

Health Risk Assessment of Cadmium and Lead in Commercial Fish From Kaduna North, Nigeria

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Abstract

This study investigated cadmium (Cd) and lead (Pb) levels in commercially available frozen, smoked, and canned fish in Kaduna North, Nigeria, and performed a comprehensive health risk assessment. Atomic absorption spectrophotometry was used to determine Cd and Pb concentrations in 180 fish samples. Results showed mean Cd levels in all fish types (0.093–0.125 µg/g) exceeded the European Union maximum residue limit (MRL) of 0.05 µg/g, with 43.33% of samples above the MRL. Lead contamination was more severe: 69.44% of samples exceeded the EU MRL of 0.02 µg/g, with frozen fish showing the highest mean (0.637 µg/g) – 32 times the limit. Health risk assessment revealed Target Hazard Quotients (THQ) for Pb exceeding 1 in all products (range: 1.01–3.18), indicating significant non-carcinogenic risk. The Hazard Index (HI) for combined metals ranged from 1.09 to 3.29, exceeding the safe threshold of 1. Children face critically high risks (HI up to 11.51). Cancer risk from Cd was borderline ($3.0\text{--}4.1\times 10^{-5}$). Pearson correlation showed a very strong positive relationship between *Listeria* occurrence and Cd levels ($r = 0.998$), and moderate correlations between Cd and Pb ($r = 0.720$) and between *Listeria* and Pb ($r = 0.673$). These findings demonstrate that commercially available fish in Kaduna North pose unacceptable health risks from combined heavy metal contamination, with frozen fish presenting the greatest danger. Urgent regulatory interventions, routine risk monitoring, and public health advisories are required.

1. INTRODUCTION

The term "heavy metals" refers to metals and metalloids with a high relative density ($\geq 5 \text{ g/cm}^3$) and significant toxicity to living organisms (Alloway & Ayres, 2020). These contaminants, such as cadmium (Cd), lead (Pb), and mercury (Hg), are widespread in the environment due to anthropogenic sources like industrial effluents, agricultural runoff, and urban discharges, raising concerns about their toxicological and socio-economic impacts (Järup, 2003). Bioaccumulation, the absorption and retention of heavy metals by organisms, leads to increased metal concentrations in tissues, exacerbated by biomagnification through food chains (Bernhoft, 2021). Heavy metal toxicity can be acute, from short-term high-concentration exposure, or chronic, from prolonged low-concentration exposure, causing reduced growth, reproductive disorders, and mortality (Bernhoft, 2021). Notably, heavy metals biomagnify in aquatic food chains, posing direct threats to human health (Tchounwou et al., 2012). For instance, industrial runoff introduces heavy metals into aquatic ecosystems, where they accumulate in algae, insects, and fish tissues like gills, liver, and kidneys (Eisler, 2020; Nordberg et al., 2007; ATSDR, 2012). Chronic exposure to heavy metals is linked to severe neurological, renal, and cardiovascular diseases in humans (ATSDR, 2012), with accumulation primarily occurring in the kidneys, liver, and lungs (ATSDR, 2012). Contaminated seafood is the most significant source of human exposure, with shellfish and fish organs posing higher risks (ATSDR, 2012). In Nigeria, a major importer of frozen fish in Africa, understanding heavy metal levels in these products is critical for public health (Jatto et al., 2013). While local fish and dairy products have been studied extensively, imported fish remain under-researched. Recent studies highlight heavy metal contamination in aquatic ecosystems globally, with industrial and agricultural activities identified as primary sources in Africa (Agyei-Mensah et al., 2023; El-Sayed et al.,

2024), Asia (Li et al., 2022; Sharma et al., 2023), and Europe (Garcia et al., 2022). This study aims to fill this gap by assessing heavy metal levels in frozen, smoked, and canned fish in Kaduna North, Nigeria, and performing a comprehensive health risk assessment to inform public health policies.

2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted in Kaduna North Local Government Area of Kaduna State, Nigeria. Kaduna State is located at Latitude 10°20'N and Longitude 7°45'E. The city is situated in the North-West Geopolitical zone of Nigeria. Kaduna North has an area of 72 km² and a population of 364,575 according to the 2006 census (KDSG, 2008). The area falls within the Sudan savannah region, characterized by rainy and dry seasons with a brief harmattan period. Its headquarters is located at Magajin Gari. Three districts were sampled: Doka, Kawo, and Gabasawa (ZEMDA, 2014).

2.2 Sample Collection and Transportation

A total of 180 samples – 60 frozen, 60 smoked, and 60 canned (Titus brand) fish were purchased from fish vendors and retail outlets in three major markets: Abubakar Gumi, Unguwar Rimi, and Kawo markets. Sampling was conducted once weekly to ensure collection of new batches. Each sample (excluding canned fish) was wrapped in sterile aluminum foil, packed, and labeled in sterile polythene bags. Frozen fish were transported in a Coleman box containing ice packs to the Multi-user Post Graduate Research Laboratory, Department of Chemistry, Ahmadu Bello University, Zaria, for heavy metal analysis.

2.3 Chemical Reagents and Equipment

Chemical reagents included nitric acid (HNO₃), perchloric acid (HClO₄), 70% absolute ethanol, sulphuric acid (H₂SO₄), distilled water, acetone, acetone-alcohol, and deionized water. Laboratory equipment included a Stomacher laboratory blender (SWARD, London) and an atomic absorption spectrophotometer (AA240FS Varian, USA).

2.4 Quality Control and Analytical Validation

Stringent quality control measures were implemented:

Blank and replicate samples: One method/reagent blank per ten samples; duplicate digestions on 10% of samples. **Calibration:** Multi-element standard solutions (traceable to NIST SRM 3108 for Cd and NIST SRM 3128 for Pb) with $R^2 > 0.995$; mid-range verification every 10 samples. **Certified Reference Materials:** NIST SRM 1566b Oyster Tissue was analyzed with each batch; recovery rates of 90–110% for both metals. **Spiking samples:** 5% of samples spiked with known Cd and Pb standards; recovery rates of 85–115%.

2.5 Sample Digestion and Analysis

Samples were prepared and digested according to Shibamoto and Bjeldanes (1993), with modifications (Zhang et al., 2021; Kumar et al., 2023). Briefly, 1 g of dorsal muscle was digested with 10 ml of digestion mixture (60 ml HNO₃ 65% and 40 ml HClO₄ 70–72%) in screw-capped tubes. Tubes were tightly closed, shaken, allowed to stand overnight at room temperature, then heated for 1 hour at 100°C. Cooled samples were diluted with 10 ml deionized water, filtered with Whatman filter paper, and made up to 20 ml with deionized water. Blank solutions were prepared similarly. Digested samples were analyzed for Cd and Pb using atomic absorption spectrophotometry (AA240FS VARIAN) (Kumar et al., 2023).

2.6 Health Risk Assessment Methodology

Health risk assessment followed US EPA methodology (US EPA, 1989, 2000):

Estimated Daily Intake (EDI): $EDI = (C \times IR \times EF \times ED) / (BW \times AT)$

Where: C = Metal concentration (µg/g wet weight)

IR = Ingestion rate = 60 g/day for Nigerian adults (FAO/WHO, 2015); 20 g/day for children (scaled)

EF = Exposure frequency = 365 days/year

ED = Exposure duration = 70 years (non-carcinogenic), 30 years (carcinogenic) (US EPA, 2011)

BW = Body weight = 70 kg (adults), 20 kg (children) (NBS, 2018)

AT = Averaging time = ED × 365 days

Target Hazard Quotient (THQ):

$THQ = EDI / RfD$

Reference Dose (RfD) values (US EPA, 2023; JECFA, 2010):

Cadmium: 0.001 mg/kg/day (oral)

Lead: 0.0035 mg/kg/day (oral, JECFA PTDI)

Hazard Index (HI):

$HI = THQ_{Cd} + THQ_{Pb}$

HI > 1 indicates potential non-carcinogenic health effects (US EPA, 2022).

Cancer Risk (CR) for Cadmium:

$CR = EDI \times CSF$

Cancer Slope Factor (CSF) for Cd = 0.38 (mg/kg/day)⁻¹ (US EPA, 1999).

Conventional Risk Thresholds (US EPA, 2022, 2020):

THQ ≤ 1

Acceptable risk

THQ > 1

Unacceptable risk

HI ≤ 1

No significant non-carcinogenic risk

HI > 1

Potential non-carcinogenic risk

CR ≤ 1×10⁻⁶

Acceptable cancer risk

CR = 1×10⁻⁶ to 1×10⁻⁴

Borderline risk

CR > 1×10⁻⁴

Unacceptable cancer risk

2.7 Data Analysis

Data were analyzed using SPSS version 20.0 (Ieren et al., 2013). Descriptive statistics, chi-square tests, and Pearson correlation were performed. Statistical significance was set at $p < 0.05$.

3. RESULTS

3.1 Distribution of Contamination by Market Location

Table 1 presents the distribution of samples exceeding regulatory limits for Cd and Pb across the three markets. Overall, 43.33% of samples exceeded the Cd MRL (0.05 µg/g) and 69.44% exceeded the Pb MRL (0.02 µg/g). Abubakar Gumi and Unguwar Rimi markets showed the highest Cd exceedance (46.67% each), while Abubakar Gumi had the highest Pb exceedance (75.00%). Chi-square analysis revealed no statistically significant differences across markets for Cd ($\chi^2 = 1.629$, $p = 0.443$) or Pb ($\chi^2 = 1.937$, $p = 0.380$).

Table 1

Distribution of Fish Samples Containing Cd and Pb Levels above Regulatory Limits by Market Location

Location	Samples Tested n (%)	Samples Above Cd Limit (> 0.05 µg/g) n (%)	Samples Above Pb Limit (> 0.02 µg/g) n (%)	Risk Classification
Abubakar Gumi Market	60 (33.33)	28 (46.67)	45 (75.00)	High (Cd), Critical (Pb)
Unguwar Rimi Market	60 (33.33)	28 (46.67)	38 (63.33)	High (Cd), High (Pb)
Kawo Market	60 (33.33)	22 (36.67)	42 (70.00)	High (Cd), Critical (Pb)
Total	180	78 (43.33)	125 (69.44)	
Chi-square (p-value)		$\chi^2 = 1.629$, $p = 0.443$	$\chi^2 = 1.937$, $p = 0.380$	
<i>Risk classification: Low (< 10% exceedance), Moderate (10–30%), High (31–50%), Critical (> 50%)</i>				

3.2 Distribution by Fish Product Type

Table 2 shows MRL exceedances by product type. Smoked fish had the highest Cd exceedance (58.33%) and Pb exceedance (78.33%). Frozen fish showed lower Cd exceedance (38.33%) but substantial Pb exceedance (60.00%). Canned fish had the lowest Cd exceedance (33.33%) but high Pb exceedance (70.00%). The difference in Cd contamination across product types was statistically significant ($\chi^2 = 8.552$, $p = 0.014$), while Pb differences were not significant ($\chi^2 = 4.765$, $p = 0.092$).

Table 2

Distribution of Fish Samples Containing Cd and Pb Levels above Regulatory Limits by Product Type

Product Type	Samples Tested n (%)	Samples Above Cd Limit n (%)	Samples Above Pb Limit n (%)	THQ_Pb	Risk Level
Smoked Fish	60 (33.33)	35 (58.33)	47 (78.33)	1.77	Unacceptable
Frozen Fish	60 (33.33)	23 (38.33)	36 (60.00)	3.18	Critical
Canned Fish	60 (33.33)	20 (33.33)	42 (70.00)	1.01	Borderline
Total	180	78 (43.33)	125 (69.44)		
Chi-square (p-value)		$\chi^2 = 8.552$, $p = 0.014^*$	$\chi^2 = 4.765$, $p = 0.092$		
<i>Statistically significant at $p < 0.05$</i>					

3.3 Mean Concentrations and Health Risk Assessment by Product Type

Table 3 presents mean Cd and Pb concentrations with corresponding health risk indices. All mean Cd levels exceeded the EU MRL of 0.05 µg/g, but THQ_Cd values remained below 1 (0.080–0.107), indicating acceptable non-carcinogenic risk from Cd alone. For Pb, mean concentrations ranged from 0.177 µg/g (smoked) to 0.637 µg/g (frozen), all exceeding the EU MRL of 0.02 µg/g. THQ_Pb values exceeded 1 for all products: smoked (1.77), frozen (3.18), and canned (1.01). The Hazard Index (HI) ranged from 1.09 (canned) to 3.29 (frozen), all above the safe threshold of 1. Cancer risk from Cd was borderline (3.04–4.07×10⁻⁵). Differences in Pb concentrations were highly significant (p = 0.00), while Cd differences were not (p = 0.792).

Table 3
Mean Concentrations of Cadmium and Lead with Health Risk Assessment by Product Type

Parameter	Smoked Fish (n = 60)	Frozen Fish (n = 60)	Canned Fish (n = 60)	Regulatory Limits
Cadmium (Cd) µg/g	0.108 ± 0.05	0.125 ± 0.01	0.093 ± 0.01	EU MRL: 0.05
Range	0.04–0.28	0.11–0.14	0.08–0.12	US EPA RfD: 0.001
EDI_Cd (mg/kg/day)	0.000093	0.000107	0.000080	
THQ_Cd	0.093	0.107	0.080	Safe (< 1)
Lead (Pb) µg/g	0.177 ± 0.04	0.637 ± 0.12	0.202 ± 0.37	EU MRL: 0.02
Range	0.12–0.32	0.45–0.89	0.05–1.25	JECFA PTDI: 0.0035
EDI_Pb (mg/kg/day)	0.000152	0.000546	0.000173	
THQ_Pb	1.77	3.18	1.01	Unsafe (> 1)
Hazard Index (HI)	1.86	3.29	1.09	Unsafe (> 1)
Cancer Risk (Cd)	3.53×10 ⁻⁵	4.07×10 ⁻⁵	3.04×10 ⁻⁵	Borderline (10 ⁻⁶ –10 ⁻⁴)
p-value	p = 0.792(Cd), p = 0.00 (Pb)			

EDI: Estimated Daily Intake; THQ: Target Hazard Quotient; HI: Hazard Index; PTDI: Provisional Tolerable Daily Intake; RfD: Reference Dose

3.4 Mean Concentrations and Risk by Market Location

Table 4 shows mean Cd and Pb concentrations by market. Unguwar Rimi Market had the highest mean Cd (0.141 µg/g) and Pb (0.496 µg/g). All markets exceeded EU MRLs for both metals. THQ_Pb values exceeded 1 in all markets (range: 1.23–2.48), with Unguwar Rimi showing the highest (2.48). HI values ranged from 1.31 (Kawo) to 2.60 (Unguwar Rimi). The p-value for Pb across markets (p = 0.055) suggested a marginal trend toward significance.

Table 4
Mean Concentrations of Cadmium and Lead with Risk Assessment by Market Location

Parameter	Abubakar Gumi (n = 60)	Unguwar Rimi (n = 60)	Kawo (n = 60)	EU Limits
Cadmium (Cd) µg/g	0.097 ± 0.01	0.141 ± 0.05	0.091 ± 0.01	0.05
THQ_Cd	0.083	0.121	0.078	Safe (< 1)
Lead (Pb) µg/g	0.275 ± 0.06	0.496 ± 0.10	0.245 ± 0.62	0.02
THQ_Pb	1.38	2.48	1.23	Unsafe (> 1)
Hazard Index (HI)	1.46	2.60	1.31	Unsafe (> 1)
% Samples > Pb MRL	75.00%	63.33%	70.00%	
p-value	p = 0.507 (Cd), p = 0.055 (Pb)			

3.5 Correlation between Heavy Metals and *Listeria* Species

Table 5 presents Pearson correlation coefficients. A very strong positive correlation was observed between *Listeria* occurrence and Cd levels (r = 0.998, p < 0.05). A moderate positive correlation was found between Cd and Pb (r = 0.720, p < 0.05). A weaker but significant positive correlation was identified between *Listeria* and Pb (r = 0.673, p < 0.05).

Table 5
Pearson Correlation Matrix for Heavy Metals and *Listeria* Species Occurrence

Variable	<i>Listeria</i> species	Cadmium (Cd)	Lead (Pb)	Interpretation
<i>Listeria</i> species	1	0.998	0.673	Extremely strong Cd- <i>Listeria</i> association
Cadmium (Cd)	0.998	1	0.720	Very strong Cd-Pb co-contamination
Lead (Pb)	0.673	0.720	1	Strong <i>Listeria</i> -Pb association
Significance	p < 0.05	p < 0.05	p < 0.05	All correlations significant

3.6 Summary Risk Assessment by Consumer Group

Table 6 summarizes risk ratings for adults and children. Children face critically high risks across all product types, with HI values ranging from 3.82 to 11.51 and THQ_Pb values up to 11.13.

Table 6
Summary Risk Assessment Matrix for Fish Consumption in Kaduna North

Consumer Group	Fish Type	THQ_Cd	THQ_Pb	HI	Cancer Risk (Cd)	Overall Risk Rating
Adults (70 kg)	Smoked	0.09	1.77	1.86	3.5×10^{-5}	HIGH
	Frozen	0.11	3.18	3.29	4.1×10^{-5}	CRITICAL
	Canned	0.08	1.01	1.09	3.0×10^{-5}	MODERATE-HIGH
Children (20 kg)	Smoked	0.32	6.20	6.52	1.2×10^{-4}	CRITICAL
	Frozen	0.38	11.13	11.51	1.4×10^{-4}	CRITICAL
	Canned	0.28	3.54	3.82	1.1×10^{-4}	CRITICAL
Risk Rating: LOW ($HI < 0.1$, $THQ < 0.1$, $CR < 10^{-6}$); MODERATE ($HI 0.1-1.0$); HIGH ($HI 1.0-5.0$, $THQ > 1$); CRITICAL ($HI > 5.0$, $THQ > 5.0$, $CR > 10^{-4}$)						

4. DISCUSSION

4.1 Magnitude of Heavy Metal Contamination and Regulatory Exceedances

This study provides compelling evidence of widespread cadmium and lead contamination in commercially available fish from Kaduna North, Nigeria, with concentrations consistently exceeding multiple international safety thresholds. The mean Cd concentrations observed across all fish types

(0.093–0.125 µg/g) surpassed the European Union Maximum Residue Limit of 0.05 µg/g (European Commission, 2023), the Codex Alimentarius standard of 0.05 µg/g (Codex Alimentarius Commission, 2021), and the Nigerian Industrial Standard for fish products of 0.05 µg/g (Standards Organisation of Nigeria, 2015). The fact that 43.33% of all samples exceeded the Cd MRL indicates that nearly half of the fish products available to consumers in Kaduna North are potentially unsafe with respect to cadmium content.

Lead contamination presented an even more alarming scenario. Mean Pb concentrations in frozen fish (0.637 ± 0.12 µg/g) exceeded the EU MRL by 32-fold, the US FDA action level for fish of 0.3 µg/g (FDA, 2020) by 2.1-fold, and the Nigerian maximum permissible limit of 0.02 µg/g (Standards Organisation of Nigeria, 2015) by 31.8-fold. The overall prevalence of Pb exceedance (69.44% of all samples) demonstrates that lead contamination is a systemic problem affecting the vast majority of fish products in the study area. This finding is particularly concerning given that lead is a neurotoxicant with no known safe level of exposure (Lanphear et al., 2005; Bellinger, 2008).

The lack of statistically significant differences in Pb distribution across markets ($p = 0.380$) suggests that contamination is not localized to specific vendors or market areas but rather represents a widespread supply chain issue. This pattern is consistent with observations by Jimoda et al. (2024) regarding atmospheric lead pollution in Nigerian urban centers, and with Alloway and Ayres (2020), who documented that lead contamination often originates from diffuse sources including vehicular emissions, industrial discharges, and contaminated feed sources. The near-significant p-value for market-specific Pb levels ($p = 0.055$) hints at localized pollution sources near Unguwar Rimi Market, such as industrial discharges or high vehicular emissions (World Health Organization, 2019), warranting further investigation.

The significant difference in Cd contamination across fish product types ($\chi^2 = 8.552$, $p = 0.014$) warrants careful consideration. Smoked fish exhibited the highest Cd exceedance (58.33%), followed by frozen (38.33%) and canned (33.33%). This pattern may be explained by processing-related concentration effects. Smoking involves dehydration, which reduces water content and effectively concentrates any heavy metals present in the original fish tissue (Adeolu et al., 2019). Additionally, the smoking process itself may introduce contaminants if the smoking fuel (often scrap wood, tires, or other waste materials in informal settings) contains heavy metals (United Nations Environment Programme, 2020). Similarly, frozen fish may accumulate metals through repeated freeze-thaw cycles during transportation and storage, which can disrupt cellular integrity and redistribute metals (Zhang et al., 2021).

For lead, although the chi-square test did not reach statistical significance ($p = 0.092$), the pattern of exceedance was notably different: smoked fish had the highest Pb exceedance (78.33%), followed by canned (70.00%) and frozen (60.00%). The high Pb levels in canned fish deserve particular attention, as they may originate from lead-soldered seams in older canning equipment or from leaching of lead from can linings, especially when acidic fish products are stored for extended periods (Kumar et al., 2023).

The European Food Safety Authority (2012) has previously documented that canned foods, particularly fish in acidic sauces, can show elevated lead levels due to can construction materials.

The extremely high mean Pb concentration in frozen fish (0.637 µg/g) is particularly puzzling and concerning. Unlike smoked or canned fish, frozen fish typically undergo minimal processing, suggesting that the contamination likely occurs at the source – either in the aquatic environment where the fish were harvested or during initial processing before freezing. This finding aligns with reports by Adeogun et al. (2020) from Lagos Lagoon and by Oluah et al. (2021) from Ikpoba Reservoir, both of which documented significant lead accumulation in fish from Nigerian waters. The implication is that source waters for these frozen fish (which are often imported) may be severely contaminated with lead, necessitating international supply chain investigations.

The Target Hazard Quotient analysis provides critical insights into actual health risks that transcend simple regulatory exceedance reporting. While THQ values for cadmium remained below 1 across all product types (range: 0.078–0.121), this should not be interpreted as complete safety. The THQ for Cd being below 1 indicates that, for non-carcinogenic effects, cadmium alone does not present an unacceptable risk at current consumption levels. However, this finding must be contextualized within the framework of cumulative risk assessment. As noted by Cobbina et al. (2015) and Wang and Du (2013), the combined effects of multiple heavy metals can be additive or synergistic, meaning that even individual THQ values below 1 can combine to exceed safe thresholds when considered together.

The THQ values for lead exceeding 1 in all product types represent a clear public health warning. Frozen fish presented the highest THQ_{Pb} (3.18), indicating that regular consumption of frozen fish would result in lead intakes exceeding the JECFA Provisional Tolerable Daily Intake of 0.0035 mg/kg/day (JECFA, 2010) by a factor of 3.2. This means that an adult consuming a typical 60 g portion of frozen fish from Kaduna North would ingest 156% of the recommended maximum daily lead intake from that single food source alone, without accounting for other dietary and environmental exposures. Smoked fish (THQ_{Pb} = 1.77) and canned fish (THQ_{Pb} = 1.01) also exceed the safe threshold, with canned fish falling on the borderline where even small increases in consumption frequency or portion size would elevate risk further.

The Hazard Index, which sums THQ values for all metals, exceeded 1 across all product types (range: 1.09–3.29), confirming that combined exposure to cadmium and Pb presents unacceptable non-carcinogenic risk regardless of product type. The highest HI was observed for frozen fish (3.29), followed by smoked fish (1.86) and canned fish (1.09). These findings are consistent with health risk assessments from other African water bodies. For example, Orisakwe et al. (2021) identified carcinogenic risks from multiple metals in fish from the River Niger, and Adeogun et al. (2020) reported similar concerns for Lagos Lagoon. The HI values reported in our study are comparable to or higher than those reported for heavily industrialized Asian watersheds (Li et al., 2022; Sharma et al., 2023), indicating that Nigeria faces a heavy metal contamination problem of global significance.

The risk assessment for children (20 kg body weight) reveals a public health emergency. Children are disproportionately vulnerable to heavy metal toxicity due to several physiological and behavioral factors: higher food and water intake per unit body weight, developing organ systems with windows of heightened susceptibility, increased gastrointestinal absorption of metals, and ongoing neurological development that is particularly sensitive to lead and cadmium neurotoxicity (World Health Organization, 2017).

The THQ_{Pb} values for children consuming frozen fish reached 11.13 – more than eleven times the safe threshold. This means that a child eating a typical 20 g portion of frozen fish (approximately one small fish fillet) would receive lead doses equivalent to 1,113% of the reference dose. The Hazard Index for children ranged from 3.82 (canned fish) to 11.51 (frozen fish), all exceeding the critical threshold of 5.0 established by US EPA (2022) for high-priority risk management.

The implications for child neurodevelopment are severe. Lanphear et al. (2005) demonstrated that even blood lead levels below 5 µg/dL are associated with reduced IQ, attention deficits, and behavioral problems. Bellinger (2008) documented that there is no threshold for lead-induced neurotoxicity – any exposure carries some risk. In the Nigerian context, where baseline blood lead levels in children are already elevated due to environmental sources including lead-contaminated soil, paint, and traditional remedies (Orisakwe et al., 2021), additional dietary lead exposure from fish consumption could push vulnerable children over the threshold for clinically significant neurodevelopmental impairment.

The cancer risk for children exceeded the unacceptable threshold of 1×10^{-4} for all product types (range: 1.1×10^{-4} to 1.4×10^{-4}), indicating that lifetime exposure beginning in childhood would result in more than one additional cancer case per 10,000 people. This is particularly concerning given that cadmium is classified as a Group 1 human carcinogen by the International Agency for Research on Cancer (IARC, 2006), with strong evidence linking cadmium exposure to lung, kidney, and prostate cancers.

The extremely strong positive correlation between *Listeria* species occurrence and cadmium levels ($r = 0.998$, $p < 0.05$) is among the most novel and concerning findings of this study. This near-perfect association suggests a mechanistic relationship beyond simple co-occurrence. Several biological mechanisms may explain this phenomenon.

First, cadmium exposure is known to suppress fish immune function through multiple pathways. Rady et al. (2024) demonstrated that cadmium induces glutathione depletion in fish tissues, reducing antioxidant capacity and impairing macrophage and neutrophil function. This immunosuppression creates an opportunistic environment where *Listeria* – an intracellular pathogen normally controlled by cell-mediated immunity – can proliferate more readily. Second, *Listeria* species possess heavy metal resistance genes, including the *cadA* and *cadC* operons that encode efflux pumps for cadmium and lead (Adeogun & Ibor, 2022). These resistance mechanisms allow *Listeria* to survive and even thrive in metal-contaminated environments, giving them a competitive advantage over metal-sensitive microbiota.

Third, there may be a shared environmental source for both cadmium and *Listeria*. Industrial and agricultural runoff that contains heavy metals often also contains fecal contamination and pathogens (Tchounwou et al., 2012). The moderate correlation between Cd and Pb ($r = 0.720$) supports the hypothesis of common pollution sources. This finding mirrors observations in Nigeria's Ologe Lagoon by Adeogun and Ibor (2022), who reported significant associations between heavy metal concentrations and microbial loads in *Clarias gariepinus*, but contrasts with findings from Ethiopia's Omo Delta by Desta et al. (2022), where such correlations were not observed – a difference likely attributable to varying industrial activities and pollution sources.

The weaker but still significant correlation between *Listeria* and Pb ($r = 0.673$) suggests that lead contamination may also contribute to *Listeria* proliferation, though through different mechanisms. Lead is known to disrupt tight junctions in the intestinal epithelium (Bernhoft, 2021), potentially enhancing translocation of *Listeria* across the gut barrier. Additionally, lead-induced oxidative stress may further compromise immune function (Järup, 2003). The practical implication of these correlations is that fish products contaminated with heavy metals are not only chemically hazardous but also more likely to harbor *Listeria* pathogens, creating a dual hazard that requires integrated food safety interventions.

The contamination levels observed in this study are substantially higher than those reported in similar studies from other regions, highlighting the severity of Nigeria's heavy metal pollution problem. For fish from the Mediterranean Sea, Storelli et al. (2020) reported Cd levels ranging from 0.008–0.025 µg/g and Pb levels from 0.010–0.045 µg/g – both significantly lower than our findings. In European markets, the European Food Safety Authority (2014) documented average Pb levels of 0.023–0.089 µg/g in fish products, compared to our range of 0.177–0.637 µg/g. Garcia et al. (2022) conducted a systematic review of heavy metals in European fish and concluded that regulatory standards are generally met in most commercial products, unlike the situation in Kaduna North.

Within the African context, our findings are consistent with reports from other Nigerian studies. Adeogun et al. (2020) found mean Pb levels of 0.45–0.89 µg/g in fish from Lagos Lagoon – values remarkably similar to our frozen fish Pb levels. Oluah et al. (2021) reported Pb concentrations of 0.32–0.78 µg/g in *Tilapia zillii* from Ikpoba Reservoir, Benin City. These consistent findings across multiple Nigerian locations suggest a national pattern of severe lead contamination in aquatic ecosystems, likely stemming from widespread industrial pollution, improper waste disposal, and the legacy use of leaded gasoline (which was only phased out in Nigeria in 2004).

However, our findings contrast with lower levels reported in some other African regions. Desta et al. (2022) found relatively low heavy metal levels in fish from Ethiopia's Omo Delta, which the authors attributed to limited industrial development in the catchment area. Similarly, Ochieng et al. (2021) reported moderate contamination levels in Lake Turkana, Kenya, though they noted transboundary pollution as a growing concern. These contrasts underscore that heavy metal contamination is highly localized and closely tied to industrialization, urbanization, and regulatory enforcement.

The findings of this study have profound implications for public health and food safety policy in Nigeria and similar low- and middle-income countries. The combination of widespread regulatory exceedances, unacceptable health risk indices, and correlations with pathogen occurrence demands urgent, multi-pronged interventions.

First, regulatory limits themselves may need revision. While the EU MRLs provide useful benchmarks, they may not be immediately achievable in Nigerian contexts given current contamination levels. A phased approach could be adopted: immediate implementation of achievable interim limits, with progressive tightening over a 5–10 year period as pollution control measures take effect. The Nigerian Industrial Standard of 0.02 µg/g for lead (Standards Organisation of Nigeria, 2015) is already aligned with EU standards, but our data show that 69.44% of samples exceed this limit, indicating either non-enforcement or the infeasibility of current standards. Risk-based standards that account for local consumption patterns and vulnerable populations may be more appropriate.

Second, source identification and pollution control are paramount. The extremely high lead levels in frozen fish suggest contamination at the harvest source — likely in the marine or freshwater environments where these fish were caught. Nigeria is a major importer of frozen fish (Jatto et al., 2013), meaning that some contamination may originate in exporting countries. International cooperation and supply chain traceability are needed to identify and remediate contaminated sources. Domestically, stricter enforcement of industrial effluent regulations, improved waste management systems, and remediation of contaminated water bodies are essential (United Nations Environment Programme, 2018, 2020).

Third, public health advisories should be developed for vulnerable populations. Pregnant women, nursing mothers, and parents of young children should receive targeted messaging about the risks of heavy metal exposure from fish consumption. While fish remains an important source of protein and omega-3 fatty acids (FAO, 2020), consumption of certain product types (particularly frozen fish) should be limited for these vulnerable groups. The World Health Organization (2018) has emphasized that risk communication is a critical component of food safety management, yet such advisories are largely absent in Nigeria.

Fourth, routine monitoring programs must be established and adequately funded. The lack of statistically significant differences across markets suggests that spot checks or occasional testing are insufficient. What is needed is a continuous, risk-based surveillance system that tests fish products at import points, processing facilities, and retail markets. Such systems exist in the European Union (European Food Safety Authority, 2012, 2014) and United States (FDA, 2020), but are largely absent in Nigeria. The Food and Agriculture Organization (2020) has called for strengthening food safety monitoring systems in low- and middle-income countries as a global health priority.

The risks identified in this study are likely to be amplified by climate change, an often-overlooked dimension of heavy metal contamination. Han et al. (2024) demonstrated that rising water temperatures increase cadmium bioaccumulation in fish by approximately 50% at 32°C compared to 25°C, due to

increased metabolic rates and gill permeability. In Kaduna State, average temperatures have increased by 1.2°C over the past three decades and are projected to rise further (ZEMDA, 2014). Additionally, climate change is increasing the frequency and intensity of flooding events in northern Nigeria. Adeogun et al. (2020) reported that flooding mobilizes sediment-bound metals, increasing lead bioavailability by 300% during Lagos rainy seasons. These climate-metal interactions suggest that the contamination problem may worsen over time, even without increases in industrial emissions.

Furthermore, climate change may exacerbate the *Listeria* risk identified in this study. *Listeria monocytogenes* grows more rapidly at higher temperatures, and climate-driven changes in water quality may enhance its survival and transmission (World Health Organization, 2018). The combined effect of climate change on both heavy metal bioavailability and pathogen proliferation represents a "perfect storm" for food safety in tropical regions like Kaduna North.

The health risks identified in this study must be considered within the context of Nigeria's healthcare system capacity. The United Nations Environment Programme (2018) reported that Nigeria faces a health worker shortage of 11.1 million by 2030, severely limiting its capacity to manage contamination-related health burdens. Environmental exposures already account for an estimated 24% of national mortality in Nigeria (United Nations Environment Programme, 2018), with heavy metal-related diseases (chronic kidney disease, hypertension, neurodevelopmental disorders, cancers) placing substantial strain on an already overburdened system.

The economic implications are equally concerning. The World Health Organization (2019) estimates that lead exposure alone cost African economies approximately \$134 billion annually in lost productivity and healthcare expenditures. For Nigeria specifically, Orisakwe et al. (2021) calculated that childhood lead exposure reduces lifetime earnings by 2–5% due to cognitive impairment. The additional burden from cadmium-related kidney disease and cancer further compounds these economic losses. From a cost-benefit perspective, investments in pollution control and food safety monitoring are likely to yield substantial economic returns through avoided healthcare costs and preserved human capital.

5. CONCLUSION

This study unequivocally demonstrates pervasive and alarming levels of cadmium and lead contamination in commercially available fish across Kaduna North, Nigeria, with concentrations consistently exceeding multiple international safety thresholds. The health risk assessment reveals that Hazard Index values exceed 1 for all product types (range: 1.09–3.29), indicating unacceptable non-carcinogenic risk from combined metal exposure, and for children, HI values reach as high as 11.51, representing a critical public health emergency. Lead THQ values for frozen fish (3.18) and smoked fish (1.77) exceed safe thresholds, with children facing critically high risks (THQ_{Pb} up to 11.13); given that there is no known safe level of lead exposure, any exceedance of the reference dose is cause for concern. Cancer risks from cadmium fall within the borderline range ($3-4 \times 10^{-5}$) for adults but exceed the unacceptable threshold ($> 1 \times 10^{-4}$) for children, indicating that lifetime exposure beginning in

childhood would result in more than one additional cancer case per 10,000 people. Frozen fish present the highest overall risk, followed by smoked and canned products, and the extremely high lead levels in frozen fish ($0.637 \pm 0.12 \mu\text{g/g}$) – 32 times the EU MRL, warrant immediate regulatory investigation of supply chains. Additionally, the extremely strong correlation between Cd and *Listeria* occurrence ($r = 0.998$) highlights a synergistic food safety challenge where chemical and microbiological hazards co-occur, requiring integrated intervention strategies. Therefore, the following actions are recommended: establish Nigerian-specific, risk-based MRLs with routine health risk assessment as part of national food safety monitoring and implement immediate enforcement actions for the most contaminated products, particularly frozen fish; strengthen environmental regulations for industrial discharges, improve waste management systems, remediate contaminated water bodies, and conduct international supply chain investigations for imported frozen fish; develop and disseminate consumption advisories for vulnerable populations (children, pregnant women, nursing mothers) and integrate heavy metal biomonitoring into routine healthcare; establish a continuous, risk-based monitoring system for heavy metals and pathogens in fish products at import points, processing facilities, and retail markets; conduct source apportionment studies to identify contamination origins, longitudinal studies to capture seasonal variability, and biomonitoring studies to validate risk assessment predictions; and invest in laboratory infrastructure, analytical chemistry training, and food safety inspection personnel while strengthening Nigeria's participation in international food safety networks. The findings of this study demonstrate that commercially available fish in Kaduna North pose unacceptable health risks from combined heavy metal contamination and without urgent, coordinated intervention from government, industry, and international partners, the public health consequences particularly for children will continue to accumulate, with lifelong and intergenerational impacts.

Declarations

Ethical approval:

All authors have read, understood, and complied with the statement on ethical responsibilities of authors.

Competing interests:

The authors declare no competing interests.

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Author Contribution

Musa Alhaji Musa conceived and designed the study, collected and analyzed the samples, performed the statistical and risk assessment analyses, and drafted the manuscript. Abdulwakil Olawale Saba, Iami Jafiya and Abubakar Bilal Ahmed contributed to the methodology development, validation of analytical procedures, and critical revision of the manuscript. Dahiru Sani supervised the research, contributed to the interpretation of toxicological data, and reviewed the final manuscript. All authors read and approved the final version of the manuscript.

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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