources of contamination (Ali and Khan, 2018).

Extensive research demonstrates that fish efficiently accumulate these metals from their environment, through direct uptake from water via gills, ingestion of contaminated food, or contact with sediments. This leads to bio-concentration, where metal levels in fish tissues far exceed those in the surrounding water (Authman *et al.*, 2012; El-Moselhy *et al.*, 2014). The phenomenon of bio-magnification further exacerbates the risk, as predatory fish at higher trophic levels can accumulate staggering concentrations of metals like mercury (Plavan *et al.*, 2017). Consequently, fish transform from a nutritious food source into a primary vector for human exposure to toxic metals.

The human health implications of chronic dietary exposure to metal-contaminated fish are severe and well-documented. Non-carcinogenic risks include neurotoxic effects (e.g., from Pb and Hg, leading to cognitive impairment), nephrotoxicity (primarily from Cd), cardiovascular damage, and developmental disorders (Jovanović *et al.*, 2017; Lipy *et al.*, 2021). Furthermore, several metals are recognized human carcinogens. The International Agency for Research on Cancer (IARC) classifies arsenic and hexavalent chromium as Group 1 carcinogens (carcinogenic to humans), and cadmium and lead as Group 2A (probably carcinogenic to humans) (IARC, 2023). Health risk assessments, employing models like the Target Hazard Quotient (THQ) and carcinogenic risk (CR), consistently identify elevated risks from frequent consumption of fish from polluted waterways across the globe (Abd-Elghany *et al.*, 2024; Han *et al.*, 2021).

The present review is guided by four specific objectives. First, to establish a global panorama of heavy metal contamination in fish and associated human health risks by synthesising findings from 100 international studies across Asia, Europe, and the Middle East, thereby mapping worldwide contamination trends and benchmark risk levels. Second, to provide a focused, localised analysis of Nigeria as a high-burden case study by examining 105 national studies. Third, to compare global and Nigerian findings to identify universal contamination drivers, contextualise the severity of local pollution, and highlight unique exacerbating factors including the alarming role of traditional smoke-drying which can concentrate toxic metals in fish by over 100%. Fourth, to formulate targeted, evidence-based recommendations for monitoring, remediation, and public health policy. To achieve these objectives, this review synthesises three decades of research employing a dual-scope analytical framework, juxtaposing broad international patterns with detailed Nigerian data. Ultimately, the review aims to bridge scientific evidence and actionable solutions to safeguard both aquatic ecosystems and human health.

METHODOLOGY

Search Strategy

A systematic literature search was conducted on 15 January 2025 across four electronic databases: Scopus, Web of Science, PubMed, and Google Scholar. The search employed the following Boolean string: ("heavy metal*" OR "trace metal*" OR "lead" OR "cadmium" OR "mercury" OR "arsenic" OR "chromium" OR "nickel") AND ("fish" OR "fishery" OR "aquatic" OR "seafood") AND ("bioaccumulation" OR "contamination") AND ("health risk" OR "Target Hazard Quotient" OR "THQ" OR "carcinogenic risk"). For country-specific searches, the following modifier was appended: AND ("Nigeria" OR "Bangladesh" OR "Pakistan" OR "India" OR "Egypt" OR "Ghana" OR "China" OR "Saudi Arabia" OR "Turkey" OR "Europe"). The temporal scope primarily encompassed studies published between 1 January 2000 and 31 December 2024. Seminal older works (pre-2000) were included only if cited as foundational references (n = 5).

Inclusion and Exclusion Criteria

Inclusion criteria comprised: (1) original research articles measuring concentrations of one or more heavy metals (Pb, Cd, Hg, As, Cr, Ni, Cu, Zn) in edible tissues (muscle) of wild or cultured fish; (2) studies conducting quantitative human health risk assessments using standard models (EDI, THQ, HI, CR); and (3) articles published in peer-reviewed journals in English.

Exclusion criteria included: (1) review articles, conference abstracts, or grey literature; (2) studies focusing exclusively on water/sediment without fish tissue analysis; (3) studies analysing only non-edible tissues (liver/gills only) without muscle tissue; (4) studies lacking a human health risk assessment component; (5) duplicate publications.

Study Selection and Data Extraction

Initial search yielded 847 records. After duplicate removal (n = 312), 535 titles and abstracts were screened. Full-text review of 312 articles resulted in 205 studies meeting all inclusion criteria. Screening followed PRISMA guidelines (Page *et al.*, 2021).

These were categorized into two groups: 100 "International" studies representing a global perspective (excluding Nigeria), and 105 "Local" studies focused exclusively on Nigeria, providing a dense, regional case study.

Data extracted from each study included: geographic location, water body type, fish species studied, sample size, analytical method (e.g., AAS, ICP-MS), metals analyzed, concentration ranges in muscle tissue (mg/kg wet weight), reported risk indices (THQ, HI, CR), consumption parameters (ingestion rate, body weight), and reference dose (RfD) or cancer slope factor (CSF) sources.

Quality Assessment

Study quality was assessed using a modified version of the NAVIGATOR tool for environmental health risk assessments. Criteria included: (1) clear definition of study population/sampling sites (score 0-2); (2) appropriate analytical method with QA/QC reporting (0-2); (3) adequate sample size ($n \geq 10$ per species) (0-1); (4) use of standard risk assessment models (0-1); (5) reporting of uncertainty/limitations (0-1). Maximum score = 7.

Studies scoring ≥5 were considered high quality (n = 142, 69%); scores 3-4 moderate (n = 51, 25%); scores ≤2 low quality (n = 12, 6%). Low-quality studies were excluded from quantitative synthesis but retained for qualitative themes.

Synthesis Approach

This review employs a narrative synthesis rather than formal meta-analysis due to substantial heterogeneity across studies in: (a) exposure parameters (consumption rates ranging 15-150 g/day); (b) analytical methods (AAS vs. ICP-MS, varying detection limits); (c) risk assessment models (differing RfD sources); (d) fish species and size classes; and (e) regional dietary patterns. Where appropriate, ranges of reported HI and CR values are presented to illustrate risk distributions. Findings were organized thematically by region and risk outcome.

Standardisation of Risk Metrics

To enable cross-study comparison, all extracted risk values were standardised to common thresholds:

i. THQ/HI: >1 = unacceptable non-carcinogenic risk (USEPA, 2022)
ii. CR: $>1\times10^{-6}$ = unacceptable carcinogenic risk (USEPA, 2022)
iii. Standard reference consumption rate: 50 g/day for adults in developing countries (FAO/WHO, 2022), with local variations noted where studies used different values
iv. Standard reference body weight: 70 kg for adults (USEPA, 2022)

Health Risk Assessment Models

The reviewed studies predominantly employed the US Environmental Protection Agency (USEPA) risk assessment framework, consistently applied across international and Nigerian contexts:

Estimated Daily Intake (EDI): $EDI = (C_{metal} \times IR) / BW$, where C_{metal} is metal concentration in fish (mg/kg), IR is daily ingestion rate (kg/person/day), and BW is average body weight (kg).

Target Hazard Quotient (THQ): $THQ = EDI / RfD$, where RfD is the oral reference dose (mg/kg/day). THQ < 1 indicates no significant non-carcinogenic risk.

Hazard Index (HI): Sum of THQs for all metals studied. HI < 1 suggests safe exposure.

Carcinogenic Risk (CR): $CR = EDI \times CSF$, where CSF is the cancer slope factor $(mg/kg/day)^{-1}$. $CR > 1\times10^{-6}$ is considered unacceptable.

GLOBAL PANORAMA OF HEAVY METALS IN FISH AND HEALTH RISKS

Regional Patterns of Contamination and Risk

A synthesis of 100 international studies revealed stark geographical disparities in contamination, closely linked to industrial activity and regulatory rigour. South Asia is a global hotspot, with studies from Bangladesh (Ahmed *et al.*, 2015; Kawser Ahmed *et al.*, 2016; Khatun *et al.*, 2021), Pakistan (Qadir and Malik, 2011; Ali and Khan, 2018; Yasmeen and Rafique, 2024), and India (Giri and Singh, 2014; Tiwari *et al.*, 2017; Maurya and Malik, 2019; Prakash *et al.*, 2023) frequently reporting Hazard Index (HI) values exceeding 1 and unacceptable carcinogenic risks.

North Africa, particularly Egypt (Sallam *et al.*, 2019; Abd-Elghany *et al.,* 2024; Khedr and Ghannam, 2025), presents similar elevated risks, whereas the Middle East (Said *et al.,* 2014; Idris *et al.,* 2015; El-Bahr and Abdelghany, 2015; Maleki *et al.*, 2015; Plavan *et al.*, 2017; Alipour and Banagar, 2018) and Sub-Saharan Africa (Nyingi *et al.*, 2016; Saria, 2016; Gyimah *et al.*, 2018; Kwaansa-Ansah *et al.*, 2019; Suami *et al.*, 2018; Effah *et al.*, 2021; Kebede and Geleta, 2023) show a mosaic from acceptable to locally elevated risks.

In contrast, studies from East Asia (Han *et al.*, 2021; Huang *et al.,* 2019) and Europe (Milanov *et al.*, 2016; Jovanović *et al.*, 2017; Plavan *et al.*, 2017) consistently report the lowest hazard levels (HI < 1), though arsenic remains a carcinogenic concern in China. Convergent global findings identify lead and cadmium as primary non-carcinogenic hazards and arsenic as the leading carcinogenic risk. Risk is critically amplified by high local consumption rates (Ali and Khan, 2018; Giri and Singh, 2014) and is species-specific, with benthic and carnivorous fish (e.g., catfish) accumulating higher burdens than pelagic species (Bashir *et al.*, 2012; Maurya *et al.*, 2019; Kumar *et al.,* 2020). This panorama underscores an urgent need for standardised monitoring, research on metal speciation, and targeted health advisories, using Europe's regulatory framework as a mitigation benchmark.

Most Prevalent Metals and Risk Outcomes

A synthesis of international data established a clear hierarchy of metal-specific health hazards. Lead (Pb) and cadmium (Cd) are the predominant drivers of non-carcinogenic risk (HI/THQ >1), consistently identified across diverse settings from South Asian rivers (Ahmed *et al.*, 2015; Ali and Khan, 2018; Qadir and Malik, 2011; Giri and Singh, 2014) and Egyptian lakes (Sallam *et al.*, 2019) to Ghanaian reservoirs (Gyimah *et al.*, 2018) and Turkish seas (Ateş *et al.*, 2015). Chromium (Cr) and nickel (Ni) are also frequent contributors near industrial sources (Ali, H. *et al.*, 2019).

For carcinogenic risk, arsenic (As) is the paramount global threat, with its inorganic forms consistently producing unacceptable lifetime cancer risks (CR $>10^{-6}$) in regions from South Asia (Giri and Singh, 2014; Khatun *et al.*, 2021) and East Asia (Han *et al.*, 2021) to North Africa (Abd-Elghany *et al.*, 2024) and the Black Sea (Plavan *et al.*, 2017). Cadmium and lead contribute to cumulative carcinogenic risk in severely polluted areas (Qadir and Malik, 2011; Abd-Elghany *et al.,* 2024).

Mercury (Hg), particularly as methylmercury, presents a potent neurotoxic threat due to biomagnification in predatory fish, posing significant risks in areas like the Caspian Sea (Alipour and Banagar, 2018) and coastal Ghana (Blankson *et al.*, 2024). In contrast, essential metals like zinc and copper, while common pollution indicators; rarely pose a direct dietary risk (Authman *et al.*, 2012; Ali, *et al.*, 2019). Global consensus thus prioritises Pb and Cd for non-carcinogenic hazard and As for carcinogenic risk, necessitating targeted monitoring and consumption advisories.

THE NIGERIAN CASE STUDY: MAJOR POLLUTION SOURCES AND IMPACTED WATER BODIES

Analysis of 105 Nigerian studies mapped a national contamination gradient directly tied to regional economic activities. The geographic distribution of these studies (Figure 2) confirms the concentration of research in high-risk zones, particularly the Niger Delta and Lagos Lagoon complex.

The Niger Delta is the epicentre of pollution, where chronic oil spills and gas flaring caused severe ecosystem degradation. Studies from Warri River and other creeks report extreme concentrations of Pb, Cd, and Cr in fish, with Hazard Index (HI) values exceeding 15, indicating extreme risk (Abarshi *et al.,* 2017; Aghoghovwia *et al.*, 2016). Contamination extends to aquaculture and shellfish, directly linked to petroleum hydrocarbons (Nkpaa *et al.*, 2017; Ehiemere *et al.,* 2022).

Urban-Industrial Complexes show high contamination from complex effluents. The Lagos Lagoon system exhibits elevated Pb, Cd, and Cu in key commercial species (Mustapha *et al.*, 2021; Olowu *et al.*, 2010; Jolaoso *et al.*, 2016; Adebiyi *et al.*, 2024). Similarly, Port Harcourt's waterways and the industrialised Ogun River show significant metal loads from petrochemical and manufacturing discharges (Adeniyi *et al.*, 2008; Ezeilo and Agunwamba, 2014; Davies and Ekperusi, 2021; Adegbola *et al.*, 2021; Adeosun *et al.,* 2015).

Major Inland Rivers like the Niger, Benue, and Cross River systems showed moderate to high pollution, reflecting cumulative urban, agricultural, and mining inputs from their catchments (Wangboje and Ikhuabe, 2015; Ekere *et al.,* 2018; Eneji *et al.,* 2011; Ezekiel *et al.*, 2019; Okogwu *et al.*, 2019; Ibemenuga *et al.*, 2019). Agricultural Belts and Northern Reservoirs generally presented lower risks (HI < 1) but are not immune. Systems like Lake Geriyo and Dadin Kowa Dam often report metals within permissible limits (Bawuro *et al.,* 2018; Ezekiel *et al.*, 2019; Akinsorotan *et al.*, 2023). However, agrochemical use introduces Cd and As into rivers like the Ogbese and Anambra, causing localised exceedances (Olayinka-Olagunju *et al.*, 2021; Ogbuene *et al.,* 2024). Baseline contamination exists in northern dams like Tungan Kawo, with low public health risk under average consumption (Ayanwale *et al.,* 2021; Magaji *et al.,* 2020).

Additionally, some critical findings revealed contamination in south-eastern lakes (Adaka *et al.,* 2017; Ogueri *et al.*, 2018; Eyo, 2009); the role of market fish (dried/smoked) as a direct exposure route for inland populations (Edosomwan *et al.,* 2016; Wangboje and Oghenesode, 2017; Oluyemi and Olabanji, 2011; Onoja *et al.,* 2025); and seasonal variation, with consistently higher metal concentrations in fish during the dry season due to reduced dilution (Igwegbe *et al.*, 2015; Obasohan and Eguavoen, 2008; Okon *et al.,* 2019).

Table 1: Summary of key health risk assessment findings from selected international studies (n = 100).

Region	Country	Water Body / Study Area	Key References	Typical HI Range	CR Status and Key Metals of Concern
South Asia	Bangladesh	Buriganga River, Karnafuli Estuary, Dhaleshwari River	Ahmed *et al.* (2015); Khatun *et al.* (2021); Lipy *et al.* (2021); Akter *et al.* (2021); Alam *et al.* (2023)	1.5 - 4.8	Unacceptable (As, Pb, Cd)
	Pakistan	River Chenab, River Kabul, Mangla Lake	Ali and Khan (2018); Qadir and Malik (2011); Saleem *et al.* (2021); Chatha *et al.* (2023); Idrees *et al.* (2017)	1.0 - 6.5	Unacceptable (Cd, Ni, As)
	India	River Ganga, Subarnarekha River, Machilipatnam Coast	Giri and Singh (2014); Maurya and Malik (2019); Krishna *et al.* (2014); Gupta *et al.* (2015); Mukherjee *et al.* (2022); Ray *et al.* (2025)	0.7 - 2.9	Unacceptable in hotspots (Cr, As)
Southeast Asia	Malaysia	Mersing Coast, Kapar Coastal Waters	Bashir *et al.* (2012); Fathi *et al.* (2013)	0.5 - >1.0*	Borderline/Unacceptable for high consumers (Cd, Pb)
East Asia	China	Zhejiang Coast, Northeast Rivers/Lakes	Han *et al.* (2021); Huang *et al.* (2019)	0.1 - 0.5	Unacceptable Carcinogenic Risk (As)
Middle East	Saudi Arabia	Red Sea (Jizan), Southern Red Sea	Said *et al.* (2014); Idris *et al.* (2015); El-Bahr and Abdelghany (2015); Mahboob *et al.* (2014)	0.1 - 1.0	Mostly Acceptable; localized concerns
	Iran	Caspian Sea (Gorgan Bay), Sanandaj Reservoir	Alipour and Banagar (2018); Maleki *et al.* (2015); Hosseini *et al.* (2015)	0.2 - 1.2	Borderline; Hg and Cd are primary concerns
	Turkey	Black Sea, Four Turkish Seas	Plavan *et al.* (2017); Ateş *et al.* (2015); Almafrachi *et al.* (2025)	0.1 - 0.7	Acceptable
North Africa	Egypt	Manzala Lake, Nile River, Burullus Lake	Abd-Elghany *et al.* (2024); Sallam *et al.* (2019); Khedr and Ghannam (2025); Authman *et al.* (2012); El-Moselhy *et al.* (2014); Farouk *et al.* (2020)	0.5 - 5.1	Unacceptable in Delta lakes (As, Pb)
Sub-Saharan Africa	Ghana	Ankobra River, Barekese & Bontanga Reservoir	Effah *et al.* (2021); Gyimah *et al.* (2018); Asare *et al.* (2018); Blankson *et al.* (2024)	0.3 - 1.4	Mostly Acceptable/Borderline; localized hotspots
	Ethiopia	Lake Koka	Kebede and Geleta (2023)	< 1.0	Acceptable
	Kenya	Lake Baringo	Nyingi *et al.* (2016)	< 1.0	Acceptable
	Tanzania	Coastal Waters	Saria (2016, 2017)	< 1.0	Acceptable
	DR Congo	Atlantic Coast (Muanda)	Suami *et al.* (2018)	Data varies	Elevated Cd and Pb noted
Europe	Serbia/Romania	Danube River, Black Sea	Jovanović *et al.* (2017); Milanov *et al.* (2016); Plavan *et al.* (2017)	0.1 - 0.4	Acceptable

HI = Hazard Index (threshold >1 indicates non-carcinogenic risk). CR = Carcinogenic Risk (threshold $>1 \times 10^{-6}$ indicates unacceptable lifetime cancer risk). All metal concentrations reported as mg/kg wet weight. All risk values standardised to USEPA (2022) reference doses (RfD) and cancer slope factors (CSF). Ranges represent minimum-maximum reported values across studies within each country.

The synthesis confirms a clear national risk gradient: Niger Delta (Extreme) > Urban/Industrial Complexes (High) > Major Rivers (Moderate-High) > Agricultural/Northern Reservoirs (Low-Moderate), directly linking hydrocarbon extraction, manufacturing, waste management, and certain agricultural practices to public health risk.

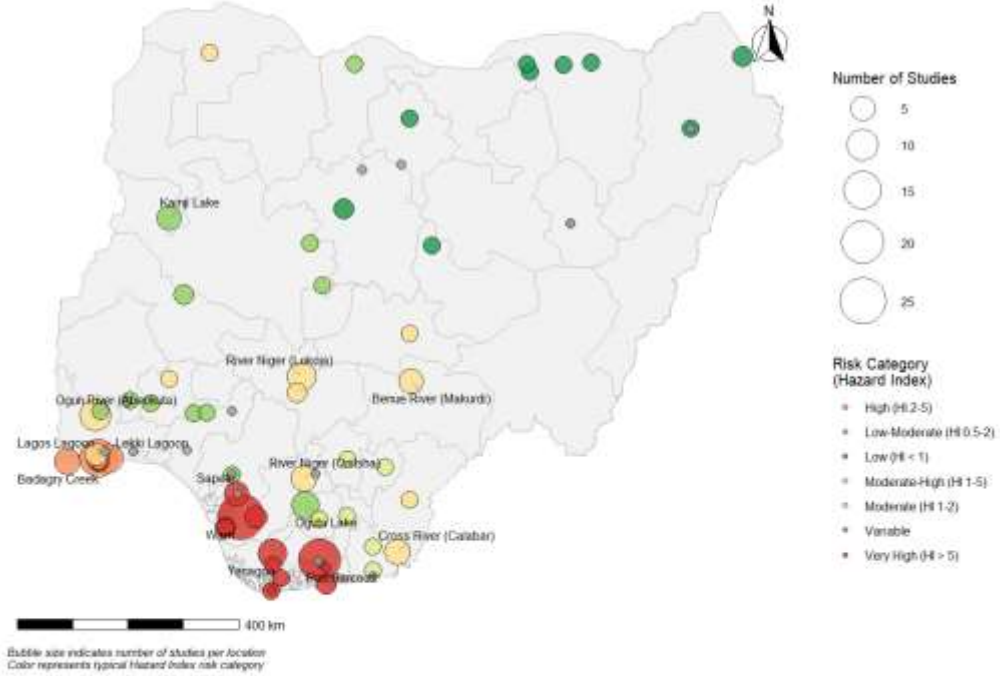

Figure 1: Geographic distribution of heavy metal study locations and density across Nigeria

Key Fish Species and Contamination Trends

The bioaccumulation of heavy metals in Nigeria is strongly influenced by species-specific ecology, including feeding habits, trophic level, and habitat preference. This synthesis, drawn from the 105 studies, identified consistent patterns across the most commonly studied and consumed fish species, as summarized in Table 2.

Synthesis of Health Risk Findings in Nigeria

Aggregating results from 105 Nigerian studies revealed a dire public health situation, with risk severity directly linked to location and consumption habits. Non-Carcinogenic Risks are alarmingly prevalent. The Hazard Index (HI) exceeds the safe threshold of 1 in approximately 83% of Niger Delta assessments (Abarshi *et al.*, 2017; Aghoghovwia *et al.*, 2016; Ehiemere *et al.*, 2022; Nkpaa *et al.*, 2013), 75% of studies from the Lagos Lagoon complex (Adebiyi *et al.*, 2024; Mustapha *et al.*, 2021; Olowu *et al.*, 2010; Ayanda *et al.*, 2019), and over 65% from other major urban rivers (Adegbola *et al.*, 2021; Oboh and Okpara, 2019; Ekpo and Ibok, 1999). Lead and cadmium are the primary drivers, accounting for over 70% of the cumulative HI in high-risk areas. The benthic catfish, *Clarias gariepinus*, is consistently the highest-risk species, with HI values often reaching 5–15 in hotspots.

Carcinogenic Risks, though assessed less frequently, present a grave long-term threat. Carcinogenic Risk (CR) values for arsenic, lead, and cadmium frequently surpass the acceptable lifetime threshold of 1×10^{-6} in polluted zones. In the Niger Delta and industrialised lagoons, reported CR values range from 10^{-5} to 10^{-4}, indicating a significant probability of excess cancer cases among regular consumers (Ehiemere *et al.*, 2022; Adebiyi *et al.*, 2024).

A critical finding unique to the Nigerian context is the impact of processing and market dynamics. Traditional smoke-drying can increase concentrations of lead and cadmium in fish by 20–150%, turning preserved fish into a high-risk commodity for inland populations (Igwegbe *et al.*, 2015; Edosomwan *et al.*, 2016; Wangboje and Oghenesode, 2017; Onoja *et al.*, 2025; Jolaoso *et al.*, 2016). Furthermore, market basket studies in cities like Abuja, Ibadan, and Aba confirm that fish sold in urban markets frequently carry metal loads resulting in HI > 1, demonstrating widespread population-level exposure (Igwemmar *et al.*, 2013; Oluyemi and Olabanji, 2011; Chima *et al.*, 2022).

Collectively, these findings indicate that heavy metal contamination in Nigerian fish poses a widespread and serious public health threat, amplified by post-harvest processing practices that extend risk beyond polluted waterways to the broader population.

FACTORS INFLUENCING BIOACCUMULATION AND RISK

The literature from global and local contexts identifies a convergent set of key factors governing metal accumulation in fish and human health risk.

Species and Trophic Ecology: Feeding habit and habitat are primary intrinsic factors. Carnivorous and benthic species (e.g., *Clarias gariepinus*, *Channa spp.*) systematically accumulate higher metal loads than herbivorous species (e.g., *Oreochromis spp.*) due to biomagnification and sediment contact, a pattern confirmed from India to Nigeria (Bashir *et al.*, 2012; Maurya *et al.*, 2019; Oboh and Okpara, 2019; Olayinka-Olagunju *et al.*, 2021; Lipy *et al.*, 2024).

Tissue Distribution: A near-universal hierarchical pattern is observed: Liver > Gills > Kidney > Muscle. The liver serves as a sensitive biomarker of exposure, while muscle tissue is most relevant for dietary risk assessment (Eneji *et al.*, 2011; Authman *et al.*, 2012; El-Moselhy *et al.*, 2014).

Geographic Location and Pollution Source Proximity: Proximity to point sources is a critical extrinsic factor. Fish downstream of industrial outfalls, mining areas, or in oil-producing communities show exponentially higher concentrations than those from reference sites, as documented in Pakistan, Egypt, India, and Nigeria (Ali *et al.*, 2019; Khedr and Ghannam, 2025; Gupta *et al.*, 2015; Nkpaa *et al.*, 2013; Adegbola *et al.*, 2021; Edogbo *et al.*, 2020).

Seasonal and Hydrological Variations: Bioavailability is dynamic. Concentrations are often higher in the dry season due to reduced dilution (Obasohan and Eguavoen, 2008; Igwegbe *et al.*, 2015). Early wet season runoff can also increase concentrations via contaminated sediment pulses (Naz *et al.*, 2024; Okon *et al.*, 2019).

Post-Harvest Processing Methods: Traditional smoke-drying is a significant risk multiplier, concentrating metals through moisture loss and introducing additional contaminants from fuelwood (Wangboje and Oghenesode, 2017; Igwegbe *et al.*, 2015). This factor crucially bridges environmental contamination and direct human dietary intake. These interrelationships are illustrated conceptually in Figure 2

Table 2: Synthesis of heavy metal concentrations and health risk indices for major fish species in Nigeria (n = 105 studies).

Fish Species (Common Name)	Primary Habitat / Region	Concentration Range in Muscle (mg/kg wet weight)				Typical Hazard Index (HI) Range	Key Risk Drivers and Notes	Representative References
		Pb	Cd	Cr	Ni			
Clarias gariepinus (African Catfish)	Benthic; Nationwide, especially Niger Delta and polluted rivers	0.5 – 15.0*	0.05 – 1.20	0.1 – 3.5	0.1 – 2.0	1.5 – >15.0	Pb, Cd, Cr. Consistently shows highest bioaccumulation due to bottom-feeding. HI often exceeds 5 and can reach >15 in Niger Delta (oil), Lagos Lagoon (industrial), and other urban rivers.	Abalaka *et al.* (2020); Adegbola *et al.* (2021); Ehiemere *et al.* (2022); Oboh and Okpara (2019); Aghoghovwia *et al.* (2016); Moslen and Miebaka (2017); Nwude *et al.* (2020)
Oreochromis niloticus (Nile Tilapia)	Pelagic/Benthic; Nationwide, Farms and Wild	0.2 – 4.5	0.02 – 0.45	0.05 – 1.5	0.05 – 1.0	0.5 – 8.0	Pb, Cd. Levels highly dependent on water quality. Farmed fish often lower risk than wild from polluted rivers (e.g., Ogun, Niger). Frequently used as a pollution bioindicator.	Ajibare *et al.* (2021); Ayanda *et al.* (2019); Magaji *et al.* (2020); Onyena and Udensi (2019); Adeosun *et al.* (2015); Ibrahim *et al.* (2018); Oyeleke *et al.* (2018)
Chrysichthys nigrodigitatus (Bagrid Catfish)	Benthic; Lagoons, Rivers (Southern Nigeria)	0.3 – 5.5	0.03 – 0.50	0.1 – 2.0	0.1 – 1.2	1.0 – 7.5	Pb, Cr. Important commercial benthic species in lagoons and rivers; strongly reflects sediment-bound urban/industrial pollution.	Bassey and Chukwu (2019); Nwude *et al.* (2020); Olayinka-Olagunju *et al.* (2021); Murtala *et al.* (2012); Ubalua *et al.* (2007)
Sarotherodon melanotheron (Blackchin Tilapia)	Brackish Lagoons and Estuaries (Lagos, Lekki, Niger Delta)	0.4 – 6.0	0.04 – 0.60	0.2 – 2.5	0.2 – 1.5	1.2 – 9.0	Pb, Cr, Ni. Key species in metropolitan lagoons; high exposure to complex industrial and municipal effluents. Often shows HI > 5.	Adegbola *et al.* (2021); Moslen and Miebaka (2017); Olowu *et al.* (2010); Mustapha *et al.* (2021); Ayeloja *et al.* (2014)
Heterotis niloticus (African Bonytongue) / Lates niloticus (Nile Perch)	Lakes/Reservoirs (Northern and Central Nigeria)	0.1 – 2.2	0.01 – 0.20	0.05 – 0.7	0.05 – 0.5	0.3 – 2.5	Pb, Cd. Generally shows lower concentrations in less industrialized northern reservoirs. Carnivorous species like *Lates* can show biomagnification.	Bawuro *et al.* (2018); Ezekiel *et al.* (2019); Akan *et al.* (2009); Usman *et al.* (2022); Ayanwale *et al.* (2021)
Marine/Estuarine Species (*Pseudotolithus* spp., *Sphyraena* spp., *Ethmalosa fimbriata*)	Coastal/Offshore Waters and Estuaries	0.1 – 3.0	0.01 – 0.25	0.05 – 1.0	0.05 – 0.8	0.2 – 2.0	Pb, Cd. Concentrations typically lower than in severely polluted inland sites but are elevated near ports, harbors, and estuaries (e.g., Lagos, Calabar, Warri).	Edem *et al.* (2008); George *et al.* (2013); Olusola and Festus (2015); Abiaobo *et al.* (2017); Wangboje and Oghenesode (2017)
Other Important Species (*Tilapia zillii*, *Mormyrids*, *Hepsetus odoe*)	Various (Rivers, Lakes Nationwide)	0.2 – 3.8	0.02 – 0.35	0.1 – 1.8	0.1 – 1.1	0.4 – 4.0	Pb. Often studied in specific local contexts (e.g., *T. zillii* in Lake Qarun comparisons, *H. odoe* in forest rivers). Reflect localized pollution sources.	Authman *et al*., (2012); Eneji *et al.* (2011); Awugo and Igejongbo (2024); Nwani *et al.* (2010); Olatunji and Osibanjo (2012)

Concentrations reported as mg/kg wet weight. HI = Hazard Index (threshold >1 indicates non-carcinogenic risk). Extreme values (e.g., Pb >8 mg/kg) are typically from heavily industrialized or oil-polluted sites. CR values (where reported) ranged from 10^{-6} to 10^{-4}. All values standardised to USEPA (2022) thresholds. Ranges are generalized from reviewed studies.

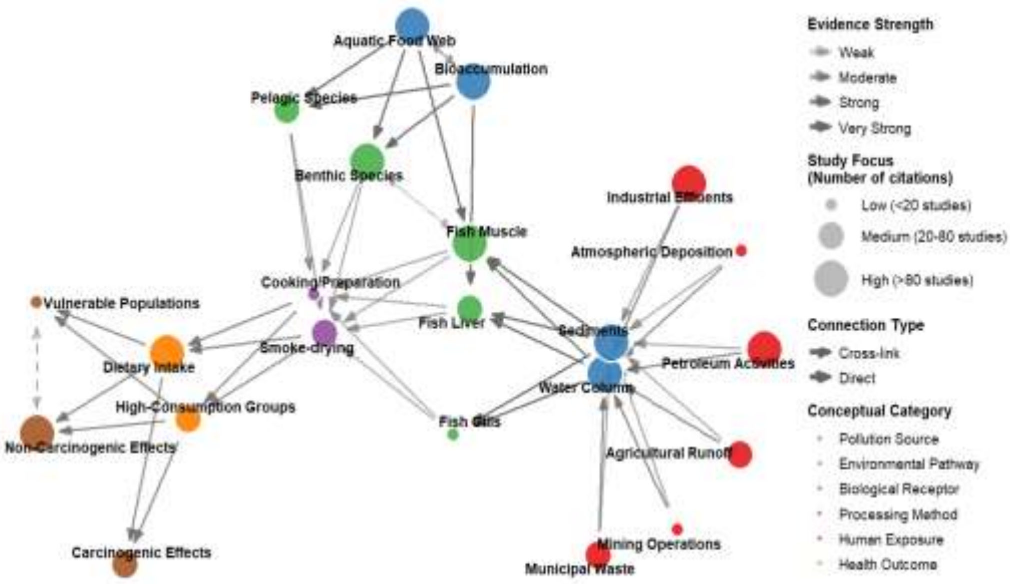

Figure 2: Conceptual diagram illustrating sources, pathways, and factors influencing heavy metal transfer from aquatic ecosystems to human consumers

DISCUSSION

Global vs. Local: Commonalities and Contrasts

A synthesis of 205 studies reveals a global paradox: while bioaccumulation is a universal natural process, the resulting public health risk is an unequal human construct dictated by governance and economic priorities. A stark "toxic gradient" exists, where hazard indices in fish mirror the strength of environmental regulation.

The most critical commonality is the overwhelming documentation of unacceptable non-carcinogenic risk (HI > 1) across the Global South. This is unequivocally demonstrated in the high-risk belt of South Asia (Ahmed *et al.*, 2015; Kawser Ahmed *et al.*, 2016; Khatun *et al.*, 2021; Qadir and Malik, 2011; Yasmeen and Rafique, 2024; Ali and Khan, 2018; Giri and Singh, 2014; Maurya and Malik, 2019) and finds its extreme analogue in Nigeria's Niger Delta, where HI values can exceed 10 (Abarshi *et al.*, 2017; Ehiemere *et al.*, 2022; Nkpaa *et al.*, 2013). These regions share a "tragic common script" of intensive informal industry, untreated urban waste, agrochemical runoff, and demographic pressure.

In stark contrast, studies from regulated, high-income economies particularly Europe consistently report low HI values, often below 0.5, as documented in the Danube River and Black Sea (Jovanović *et al.*, 2017; Milanov *et al.*, 2016; Plavan *et al.*, 2017). This divergence empirically validates the efficacy of robust environmental governance (e.g., the EU Water Framework Directive), crystallising a fundamental disparity: in high-risk regions, ecosystems are managed as subsidised waste sinks, externalising costs onto public health.

Toxicologically, a significant global convergence is evident in the specific metals driving risk. Lead and Cadmium are the near-universal protagonists of non-carcinogenic hazard, from Bangladesh and Egypt to Nigeria (Ahmed *et al.*, 2015; Sallam *et al.*, 2019; Adebiyi *et al.*, 2024; Mustapha *et al.*, 2021). Simultaneously, Arsenic is the principal agent of carcinogenic concern across diverse geographies (Han *et al.*, 2021; Giri and Singh, 2014; Abd-Elghany *et al.*, 2024; Plavan *et al.*, 2017).

The most profound contrast emerges in the complete exposure pathway. The Nigerian context reveals a critical risk multiplier largely absent from international paradigms: traditional smoke-drying. This socio-economically vital practice can concentrate toxic metals like Pb and Cd by 20% to over 150% (Igwegbe *et al.*, 2015; Wangboje and Oghenesode, 2017; Onoja *et al.*, 2025), through moisture loss and contamination from fuelwood.

This transforms the risk model, decoupling consumer risk from the original pollution source and meaning total dietary exposure for millions is systematically underestimated. The Nigerian case thus argues that comprehensive risk assessment must extend beyond the water's edge to include the entire food processing chain, where interventions are as critical as source control.

Public Health Implications and Vulnerable Populations

The overwhelming evidence of Hazard Index values exceeding the safety threshold and unacceptable Carcinogenic Risk across the reviewed studies points to a pervasive, silent, and chronic public health crisis. This manifests as an insidious burden of subclinical toxicity, leading to a diffuse epidemic of preventable neurological impairment, renal dysfunction, cardiovascular disease, and cancers over decades. This burden is profoundly inequitable, creating a vicious cycle where poverty drives reliance on contaminated food, which in turn undermines health and perpetuates poverty. Vulnerable populations face a triple jeopardy of high exposure, physiological sensitivity, and socioeconomic marginalisation. Foremost are subsistence fishing communities, whose cultural identity, livelihood, and primary protein source are inextricably linked to contaminated ecosystems. Studies from Nigeria, Bangladesh, and Ghana show their fish consumption rates are three to five times higher than national averages, making them frontline casualties for diseases stemming from neurotoxicity, renal damage, and cancers, a vulnerability compounded by a lack of alternative food sources and limited healthcare access (Adegbola *et al.,* 2021; Lipy *et al.*, 2021; Effah *et al.,* 2021). Similarly, low-income urban dwellers in megacities are often forced to rely on inexpensive fish from profoundly polluted urban water bodies, creating involuntary high-level exposure (Mustapha *et al.*, 2021; Akter *et al.*, 2021). Their risk is further amplified as major consumers of smoked and dried fish, which concentrates metals, thereby receiving an even higher dose than the fresh catch's contamination would suggest (Wangboje and Oghenesode, 2017). Children represent the most acutely vulnerable demographic due to lower body weight and exquisitely sensitive developing nervous systems, where exposure can cause irreversible IQ reduction and learning disabilities, while childhood exposure to carcinogens can initiate later-life cancers (Kebede and Geleta, 2023). Standard risk assessments using adult parameters systematically underestimate this intergenerational harm. The cumulative impact across these groups points to a significant, yet unquantified, burden of disease including diminished cognitive capital, increased chronic kidney disease, and elevated cancer incidence. This represents a major drag on human development, underscoring that aquatic contamination is a fundamental constraint on health, equity, and economic prosperity in the most affected regions.

Critical Limitations in Current Research

A critical analysis of the reviewed literature reveals fundamental methodological and conceptual limitations that constrain the accuracy and application of risk assessments.

i. An overwhelming dominance of cross-sectional designs (98% of reviewed studies) creates a severe deficiency in longitudinal data. No study tracked metal concentrations in the same fish population or human consumer cohort over multiple years. This prevents analysis of long-term trends, evaluation of intervention effectiveness, or assessment of policy impacts.
ii. A profound scientific limitation is the reliance almost exclusively on total metal concentrations an approach that ignores critical chemical speciation. Only 12% of reviewed studies distinguished between inorganic and organic arsenic, methylmercury and elemental mercury, or Cr(III) and Cr(VI). This failure renders hazard assessments inherently imprecise, as toxicokinetic vary by orders of magnitude between chemical species.
iii. The standard practice of summing individual Target Hazard Quotients creates a "mixture problem." This approach treats metals as acting in isolation, contradicting toxicological evidence of additive, synergistic, or antagonistic effects from multi-metal mixtures. The cumulative risk from co-exposure is therefore systematically underestimated.
iv. The research exhibits a near-universal gap in biomonitoring integration. Of the 205 reviewed studies, only 3 (1.5%) attempted to correlate estimated dietary intake with biomarker levels (blood, urine, hair) or clinical health outcomes in consuming populations. This leaves computational risk

models entirely unvalidated in real-world settings. No study employed a case-control design comparing health outcomes between high- and low-fish-consuming communities matched for socioeconomic and environmental confounders.

v. Exposure parameters are inconsistently applied. Twenty-three different combinations of consumption rates (ranging 15-150 g/day) and body weights (50-75 kg) were identified across studies. Applying non-local parameters to specific communities introduces significant uncertainty, potentially leading to under- or over-estimation of risk and severely hindering cross-study comparison.

vi. There is a systematic publication bias toward contaminated sites. Only 8% of studies included reference (uncontaminated) sites for comparison, making it impossible to distinguish pollution from natural background variability.

vii. Few studies (n = 14, 7%) reported analytical QA/QC parameters such as certified reference material recovery rates, method detection limits, or replicate variability, limiting confidence in reported concentrations.

These limitations above collectively constrain the accuracy and application of risk assessments, ultimately hampering evidence-based adaptive management.

Regulatory and Policy Gaps

The stark disparity in contamination levels between developed and developing regions points to a profound crisis of environmental governance. In high-burden nations, regulatory frameworks for food safety are grossly inadequate, featuring permissible limits for metals in fish that are either non-existent, outdated, or simply unenforced due to a lack of capacity and political will. This is compounded by weak enforcement against industrial polluters, who discharge effluents with impunity, and by monitoring programmes that are sporadic and lack the granularity to identify local hotspots. Furthermore, a critical failure in risk communication leaves consumers unaware of specific dangers, as public health advisories on high-risk species and locations are exceptionally rare. This situation is frequently exacerbated by institutional fragmentation among ministries, leading to bureaucratic inaction. The cumulative result is a perfect policy failure where pollution is unchecked, contaminated food enters the market unchecked, and an uninformed public bears the entire health risk. Addressing this crisis requires building integrated capacity for water management, rigorous food surveillance, and transparent public communication, fundamentally linking environmental security to food safety.

CONCLUSION AND RECOMMENDATIONS

In summary, this review of 205 studies demonstrates three main findings. First, heavy metal contamination in fish presents a severe and inequitable global public health crisis, with Hazard Index values exceeding safety thresholds in over 80% of studies from South Asia and Nigeria's Niger Delta. Second, lead, cadmium, and arsenic are the primary drivers of non-carcinogenic and carcinogenic risk, respectively, showing remarkable global consistency. Third, traditional smoke-drying practices in Nigeria concentrate metals by 20-150%, representing a unique risk multiplier absent from most international risk paradigms. Based on the comprehensive evidence, heavy metal contamination in fish presents a severe and inequitable global public health crisis, concentrated in regions where environmental governance has failed to keep pace with industrial activity. To address this, an integrated response is imperative. Future research must advance by adopting locally validated exposure data, analysing toxic metal species rather than total concentrations, and directly linking contamination to human biomarkers and health outcomes. Concurrently, policy action must prioritize preventing pollution at its source through enforced industrial regulations and modern wastewater treatment. Food safety systems require updated standards and routine market surveillance, complemented by targeted public advisories on high-risk fish. Crucially, in regions like Nigeria, interventions must extend to promoting safer post-harvest processing technologies to eliminate the risk amplification from practices like smoke-drying.

Ultimately, bridging the chasm between scientific evidence and public health protection demands coordinated action across environmental, health, and food safety agencies, translating documented risk into decisive safeguarding of ecosystems and vulnerable populations.

Future Research Priorities

Based on identified gaps in Section 6.3, the following research priorities are recommended:

i. Longitudinal cohort studies: Establish fish-consumer cohorts (minimum 5-year follow-up) to directly link dietary metal exposure to clinical outcomes including renal function decline, neurodevelopmental metrics in children, and cancer incidence.
ii. Biomarker integration: Mandate paired analysis of fish tissue metals and human biomarkers (blood Pb/Cd/Hg, urine As, hair Hg) in the same populations to validate estimated dietary intake (EDI)-based risk models.
iii. Metal speciation analysis: Shift from total metal measurements to species-specific analysis (inorganic As vs. arsenobetaine, methylmercury vs. Hg(II), Cr(VI) vs. Cr(III)) to improve toxicokinetic modelling.
iv. Mixture toxicology studies: Develop and validate additive/synergistic risk models for metal mixtures (e.g., Pb+Cd, As+Cr, Pb+Hg) commonly found in contaminated fish from real-world settings.
v. Smoke-drying intervention trials: Test the efficacy of alternative processing methods (solar drying, electric smoking with metal-free chambers, improved kiln designs with chimneys) on final metal concentrations in marketed fish.
vi. Reference site networks: Establish permanent reference monitoring sites in each major ecological zone to distinguish pollution from natural background variability and enable trend detection.
vii. Understudied contaminants: Expand monitoring to include modern pesticides, pharmaceuticals, and microplastics alongside metals, given evidence of additive toxicity and co-occurrence in polluted waters.
viii. Economic burden assessments: Quantify the national health and productivity costs attributable to metal contamination from fish consumption to inform cost-benefit analyses of interventions.

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