



Concentrations, bioaccumulation, and health risk assessments of heavy metals in fishes from Nigeria's freshwater: a general overview

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Abstract

Heavy metals (HMs) have attracted global attention due to their toxicity, persistence, and accumulation in aquatic fish in the polluted water environment. The consumption of these fishes exposed humans to a higher risk of non-carcinogenic and carcinogenic risks. In this study, we provided a critical overview of the potential sources and concentration of HMs in Nigeria's freshwater. Furthermore, we reported their pollution level in widely eaten fish species in the country. Our findings show that effluent from anthropogenic and industrial activities is one of the major sources HMs in the country. The mean concentration of Zn (9.02 mg/L), As (7.25 mg/L), Cu (4.35 mg/L), Fe (1.77 mg/L), and Pb (1.46 mg/L) in Nigeria's freshwaters were found to be high than Nigerian Standard for Drinking Water Quality permissible limit. This study demonstrated considerable health risks associated HMs via dietary consumption of different fishes from polluted waters. Therefore, we recommended an urgent need for effective management HMs in water bodies in order to protect the lives of people living in the country.

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Introduction

Over the last 50 years, several adverse environmental effects and human disasters have been associated with rapid industrialization and urbanization, thereby raising concerns for human safety. Simultaneously, the release of harmful pollutants into virtually all forms of environmental matrices has become a great deal (Ajibade et al. 2021a; Nwogwu et al. 2022a, b; Ajala et al. 2022). Worldwide, the integrity of aquatic ecosystems is affected by heavy metals (HMs) pollution, and as a result, assessing the quality of water is a pressing issue today (Anyakora et al. 2011; Adelodun et al. 2021; Ighalo et al. 2021). Mining and anthropogenic activities are responsible for HM pollution in water (Ugya et al. 2018; Oluwatuyi et al. 2020; Ajibade et al. 2021b), but it is the bioaccumulation of these pollutants that affects the aquatic fishes (Nouri et al. 2008; Maruf et al. 2021). Owing to the inherent bioaccumulation potentials of HMs as well as their long-term persistence in a different environment, concerns have been raised about the monitoring of these pollutants (Dahunsi et al. 2012; Koki et al. 2015; Ceballos et al. 2021). This is to ensure the desired sustainability of various aquatic ecosystems and functions via the monitoring of the integrity of freshwaters (Wang et al. 2014; Adewumi and Ajibade 2019). HM pollution has become one of the major problems in developing countries mainly due to the lack of or inadequate pollution checks, driven largely by unplanned industrial growth and other developmental quests (Adewumi and Ajibade 2015; Akinbile et al. 2016a, b; Ilori et al. 2019).

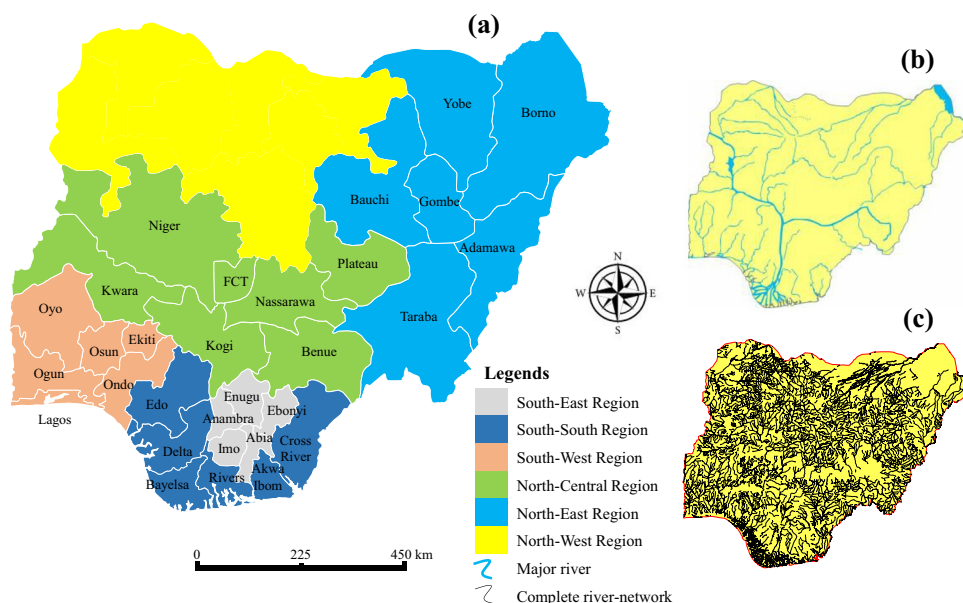
Due to this, HMs are released into the aquatic environment which contaminates the freshwaters, accumulates in the aquatic fishes, and as a result enters the human system through the food chain, thereby causing serious adverse human health effects (at higher contamination and exposure levels) (Papagiannis et al. 2004; Türkmen et al. 2005; Fernandes et al. 2007). Consequently, HMs have been listed by the United States Environmental Protection Authority (USEPA) according to their potential for toxic effects on human health (Birungi et al. 2007). Human health risk evaluation from HMs is usually examined through the consumption of fishes grown in polluted freshwater. This is because the fish populations are stable and easy to nurture and collect (Renieri et al. 2014). Also, fish living in polluted waters tend to accumulate HMs in their system (Salem et al. 2014; Renieri et al. 2017). According to the Food and Agriculture Organization (FAO), fish accounted for approximately 16% of the global intake of animal protein and 6% of all consumed protein (FAO 2010). Generally, dietary consumption of HMs accumulated in fish has been widely associated with human poisoning (Kumar et al. 2021; Zhuang et al. 2009). The

assimilation of HMs in fish occurs via the ingestion of water-suspended particles including food or by the exchange of ions via lipophilic membranes such as the gills and tissue, and/or through membrane surface adsorption. The concentration of HMs in aquatic fishes have been given special consideration due to their potential risks to human via dietary consumption. Chronic illness and potential damage to human health can result from the accumulation of HMs in the tissues of aquatic fishes (Amirah et al. 2013). Detrimental effects and non-carcinogenic hazards such as neurologic problems, headaches, and liver/kidney diseases have been associated with the chronic intake of HMs above the safety threshold (Farmer et al. 2011; Guadie et al. 2021). The development of target hazard quotients (THQ) was done by the USEPA (1989) for the evaluation of possible health risks associated with long-term exposure to chemical contaminants and as well as other parameters such as estimated daily intake (EDI), cancer risk (CR), relative risk (RR), and hazard index (HI) used for assessing the carcinogenic and non-carcinogenic effects of chemical contaminants, which have helped in recognizing harmful contaminants.

Blessed with a vast freshwater ecosystem (Fig. 1), fishing is one of the major sources of livelihood for many Nigerians. Despite the introduction of modern aquaculture to increase fish production, the demand for fish consumption still outweighs national production. Approximately 40% of the fish produced in the country are from local freshwaters while the remainder 60% are imported fish (Iwegbue et al. 2015). Therefore, the need to complement modern aquaculture production from natural water is inevitable. Fishing from the wild in order to augment national demand presented several challenges as water bodies are largely polluted with effluents from industrial and other anthropogenic activities (Chinedu and Chukwuemeka 2018). Other studies have drawn attention to the high level of HMs in freshwaters used in the production of aquatic fish in Nigeria (Ighalo and Adeniyi 2020; Abalaka et al. 2020; Edogbo et al. 2020; El-Ishaq et al. 2016).

This study set out to critically review and compile the present knowledge on HMs. We carefully examine useful trends on the sources and concentration of different HMs such as chromium (Cr), cadmium (Cd), lead (Pb), copper (Cu), manganese (Mn), nickel (Ni), iron (Fe), mercury (Hg), cobalt (Co), zinc (Zn), and arsenic (As) in Nigeria's freshwater. We evaluate the useful trend in the bioaccumulation of HMs in widely eaten fishes (*Tilapia zilli*, *Oreochromis niloticus*, *Chrysichthys walkeri*, *Chrysichthys furcatus*, *Arius gigas*, *Ilisha africana*, *Ethmalosa fimbriata*, *Parachanna obscura*, *Clarias lazera*, *Clarias gariepinus*, *Auchenoglanis occidentalis*, *Genyonemus lineatus*, *Mormyrus rume*, *Cololabis saira*, *Mugil cephalus*, *Tylosurus crocodilus*, *Trichiurus lepturus*) in polluted waters

Fig. 1 Map of Nigeria showing different geolocations alongside the river networks (**a**: geolocations of Nigeria; **b**: major river network; **c**: complete river network)



and possible health risk via dietary intake. We expounded our findings regionally, and to the best of our knowledge, no detailed article has put such into consideration. Lastly, research gaps were identified to highlight future research prospects.

Methodology of the review

Different keywords such as HMs, freshwater, aquatic fishes, HM contamination in fresh waters in Nigeria, HM bioaccumulation in aquatic fish, fish toxicity, and health risk associated with HM accumulation in fish were used to source peer-reviewed literature and original research papers from 2000 to 2021 from four databases, namely, Scopus database, ScienceDirect, ResearchGate, and Google Scholar. All sourced articles were checked, and unrelated ones were sectioned out. Those related to the focus of this study were further sectioned regionally. This was done to understand the regional perspectives. In addition, references of related sourced articles were checked and screened for relevance.

Sources of heavy metals (HMs) in Nigeria's freshwaters

Figure 2 shows different sectors which are responsible for HM pollution. Across different regional zones of Nigeria, industrial and pharmaceutical effluents (Anyakora et al. 2011; James et al. 2013; Ayeni 2014), agricultural and food processing effluents (Okunade and Adekalu 2013), leachate from dumpsites (Afolayan 2018; Ogunlaja et al. 2019), effluents from chemical plants (Agah et al.

2014), open-cast mining (Okolo and Oyedotun 2018), crude oil refinery and petrochemical effluent (Okonofua et al. 2021; Uzoekwe and Oghosanine 2011), gas flaring (Nwankwo and Ogagarue 2011), and cement production and mining activities (Inyinbor et al. 2012; Muhammad et al. 2014; Sanusi et al. 2017) are reported sources of HM pollution. Table 1 presents the various kinds of fishes in Nigeria with their common and species names.

Concentration of HMs in Nigeria's freshwater

Compared with the Nigerian Standard for Drinking Water Quality (NSDWQ), European Union (EU), and World Health Organization (WHO), this section discusses the concentration of HMs in Nigeria's freshwaters across different geographical distributions (Table 2). It is noticed in Table 2 that most of the concentrations of HMs are above the maximum permissible limits given by NSDWQ, EU, and WHO. Lo et al. (2010) and Omanayi et al. (2011) have demonstrated lead poisoning of rural water bodies caused by illegal mining activities has killed several children in northern Nigeria. Figure 3 summarizes the concentration HMs in both rainy and dry seasons as presented in Table 2. The major HM pollutants in Nigeria's freshwater are Zn (9.02 mg/L mean), As (7.25 mg/L mean), Cu (4.35 mg/L mean), Fe (1.77 mg/L mean), and Pb (1.46 mg/L mean).

Chromium (Cr)

According to the NSDWQ, EU, and WHO, 0.05 mg/L is the maximum allowable concentration of Cr in freshwater (Table 2). A high concentration of Cr in Nigeria's freshwater is reported in the Ndawuse River in Abuja (Enitan et al.

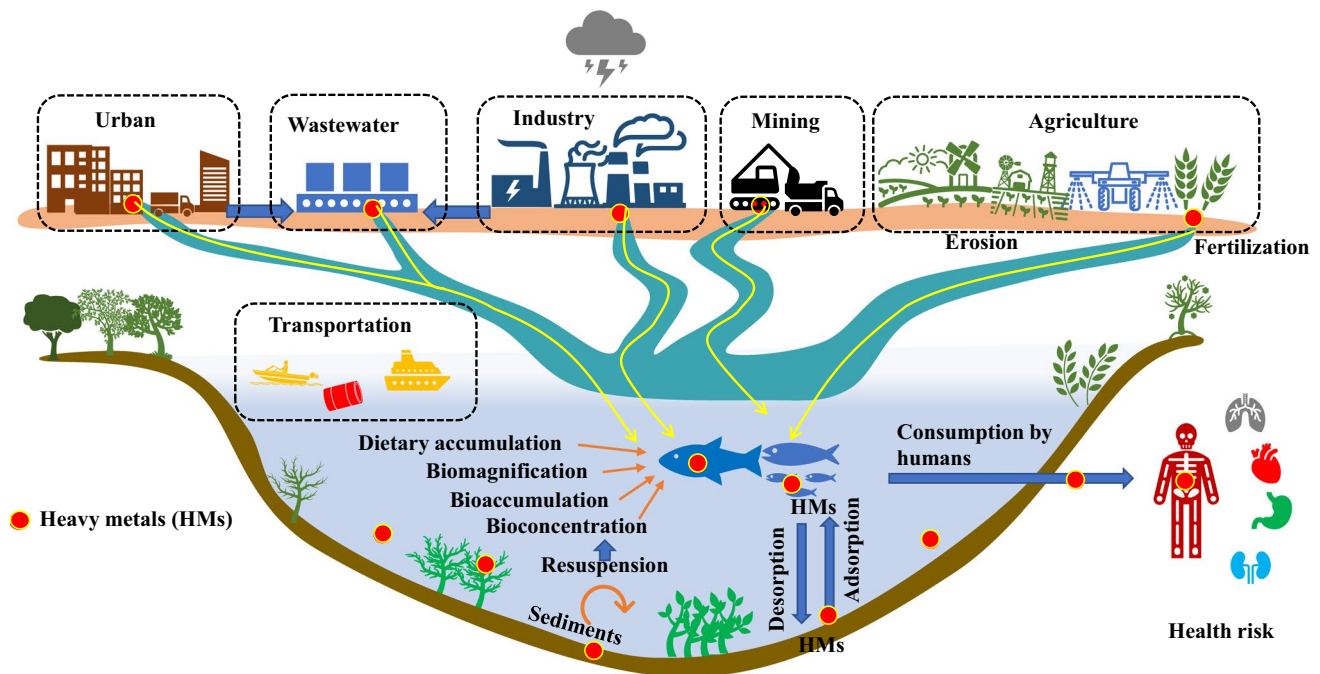


Fig. 2 Different sectors responsible for HM pollution and their bioaccumulation by aquatic biota including fishes

Table 1 Fish categories with their English names and species in Nigeria

Fish types	English name	Species
Fresh water fin	Snake head	<i>Parachanna africana</i>
	Tilapia	<i>Tilapia zilli</i>
	Tilapia	<i>Oreochromis niloticus</i>
	Electric fish	<i>Malapterus electricus</i>
	Freshwater cat fish	<i>Heterobranchius bidorsalis</i>
Marine water fin	Croaker	<i>Pseudotolithus senegalensis</i>
	Croaker	<i>Pseudotolithus elongatus</i>
	Croaker	<i>Pseudotolithus typus</i>
	Bonga fish	<i>Ethmalosa fimbriata</i>
	Catfish	<i>Chrysichthys nigrodigitatus</i>
Freshwater shell	Blue crab	<i>Callinectes pallidus</i>
	Shrimp	<i>Panaeus notialis</i>
	Shrimp	<i>Macrobrachium macrobrachion</i>
	Brackish water prawn	<i>Macrobrachium vollehoevenii</i>
	Crab	<i>Callinectes amnicola</i>
Marine water shell	Costate cockle	<i>Cardium costatum</i>
	Senegal ark	<i>Anadara senegalensis</i>
	Deep water rose	<i>Parapenaens congirostris</i>
	West African Geryon	<i>Geryon maritae</i>
	Guinea shrimp	<i>Parapenaopsis atlantica</i>

2018), Samberiro River in Rivers State (Ihunwo et al. 2020), Asejire River and Dandura River in south-west Nigeria (Adesiyani et al. 2018), River Ijana in Warri (Emoyan et al. 2006), River Kaduna in Kaduna (Abui et al. 2017), Niger–Benue River in Lokoja (Ekere et al. 2018), Elelenwo River in Rivers State (Edori et al. 2019), Silver River in Bayelsa (Ekp et al. 2019), freshwaters in southern Benue (Igwe et al. 2020), River Atuwara in south-western Nigeria (Emenike et al. 2020), and Nkalagu dam River in Ebonyi (Ugbede et al. 2020). The concentration of Cr ranged from not-detected limit (ND) (Atomic Absorption Spectrophotometer (AAS)) to 7.05 mg/L. However, the lowest concentrations of Cr are found in freshwater in Niger Delta (Nwankwo and Ogagarue 2011), Asejire River, Eleyele River, and Erinle River in south-western Nigeria (Adesiyani et al. 2018). The highest concentration of Cr was found in River Atuwara (7.05 mg/L at dry season) in south-western Nigeria (Emenike et al. 2020) and followed by River Kaduna (3.72 mg/L) in Kaduna (Abui et al. 2017) and Silver River (3.725 mg/L) in Bayelsa State (Ekp et al. 2019).

Cadmium (Cd)

Except in the surface water (<0.001 mg/L) of Bayelsa State (Uzoekwe and Aigberua 2019), the concentrations of Cd in most of the freshwater are observed to be higher than the maximum permissible values (Table 2). The concentration of Cd ranged from <0.001 to 11.01 mg/L. The highest concentration of Cd is reported at 11.01 mg/L in the Ebonyi River in south-eastern Nigeria and is attributed to open-cast mining (Okolo and Oyedotun 2018).

Table 2 The concentration of heavy metals (HMs) in Nigeria's freshwaters

Location	Season	Cr (mg/L)	Cd (mg/L)	Pb (mg/L)	Cu (mg/L)	Mn (mg/L)	Ni (mg/L)	V (mg/L)	Fe (mg/L)	Hg (mg/L)	Co (mg/L)	Zn (mg/L)	As (mg/L)	Reference
Ndawuse River	–	0.098	0.017	0.206	0.149	0.782	–	–	1.203	–	–	0.194	0.005	Enitan et al. (2018)
Samberiro River	–	1.590	0.146	3.252	2.328	–	0.109	–	–	–	–	–	BDL	Ihunwo et al. (2020)
Surface water	–	–	<0.001	<0.001–0.007	–	–	<0.001–0.023	–	0.807–3.450	–	–	–	–	Uzoekwe and Aigberua (2019)
Surface water	–	0.00–0.01	0.00–3.00	–	–	0.00–0.008	–	–	0.00–0.07	–	–	–	–	Nwankwo and Ogagarue (2011)
Fishpond water	Dry	0.00911	ND	0.0033	0.01032	0.02027	0.09022	–	0.51019	–	0.01034	0.05912	ND	Aladesanmi et al. (2014)
	Rainy	0.00826	ND	0.00299	0.00911	0.01143	0.08047	0.48012	–	–	0.00922	0.07801	–	
Asejire River	Rainy	0.043	0.018	0.014	–	0.152	–	–	–	–	–	–	0.016	Adesiyun et al. (2018)
	Dry	0.059	0.026	0.019	–	0.211	–	–	–	–	–	–	0.015	
Dandura River	Rainy	0.057	0.0189	0.013	–	0.162	–	–	–	–	–	–	0.012	
	Dry	0.071	0.024	0.019	–	0.191	–	–	–	–	–	–	0.011	
Eleyele River	Rainy	0.045	0.020	0.016	–	0.159	–	–	–	–	–	–	0.012	
	Dry	0.023	0.066	0.017	–	0.188	–	–	–	–	–	–	0.013	
	Rainy	0.040	0.018	0.015	–	0.175	–	–	–	–	–	–	0.012	
	Dry	0.043	0.024	0.022	–	0.210	–	–	–	–	–	–	0.013	
Olosuru stream	Rainy	–	0.016	0.021	–	0.085	–	–	0.220	–	–	–	0.031	Oyewale et al. (2019)
	Dry	–	0.015	0.017	–	0.064	–	–	0.217	–	–	–	0.013	
River Ijana	–	0.030–0.067	0.010–0.100	0.020–0.050	0.025–0.058	–	0.030–0.080	–	0.046–0.229	–	–	0.088–0.122	–	Emoyan et al. (2006)
River Kaduna	–	1.44–3.72	0.002–0.03	0.627–3.67	0.502–3.16	–	–	–	0.976–5.20	–	–	0.408–2.32	0.448–2.59	Abui et al. (2017)
Surface water	–	–	0.053	1.232	–	–	–	–	0.629	–	0.075	0.193	–	Addey et al. (2018)
Igbokoda River	–	–	4.9	14.8	36.2	–	–	–	–	–	–	–	61.3	Arojojoye et al. (2018)
Niger–Benue River	Dry	0.185	0.063	0.152	0.140	–	–	–	0.775	–	–	0.357	–	Ekere et al. (2018)

Table 2 (continued)

Location	Season	Cr (mg/L)	Cd (mg/L)	Pb (mg/L)	Cu (mg/L)	Mn (mg/L)	Ni (mg/L)	V (mg/L)	Fe (mg/L)	Hg (mg/L)	Co (mg/L)	Zn (mg/L)	As (mg/L)	Reference
Koko River Nigeria	–	–	0.01	0.18	0.02	0.06	0.42	–	0.14	–	0.14	0.01	–	Ezenonye et al. (2019)
Elelenwo River	–	0.111–0.174	0.218–0.276	0.413–0.447	0.685–0.843	–	0.170–0.194	–	5.170–7.34	–	0.538–0.805	1.09–2.73	–	Edori et al. (2019)
Silver River	–	1.694–3.725	0.714–2.414	1.742–3.812	2.171–3.691	0.349–2.891	0.443–2.717	–	2.891–4.489	0.0011–0.0024	–	5.167–8.239	–	Ekpet et al. (2019)
Surface water	–	0.02–0.48	0.18–4.37	0.06–10.11	–	0.04–1.16	0.02–1.21	–	0.03–2.04	–	–	0.13–7.11	–	Igwe et al. (2020)
Akpapa Izzi stream	–	–	2.33	–	2.51	–	–	–	–	–	–	31.38	11.99	Okolo and Oyedotun (2018)
Nwerugvu pond	–	–	2.13	0.03	3.56	–	–	–	–	–	–	65.38	61.44	
Ebonyi River	–	–	11.01	–	1.84	–	–	–	–	–	–	26.15	7.49	
River Atuwara	Rainy	0.27–4.94	0.04–0.99	0.05–5.69	0.185–28.21	–	–	–	–	–	–	–	–	Emenike et al. (2020)
Nigeria	Dry	0.38–7.05	0.04–1.01	0.05–2.97	0.14–31.12	–	–	–	–	–	–	–	–	Tenebe et al. (2018)
River Balogun	–	–	–	0.00	0.06	–	0.02	–	–	–	–	0.31	0.04	Titilawo et al. (2018)
River Osun	–	0.192	–	ND	0.407	0.0014	–	–	0.2	–	–	0.31	–	Ugbede et al. (2020)
Nkalagu dam	–	0.061	0.009	0.218	0.025	–	0.086	–	–	–	–	–	–	NSDWQ (2015)
River	–	–	–	–	–	–	–	–	–	–	–	–	–	Lenitech (2014)
WHO	–	–	–	–	–	–	–	–	–	–	–	–	–	Azizullah et al. (2011)
WHO	–	0.05	0.003	0.01	2	–	0.07	–	–	0.006	–	–	–	WHO (2011)

ND not detected, *BLD* below detection limit, *SON* Standard Organization of Nigeria, *EU* European Union, *WHO* World Health Organization

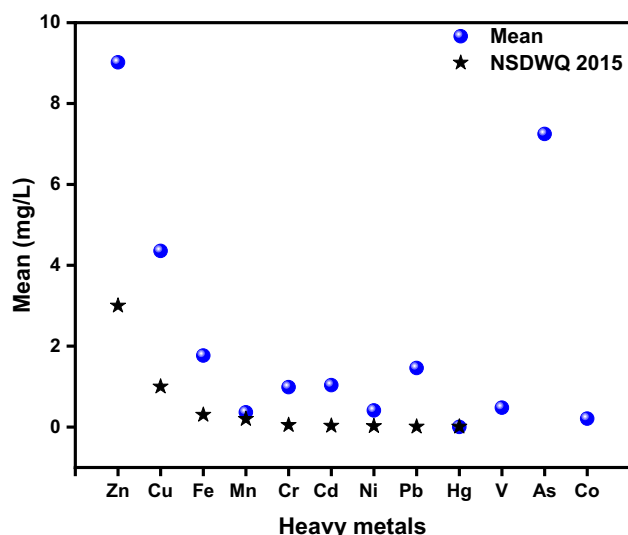


Fig. 3 Mean HM concentration in polluted surface waters across both rainy and dry seasons in Nigeria compared with SON standard (upper limits are considered for intervals)

Lead (Pb)

The concentration of lead ranged from ND (AAS) to 14.8 mg/L (Table 2). Compared to the maximum permissible limit, a higher concentration of Pb is reported in the Ndawuse River in Abuja (Enitan et al. 2018), Samberiro River in Rivers State (Ihunwo et al. 2020), Asejire River, Dandura River, Eleyele River, and Erinle River in south-western Nigeria (Adesiyani et al. 2018), Olosuru stream in Osun State (Oyewale et al. 2019), River Ijana in Warri (Emoyan et al. 2006), River Kaduna in Kaduna (Abui et al. 2017), surface water in Lagos (Addey et al. 2018), Igbokoda River in Ondo (Arojojoye et al. 2018), Niger–Benue River in Lokoja (Ekere et al. 2018), Koko River in southern Nigeria (Ezemonye et al. 2019), Elelenwo River in Rivers State (Edori et al. 2019), Silver River in Bayelsa (Ekp et al. 2019), surface water in southern Benue (Igwe et al. 2020) and Nwerugvu pond in south-eastern Nigeria (Okolo and Oyedotun 2018), River Atuwara in south-western Nigeria (Emenike et al. 2020), and Nkalagu Dam River in Ebonyi (Ugbede et al. 2020). The highest concentration of Pb (14.8 mg/L) is found in the Igbokoda River in Ondo State and is attributed to crude oil exploration activities (Arojojoye et al. 2018).

Copper (Cu)

Copper is an essential element of human nutrition. However, exposure to higher concentrations can be dangerous. Compared with the maximum permissible values, a considerably high level of Cu is reported in freshwaters across

different states in Nigeria (Table 2). The highest concentration of Cu is reported in the Igbokoda River in Ondo State (Arojojoye et al. 2018) and followed by River Atuwara in south-western Nigeria (Emenike et al. 2020), all associated with crude oil pollution. However, River Ijana in Warri (Emoyan et al. 2006), River Kaduna in Kaduna (Abui et al. 2017), Niger–Benue River in Lokoja (Ekere et al. 2018), Koko River in Southern Nigeria (Ezemonye et al. 2019), Elelenwo River in Rivers State (Edori et al. 2019), River Atuwara in southwestern Nigeria (Emenike et al. 2020), River Balogun in South-West Nigeria (Tenebe et al. 2018), and Nkalagu dam River in Ebonyi (Ugbede et al. 2020) have a safe concentration of Cu. The level of Cu ranged from 0.02 to 36.2 mg/L.

Manganese (Mn)

The concentration of Mn in freshwaters ranged from ND (AAS) to 2.891 mg/L (Table 2). Generally, as low as >0.1 mg/L concentration of Mn could be detrimental. A high concentration of Mn is found in the Ndawuse River in Abuja (Enitan et al. 2018), Asejire River, Dandura River, Eleyele River, and Erinle River in southwest Nigeria (Adesiyani et al. 2018), Olosuru Stream in Osun (Oyewale et al. 2019), Koko River in Southern Nigeria (Ezemonye et al. 2019), Silver River in Bayelsa (Ekp et al. 2019), and surface water in Southern Benue (Igwe et al. 2020). The highest concentration of Mn is reported in Silver River in Bayelsa due to the river receiving effluents from activities such as oil exploration, outboard engines, sewage and waste disposal from the communities and laundry, as well as runoffs from agricultural fields containing fertilizers, pesticides, and other agrochemicals (Ekp et al. 2019).

Nickel (Ni)

Ni ranged from <0.001 to 2.717 mg/L in Nigeria's freshwater surface (Table 2). Compared with recommended values, a high concentration of Ni is reported in Samberiro River in Rivers State (Ihunwo et al. 2020), surface water in Bayelsa State (Uzoekwe and Aigberua 2019), Ijana in Warri (Emoyan et al. 2006), Koko River in Southern Nigeria (Ezemonye et al. 2019), Elelenwo River in Rivers State (Edori et al. 2019), Silver River in Bayelsa (Ekp et al. 2019), surface water in Southern Benue (Igwe et al. 2020), and Nkalagu dam River in Ebonyi (Ugbede et al. 2020).

Iron (Fe)

The permissible limit recommended for iron is 0.02 mg/L (EU), 0.3 mg/L (WHO) (Azizullah et al. 2011), and 0.3 mg/L (NSDWQ) (Table 2). However, the concentration of Fe is found to exceed the maximum safe limit recommended

by NSDWQ as in Ndawuse River in Abuja (Enitan et al. 2018), surface water in Bayelsa State (Uzoekwe and Aigberua 2019), River Kaduna in Kaduna (Abui et al. 2017), surface water in Lagos (Addey et al. 2018), Niger–Benue River in Lokoja (Ekere et al. 2018), Elelenwo River in Rivers State (Edori et al. 2019), Silver River in Bayelsa (Ekp et al. 2019), and surface water in Southern Benue (Igwe et al. 2020). The concentration of Fe in surface water sources ranged from 0.00 to 7.34 mg/L, and the highest concentration was reported in Elelenwo River in Rivers State (Edori et al. 2019).

Mercury (Hg)

The information on the level of mercury in Nigeria's surface waters is not widely reported. Yet, Hg is a harmful metal that is not needed in water sources due to its adverse health effects. Table 2 presents data on the maximum permissible value for Hg. Ekp et al. (2019) have reported the concentration of Hg in the Silver River in Bayelsa State to range from 0.0011 to 0.0024 mg/L. However, the reported concentration is higher than the safe limit prescribed by WHO and NSDWQ. To better report the mobility of these elements, after all, when forming HgCH_3 , the risk to health is much greater than in other phases of Hg

Cobalt (Co)

Addey et al. (2018) reported the concentration of cobalt in surface water from the Commodore channel in Lagos to be 0.075 mg/L. However, there is no maximum permissible value set for Co including EU, NSDWQ, and WHO (Table 2). In other freshwaters, Co concentration ranged from 0.538 to 0.805 mg/L in Elelenwo River of Obio-Akpor in Rivers State (Edori et al. 2019). Ezemonye et al. (2019) reported the concentration of Co in the Koko River located in the coastal belt of Southern Nigeria to be 0.14 mg/L.

Zinc (Zn)

Zn is an essential metal. However, at a concentration above recommended permissible limit, it could pose a serious risk. In addition, 0.01 to 65.38 mg/L is observed as the concentration range of Zn (Table 2) in freshwaters like Elelenwo River in Rivers State (Edori et al. 2019) and Silver River in Bayelsa (Ekp et al. 2019), and surface water in southern Benue (Igwe et al. 2020) and Akpara Izzi stream, Nwerugvu pond, and Ebonyi River in south-eastern Nigeria. Okolo and Oyedotun (2018) reported a high concentration of Zn above the prescribed safe limit by NSDWQ and WHO. The highly polluted freshwaters include Ndawuse River in Abuja (Enitan et al. 2018), Ijana in Warri (Emoyan et al. 2006), River Kaduna in Kaduna (Abui et al. 2017), surface water in Lagos

(Addey et al. 2018), Niger–Benue River in Lokoja (Ekere et al. 2018), Elelenwo River in Rivers State (Edori et al. 2019), and River Balogun in South-West Nigeria (Tenebe et al. 2018) based on the EU permissible value.

Arsenic (As)

Arojoye et al. (2018) and Okolo and Oyedotun (2018) reported the highest concentration of As in Igbokoda River (61.3 mg/L) and Nwerugvu pond (61.44 mg/L), respectively. However, there is no maximum permissible value set for As by EU, NSDWQ, and WHO. The concentration of As ranged from 61.44 to 0.005 mg/L. Adesiyan et al. (2018) and Oye-wale et al. (2019) recorded seasonal variations in As concentration. Other reported concentrations of As include 0.005 mg/L in Ndawuse River (Enitan et al. 2018), 0.448–2.59 mg/L in River Kaduna (Abui et al. 2017), and 0.04 mg/L in River Balogun (Tenebe et al. 2018).

Concentration of heavy metals in Nigeria's freshwater fishes

Compared with the maximum permissible values prescribed by WHO, Food and Agricultural Organization (FAO)/WHO, and the United State Environmental Protection Agency (USEPA), this section discusses the concentration of HMs in different parts of various fish species. The concentrations of HMs that have been reported in different parts of fish are presented in Table 3.

Several fish species such as *Tilapia zilli*, *Oreochromis niloticus*, *Chrysichthys walkeri*, *Chrysichthys furcatus*, *Arius gigas*, *Ilisha africana*, *Ethmalosa fimbriata*, *Parachanna obscura*, *Clarias lazera*, *Clarias gariepinus*, *Auchenoglanis occidentalis*, *Genyonemus lineatus*, *Mormyrus rume*, *Cololabis saira*, *Mugil cephalus*, *Tylosurus crocodilus*, and *Trichiurus lepturus* have been examined for the accumulation of HMs. Aghoghovwia et al. (2016) collected the samples of *Tilapia zilli*, *Oreochromis niloticus*, *Chrysichthys walkeri*, *Chrysichthys furcatus*, *Arius gigas*, *Ilisha africana*, *Ethmalosa fimbriata*, *Parachanna obscura*, and *Clarias lazera* from the Warri River in Bayelsa State. They reported an order of $\text{Fe} > \text{Zn} > \text{Pb} > \text{Ni} > \text{Cr} > \text{Cu} > \text{Cd}$ in gills and $\text{Fe} > \text{Zn} > \text{Pb} > \text{Ni} > \text{Cu} > \text{Cr} > \text{Cd}$ in kidneys, livers, and muscles of the fishes. Also, they reported an order of $\text{liver} > \text{kidney} > \text{gill} > \text{muscle}$ for the concentration of the HMs in the various parts of the fish. Besides Cu, they reported that the concentration of Ni, Cr, Cd, Fe, Zn, and Pb exceeded the maximum permissible limit (Table 3). Similarly, Abalaka et al. (2020) reported liver and muscle bioaccumulation for Zn, Cr, Fe, and Cu in *Clarias gariepinus* from Abuja. They also concluded that the bio-accumulated HMs were higher than the permissible values, especially for liver samples.

Table 3 The concentration of heavy metals (HMs) in different tissues and organs of fishes from freshwaters in Nigeria

		Location	Season	Cr	Cd	Pb	Cu	Mn	Ni	Fe	Hg	Co	Zn	As	Reference
<i>Tilapia zillii</i> *	Gill	Warri River	–	1.60	0.81	11.56	3.76	–	0.72	87.90	–	–	69.28	–	Aghoghowwa et al. (2016)
	Muscle		–	1.61	2.44	13.28	2.19	–	11.75	53.50	–	–	43.15	–	
	Liver		–	4.23	7.40	39.50	6.23	–	37.25	187.02	–	–	130.02	–	
	Kidney		–	2.37	1.98	14.93	7.02	–	1.18	121.85	–	–	88.58	–	
<i>Oreochromis niloticus</i> *	Gill	Niger Delta	–	2.38	4.39	15.10	2.63	–	16.50	104.02	–	–	106.02	–	
	Muscle		–	2.35	3.73	7.14	1.53	–	5.84	34.50	–	–	60.13	–	
	Liver		–	6.78	12.08	17.50	3.23	–	16.00	122.02	–	–	163.02	–	
	Kidney		–	3.76	6.57	20.27	4.03	–	26.60	149.86	–	–	136.22	–	
<i>Chrysichthys walkeri</i> *	Gill	Warri River	–	2.15	0.99	12.60	6.50	–	19.20	129.20	–	–	66.13	–	
	Muscle		–	2.68	0.84	7.48	5.10	–	7.91	61.25	–	–	38.93	–	
	Liver		–	7.23	2.58	16.50	176.20	–	18.25	176.20	–	–	110.02	–	
	Kidney		–	3.74	1.73	17.72	9.42	–	25.65	168.19	–	–	93.34	–	
<i>Chrysichthys fureatus</i> *	Gill	Niger Delta	–	1.90	1.24	15.28	3.10	–	6.30	67.25	–	–	117.02	–	
	Muscle		–	2.10	1.10	38.75	3.57	–	5.20	37.95	–	–	50.50	–	
	Liver		–	5.93	3.35	20.25	10.00	–	14.45	116.20	–	–	152.20	–	
	Kidney		–	2.81	1.53	19.08	6.33	–	9.43	80.12	–	–	153.3	–	
<i>Arius gigas</i> *	Gill	Warri River	–	7.15	1.44	85.85	2.19	–	4.03	121.02	–	–	67.85	–	
	Muscle		–	3.80	1.25	39.83	2.14	–	3.58	55.00	–	–	37.10	–	
	Liver		–	11.18	3.80	94.00	26.50	–	12.05	146.02	–	–	112.20	–	
	Kidney		–	11.34	1.87	110.95	3.96	–	6.5	157.59	–	–	97.29	–	
<i>llisha africana</i> *	Gill	Niger Delta	–	6.90	1.64	97.15	3.68	–	4.78	64.25	–	–	75.63	–	
	Muscle		–	4.10	1.18	4.10	2.70	–	3.30	29.73	–	–	42.15	–	
	Liver		–	11.30	2.90	108.2	8.53	–	9.18	90.25	–	–	121.20	–	
	Kidney		–	9.07	2.29	130.22	5.3	–	8.07	88.01	–	–	89.51	–	
<i>Ethmalosa fimbriata</i> *	Gill	Warri River	–	2.88	0.65	42.08	3.85	–	7.61	78.75	–	–	173.02	–	
	Muscle		–	2.27	0.43	3.40	2.68	–	2.90	28.00	–	–	58.25	–	
	Liver		–	6.93	3.00	111.02	10.03	–	9.25	88.53	–	–	160.02	–	
	Kidney		–	4.11	1.00	65.10	6.36	–	10.72	102.20	–	–	210.20	–	
<i>Parachanna obscura</i> *	Gill	Niger Delta	–	2.06	1.20	16.83	1.80	–	12.50	75.75	–	–	66.75	–	
	Muscle		–	0.91	0.43	11.52	1.94	–	4.68	39.00	–	–	13.28	–	
	Liver		–	2.85	1.23	11.68	3.80	–	11.18	108.02	–	–	43.80	–	
	Kidney		–	3.34	2.10	25.91	3.29	–	17.52	115.89	–	–	82.88	–	
<i>Clarias lazera</i> *	Gill	Warri River	–	1.10	0.73	5.85	1.59	–	6.70	25.25	–	–	26.48	–	
	Muscle		–	0.91	0.58	0.91	0.90	–	3.65	18.13	–	–	15.18	–	
	Liver		–	4.63	33.50	11.85	2.54	–	10.63	43.43	–	–	33.50	–	
	Kidney		–	1.14	1.05	9.64	2.45	–	12.50	50.61	–	–	35.99	–	

Table 3 (continued)

		Location	Season	Cr	Cd	Pb	Cu	Mn	Ni	Fe	Hg	Co	Zn	As	Reference
<i>Clarias gariepinus</i> **	Muscle	–	–	0.34	0.15	1.26	0.23	–	–	3.08	–	–	2.64	–	Abalaka et al. (2020)
	Liver		–	4.63	0.23	6.92	21.33	–	–	221.90	–	–	22.46	–	
<i>Auchenoglanis occidentalis</i> ***	Liver	Tiga dam	–	–	0.04	0.35	–	–	–	11.66	–	–	2.17	–	Abalaka (2015)
<i>Genyonemus lineatus</i> *	Gills	Bonny River	–	–	1.50	0.50	14.00	11.02	9.60	139.90	–	–	24.90	–	Abarshi et al. (2017)
	Muscle		–	–	ND	0.20	3.50	9.34	5.33	102.00	–	–	14.00	–	
	Liver		–	–	ND	0.30	45.00	9.55	7.51	216.03	–	–	49.90	–	
	Gill	Finima River	–	–	1.50	6.38	33.92	323.00	76.50	646.25	–	–	134.00	–	
	Muscle		–	–	ND	5.00	15.75	43.72	30.00	565.60	–	–	124.50	–	
	Liver	Ogun River	–	–	ND	3.63	52.64	202.50	37.00	801.50	–	–	166.50	–	Adeniyi et al. (2008)
<i>Chrysichthys sp.</i> **		Lagos	–	–	0.002	0.04	–	0.35	–	0.16	–	–	0.20	–	
<i>Tilapia sp.</i> **			–	–	0.003	0.05	–	0.44	–	0.25	–	–	0.24	–	
<i>Brycinus longipinnis</i> **		Koko River	–	–	0.98	36.04	7.05	39.45	53.57	66.13	–	31.14	51.64	–	Ezemonye et al. (2019)
<i>Tilapia (upstream)</i> ***		Asa River	–	0.09	–	0.90	–	0.56	–	4.05	–	–	5.62	–	Eletta et al. (2003)
<i>Tilapia (downstream)</i> ***			–	0.13	–	1.16	–	2.69	–	5.59	–	–	11.13	–	
Catfish (upstream)***			–	0.35	–	1.57	–	0.62	–	3.79	–	–	15.11	–	
Catfish (downstream)***			–	0.23	–	0.78	–	0.78	–	18.16	–	–	7.30	–	
<i>Oreochromis aureus</i> **	Muscle	Challawa River	–	35.4	7.34	6.42	–	–	–	–	–	–	18.1	–	Edogbo et al. (2020)
<i>Oreochromis niloticus</i> **			–	17.3	11.8	4.70	–	–	–	–	–	–	19.5	–	
<i>Chrysichthys nigrodigitatus</i> **		Cross River basin	Wet	0.30	–	0.20	0.60	1.20	–	194.95	–	–	7.00	–	Okogwu et al. (2019)
			Dry	0.30	–	0.10	0.50	1.09	–	88.92	–	–	6.02	–	
<i>Clarias anguillaris</i> **			Wet	0.20	–	0.10	0.51	1.20	–	195.95	–	–	13.01	–	
			Dry	0.20	–	0.10	0.50	1.0	–	195.05	–	–	12.01	–	
<i>Tilapia zillii</i> **			Wet	0.50	–	0.30	1.60	2.81	–	420.01	–	–	21.95	–	
			Dry	0.50	–	0.30	1.50	2.60	–	414.99	–	–	20.01	–	
<i>Mormyrus rume</i> **			Wet	0.30	–	0.10	0.70	1.50	–	205.03	–	–	7.03	–	
			Dry	0.40	–	0.09	0.62	1.30	–	201.02	–	–	5.01	–	

Table 3 (continued)

	Location	Season	Cr	Cd	Pb	Cu	Mn	Ni	Fe	Hg	Co	Zn	As	Reference
<i>Cololabis sairi</i> **	Focados terminal Rivers	–	0.47	0.025	1.73	–	–	–	16.92	BDL	3.49	10.56	0.01	Oyibo et al. (2018)
<i>Mugil cephalus</i> **		–	0.45	0.05	5.54	1.49	–	–	20.48	BDL	–	5.54	BDL	
<i>Tylosurus crocodilus</i> **		–	0.14	0.07	1.55	2.43	–	–	10.92	BDL	–	8.46	BDL	
<i>Trichiurus lepturus</i> **		–	1.16	0.46	2.45	1.15	–	–	21.56	BDL	–	2.43	BDL	
<i>Oreochromis niloticus</i> **		–	2.69	0.68	4.77	1.54	–	–	38.73	BDL	–	5.44	0.01	
<i>Scomber scombrus</i> **		–	0.57	0.01	3.85	5.95	–	–	46.59	BDL	–	4.75	0.01	
<i>I. africana africana</i> **		–	0.04	0.05	1.44	1.34	–	–	13.74	BDL	–	3.46	0.54	
<i>Oreochromis niloticus</i> ****	Asa reservoir	–	–	0.01	0.01	0.02	–	0.10	–	–	–	0.43	0.02	Fawole et al. (2007)
<i>Sarotherodon galilaeus</i> ****		–	–	0.01	0.02	0.03	–	0.10	–	–	–	0.35	0.04	
<i>Clarias gariepinus</i> ****		–	–	0.02	0.01	0.02	–	0.14	–	–	–	0.40	0.03	
<i>Heterotis niloticus</i> ****		–	–	0.01	0.03	0.03	–	0.03	–	–	–	0.30	0.02	
<i>Oreochromis niloticus</i> **	Gill	–	–	1.85	15.5	–	604.32	ND	–	–	–	ND	–	Ayanda et al. (2019)
	Liver	–	–	3.50	8.69	–	567.93	ND	–	–	–	ND	–	
	Muscle	–	–	1.53	9.73	–	579.56	ND	–	–	–	ND	–	
<i>Parachanna obscura</i> **	Gill	–	–	1.90	ND	–	178.42	17.3	–	–	–	7.69	–	
	Liver	–	–	3.88	ND	–	187.39	15.9	–	–	–	11.80	–	
	Muscle	–	–	3.48	ND	–	187.39	24.80	–	–	–	6.78	–	
<i>Malapterurus electricus</i> **	Gill	–	–	6.67	ND	–	381.79	14.7	–	–	–	ND	–	
	Liver	–	–	7.88	ND	–	366.70	18.8	–	–	–	ND	–	
	Muscle	–	–	6.88	ND	–	365.29	16.74	–	–	–	ND	–	
<i>Chrysichthys nigrodigitatus</i> **	Gill	–	–	ND	ND	–	735.84	ND	–	–	–	ND	–	
	Liver	–	–	ND	ND	–	715.29	ND	–	–	–	ND	–	
	Muscle	–	–	ND	ND	–	727.36	ND	–	–	–	ND	–	

Table 3 (continued)

		Location	Season	Cr	Cd	Pb	Cu	Mn	Ni	Fe	Hg	Co	Zn	As	Reference
<i>Mugil cephalus</i> **	Gills	Southern Nigeria	–	0.73	38.43	22.43	51.44	–	BDL	–	–	–	–	BDL	Ihunwo et al. (2020)
	Livers		–	0.57	17.99	2.58	16.03	–	BDL	–	–	–	–	BDL	
	Muscle		–	BDL	17.44	6.75	32.98	–	BDL	–	–	–	–	BDL	
<i>Clarias gariepinus</i> *	Muscle	Osun State	Dry	13.10	ND	63.31	302.02	62.11	27.02	133.03	–	34.14	30.03	ND	Aladesanmi et al. (2014)
		Ewuru/Rara Stream	Rainy	ND	ND	ND	2.63	35.01	ND	280.11	–	ND	ND	ND	
			Dry	ND	ND	ND	2.63	35.01	ND	280.11	–	ND	ND	ND	
			Rainy	ND	ND	ND	2.63	35.01	–	280.11	–	ND	ND	ND	
<i>Palaemon hastatus</i> *		Osun State	–	3.61	1.30	0.91	9.14	1.93	–	18.88	–	–	15.72	–	Adebiyi et al. (2020)
<i>Clarias gariepinus</i> ***	Liver	South Western Nigeria	–	–	0.091	0.165	7.09	–	9.32	–	–	–	–	0.907	Arojojoye et al. (2018)
	Muscle		–	–	0.086	0.148	4.04	–	6.867	–	–	–	–	0.766	
			Dry	0.197	0.044	0.717	0.804	–	–	5.11	–	–	6.74	–	Ekere et al. (2018)
Nile tilapia**		Lokoja	Wet	0.164	0.045	0.704	0.658	–	–	7.84	–	–	6.38	–	
			Dry	0.341	0.347	1.23	0.705	–	–	5.05	–	–	6.62	–	
			Wet	0.293	0.666	1.68	0.952	–	–	8.03	–	–	6.26	–	
Sharptooth catfish**															
<i>Chrysichthys nigrodigitatus</i> **	Gill	Delta State	–	0.04	0.14	<0.01	–	0.13	0.05	–	–	–	–	–	Ekeanyanwu et al. (2010)
	Liver		–	0.14	0.28	0.01	–	0.43	0.09	–	–	–	–	–	
	Muscle		–	0.04	0.45	<0.01	–	1.89	0.13	–	–	–	–	–	
<i>Tilapia nilotica</i> **	Bone		–	0.05	0.09	<0.01	–	1.21	0.06	–	–	–	–	–	
	Gill		–	0.06	0.21	<0.01	–	0.17	0.11	–	–	–	–	–	
	Liver		–	0.17	0.31	0.01	–	0.49	0.14	–	–	–	–	–	
<i>Clarias gariepinus</i> *	Muscle		–	0.06	0.62	<0.01	–	1.97	0.17	–	–	–	–	–	
	Bone		–	0.04	0.04	<0.01	–	1.48	0.07	–	–	–	–	–	
	Fish ponds	Ilesha	–	13.00	BDL	53.01	302.02	62.11	27.02	12.12	–	34.14	30.03	–	Titilayo and Olufemi (2014)
			–	99.01	BDL	3.00	446.00	373.12	17.01	27.13	–	103.01	45.11	–	
			–	33.01	BDL	1.78	457.03	746.02	33.02	10.10	–	19.11	60.08	–	
	Fish ponds	Osogbo	–	82.32	BDL	6.01	703.01	345.13	573.34	133.03	–	44.17	70.17	–	
			–	93.21	BDL	10.11	132.23	475.23	152.21	333.41	–	114.12	33.00	–	
			–	101.01	BDL	11.20	44.00	94.22	47.31	127.11	–	103.01	14.22	–	
	Fish ponds	Yakoyo	–	42.00	BDL	2.34	57.77	79.02	53.17	112.12	–	14.41	10.18	–	
			–	89.22	BDL	2.11	201.01	399.51	43.34	410.53	–	83.12	11.10	–	
			–	113.10	BDL	3.41	72.56	221.71	97.32	253.24	–	111.14	76.13	–	
	Liver	Yakoyo	–	29.51	BDL	1.03	66.10	73.42	7.71	271.11	–	10.88	15.12	–	
			–	7.01	BDL	1.14	11.21	46.01	3.02	72.12	–	9.01	69.13	–	
			–	72.33	BDL	1.34	83.62	245.11	177.13	310.0	–	97.12	72.22	–	

Table 3 (continued)

	Location	Season	Cr	Cd	Pb	Cu	Mn	Ni	Fe	Hg	Co	Zn	As	Reference
<i>Pseudotolithus elongatus</i> **	Sombreiro River	–	6.30	0.0	0.23	5.31	–	2.89	59.63	–	1.71	11.61	–	Wokoma (2014)
<i>Mugil cephalus</i> **	–	–	9.91	0.0	0.17	2.7	–	4.17	67.43	–	2.35	21.37	–	
<i>Chrysichthys nigrodigitatus</i> **	–	–	7.41	0.0	0.21	4.84	–	3.69	48.31	–	0.74	17.40	–	
<i>Clarias gariepinus</i> **	Tissue	–	–	–	0.90–0.30	1.68–1.00	–	–	6.84–5.27	–	–	2.84–2.00	–	Olawusi-Peters and Ayo-Olusi (2014)
	Gills	–	–	–	1.40–0.1	1.44–1.10	–	–	6.70–4.23	–	–	1.44–0.27	–	
<i>Oreochromis niloticus</i> **	Tissue	–	–	–	1.00–0.10	4.46–0.51	–	–	5.83–4.27	–	–	2.45–0.54	–	
	Gills	–	–	–	1.50–0.00	2.86–1.20	–	–	6.79–1.89	–	–	1.87–0.40	–	
<i>Hydrocynus forskahlii</i> ***	Operculum	–	0.37	0.41	0.07	–	–	2.74	–	–	0.73	–	–	Murtala et al. (2012)
	Gills	–	1.35	0.39	0.25	–	–	3.00	–	–	0.48	–	–	
	Kidney	–	5.64	0.00	0.03	–	–	6.33	–	–	1.17	–	–	
	Heart	–	2.47	0.15	0.04	–	–	2.45	–	–	0.00	–	–	
	Muscle	–	1.36	0.26	0.05	–	–	2.56	–	–	0.43	–	–	
	Vertebrae	–	1.33	0.45	0.02	–	–	0.00	–	–	0.42	–	–	
<i>Hyperopisus bebe occidentalis</i> ***	Operculum	–	0.79	0.32	0.04	–	–	0.02	–	–	1.66	–	–	
	Gills	–	1.95	0.25	0.03	–	–	5.00	–	–	1.23	–	–	
	Kidney	–	4.95	0.00	0.02	–	–	3.66	–	–	0.00	–	–	
	Heart	–	0.68	0.15	0.02	–	–	3.72	–	–	2.32	–	–	
	Muscle	–	1.30	0.13	0.01	–	–	0.00	–	–	0.37	–	–	
	Vertebrae	–	0.98	0.13	0.01	–	–	0.02	–	–	1.12	–	–	
<i>Clarias gariepinus</i> ***	Operculum	–	1.76	0.13	0.09	–	–	2.67	–	–	0.46	–	–	
	Gills	–	2.54	0.29	0.01	–	–	1.30	–	–	0.06	–	–	
	Kidney	–	2.61	0.41	0.03	–	–	3.43	–	–	0.46	–	–	
	Heart	–	1.73	0.26	0.01	–	–	1.86	–	–	0.55	–	–	
	Muscle	–	1.36	0.00	0.03	–	–	1.37	–	–	0.00	–	–	
	Vertebrae	–	1.70	0.28	0.02	–	–	2.44	–	–	1.16	–	–	
WHO**	–	–	–	0.01	0.01	–	–	–	0.30	–	–	5.00	–	Abalaka (2015)
WHO/FAO*	–	–	–	0.05	0.5	30	–	–	–	–	–	30	–	Abarshi et al. (2017)

BDL below detection limit, ND not detected

*µg/g; **mg/kg; ***ppm; ****%; *****not specified

In the northern part of Nigeria, Abalaka (2015) reported the liver concentration of HMs in the order of $\text{Zn} > \text{Fe} > \text{Cd} > \text{Pb}$ in *Auchenoglanis occidentalis* collected from the Tiga dam situated in Kano State. Moreover, Edogbo et al. (2020) assessed the level of HMs in *Oreochromis aureus* and *Oreochromis niloticus* from Challawa River in the same Kano State and reported the concentration of metals in the order of $\text{Cr} > \text{Zn} > \text{Cd} > \text{Pb}$ and $\text{Zn} > \text{Cr} > \text{Cd} > \text{Pb}$ in the fishes, respectively. These studies revealed an increase in the concentration of HMs in the organs of the fishes than their respective concentrations in the surface water and attributed such difference to the pollution of the fish's external environment and the rate of ingestion and excretion in the exposed fish. A similar assertion was made by Olaifa et al. (2004) in the analysis of HM contamination in *Clarias gariepinus* collected from a lake in Ibadan, Oyo State. Other studies from northern Nigeria include bioaccumulation of HMs in *Clarias gariepinus* tissues from River Galma, River Kubanni, and fish farms in Zaria (Udiba et al. 2014); *Tilapia zilli* and *Clarias gariepinus* organs from River Benue in North-Central Nigeria (Eneji et al. 2011); the gills, muscle, and tissues of *Claria gariepinus* and *Oreochromis niloticus* from River Yobe (El-Ishaq et al. 2016); fish from Ibrahim Adamu lake in Jigawa, Nigeria (Sambo et al. 2013); *Clarias gariepinus* from some polluted zones of River Kaduna (Emere and Dibal 2013); fish samples from River Benue in Adamawa State (Akan et al. 2012); and fish from UKE stream in Nasarawa State (Opaluwa et al. 2012).

In the southern part of Nigeria, Abarshi et al. (2017) reported the concentrations of Cu (52.64 mg/g), Zn (166.50 mg/g), and Fe (801.50 mg/g) and Cu (45.00 mg/g), Zn (49.90 mg/g), and Fe (216 mg/g) in the liver of fish collected from Finima River and Bonny River, respectively (Table 3). Their findings depict a higher level of some HMs above the recommended maximum permissible limits (Table 3) in fish organs (muscles, liver, and gills). This high concentration of HMs in fish tissues was attributed to the frequent crude oil spills as well as other industrial discharges around the region. A similar conclusion was made by Oyibo et al. (2018) and Ihunwo et al. (2020). However, Oyibo et al. (2018) reported the peak concentration of Fe (46.59 mg/kg), Zn (10.56 mg/kg), and Cu (5.95 mg/kg) in *S. scrombrus*, *C. saira*, and *S. scrombrus*, respectively, from Focados terminal Rivers Ogulahan in Delta State. At the same time, Ihunwo et al. (2020) reported the mean concentration of Cu (33.48 mg/kg) > Cd (24.62 mg/kg) > Pb (10.59 mg/kg) > Cr (0.43 mg/kg) in the fish tissues. Other studies from the region include bioaccumulation of HMs in *Chrysichthys nigrodigitatus* and *Tilapia nilotica* from Okumeshi River in Delta State (Ekeanyanwu et al. 2010); three commercial fish species, namely, *Pseudotolithus elongatus*, *Chrysichthys nigrodigitatus*, and *Mugil cephalus*, from Sombreiro River in Niger Delta (Wokoma 2014); in the gill and liver of *Clarias gariepinus* from Niger

Delta wetland (Ogamba et al. 2016a); in the bones and tissues of *Oreochromis niloticus* and *Clarias camerunensis* from Ikoli creek in Niger Delta (Ogamba et al. 2016b); in the bones and muscles of *Citharinus citharus* and *Synodontis clarias* from River Nun in Niger Delta (Ogamba et al. 2015); and so on.

In southwest Nigeria, Adeniyi et al. (2008) examined the level of HMs in two fish species (*Tilapia* and *Chrysichthys*) from the Ogun Rivers in Lagos. They inferred that the concentrations of the HMs in the fishes varied to a great extent depending on the sampling locations. That is, fish species sampled near the lagoon in front of the river tend to have a greater concentration of HMs. A similar observation was made by James and Okolo (2003) in assessing the level of HM concentrations in water and freshwater fish in Niger Delta waters. Also, Ayanda et al. (2019) documented Pb and Ni contamination in muscles of *Oreochromis niloticus* and *Parachanna obscura*, respectively. However, they discovered that the liver and gills accumulated more metals than the muscles, and finally concluded that the concentrations of the metals in all four fish species (*Oreochromis niloticus*, *Malapterurus electricus*, *Parachanna obscura*, and *Chrysichthys nigrodigitatus*) from the Ogun River were beyond regulatory limits by International Standards. Other studies from the southwest include Aladesanmi et al. (2014), Titilayo and Olufemi (2014), Olawusi-Peters and Ayo-Olalus (2014), and Murtala et al. (2012).

From southeast Nigeria, Ezemonye et al. (2019) assessed the level of HM concentration in *Brycinus longipinnis* from the Koko River, Benin. They concluded that aquatic organisms take up HMs from water and accumulate them in their tissues at higher levels than that of their surrounding milieu. Thus, these metals in the tissues of aquatic organisms could accumulatively be passed on to humans via food. Okogwu et al. (2019) reported the trend of HMs ($\text{Fe} > \text{Zn} > \text{Mn} > \text{Cu} > \text{Cr} > \text{Pb}$) in commercially important fish species (*Chrysichthys nigrodigitatus*, *Clarias anguillaris*, *Tilapia zillii*, and *Mormyrus rume*) in surface water from the Cross River ecosystem. A similar observation was made for other fishes by Edem Christopher et al. (2009) and Joseph et al. (2016). Several studies have reported an increase in HM contents in fish species and attributed the phenomenon to biomagnification along the food chain as well as the uptake of metals from the environment. Hence, it can be deduced that the occurrence of HMs in the aquatic ecosystem is a major concern because of their toxicity potential, and in the following section, we addressed the potential health risk.

The mean concentration of HMs in contaminated surface water fishes in Nigeria (across all tissues and organs) is summarized in Fig. 4. This was derived from an analysis of Table 3. The analysis did not, however, consider results in parts per million or percent as these are unconventional units for such a parameter. It can be observed that the major HMs in Nigeria's freshwater fishes are Mn (180.9 mg/kg

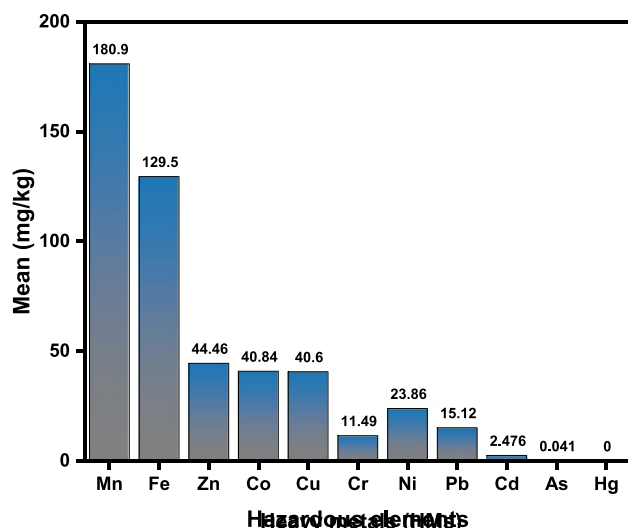
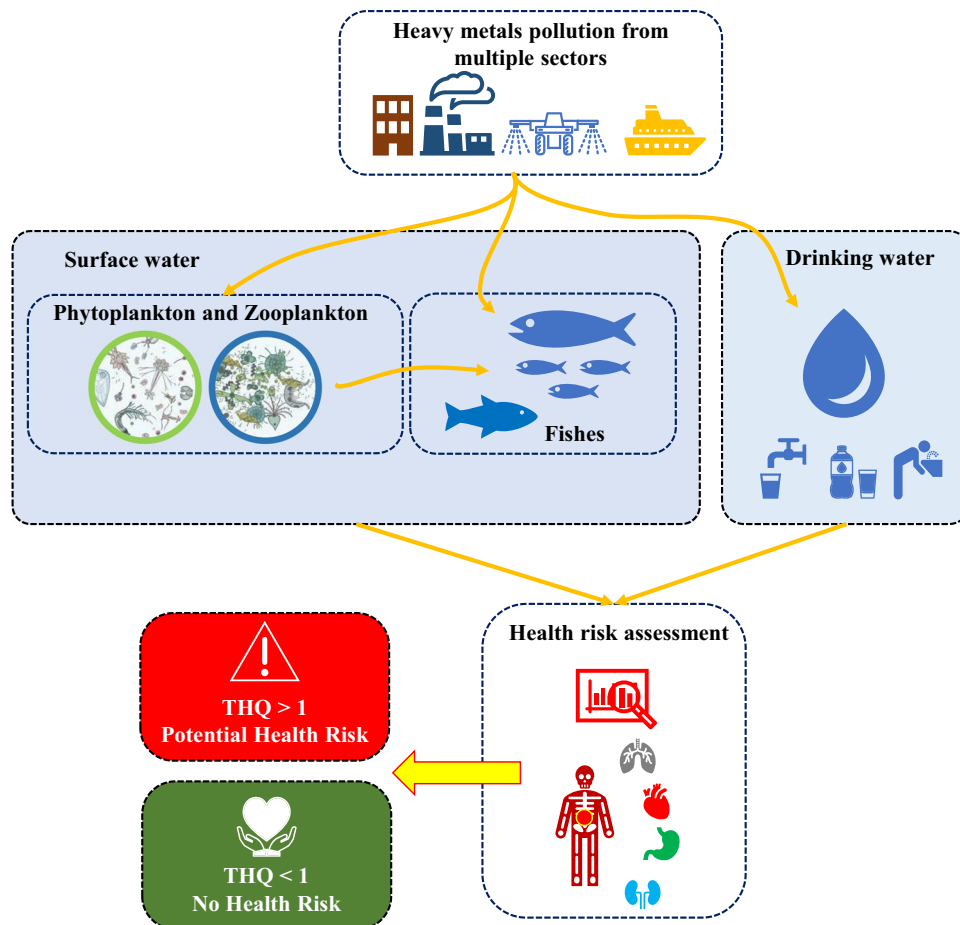


Fig. 4 Mean concentration of HMs in contaminated surface water fishes in Nigeria (across all tissues and organs)

mean) and Fe (129.5 mg/kg mean). The other HMs are also an insignificant amount in fish (10–45 mg/kg mean). These are all far above the WHO/FAO limits (Table 3) and hence bear a significant human health risk.

Fig. 5 Human health risks associated with heavy metal contamination of surface and drinking water sources



Health risk studies

There are several possible pathways of HM exposure to humans (Fig. 5). However, the pathway considered for this study is narrowed down to the intake of potentially HMs from fishes from polluted freshwaters. Hence, the compilation of the health risk covering the target hazard quotient (THQ), hazard index (HI), and cancer risk (CR) for adults and children in Nigeria via the consumption of fish is reported in this section. The THQ of HMs via the consumption of fish by average Nigerian adult and child is presented in Table 4. Highlighted in bold are THQ values greater than 1. Nevertheless, it is on record that if the THQ is >1 , then there is a possibility of hazard (Ekere et al. 2018; Ihunwo et al. 2020). Ihunwo et al. (2020) demonstrated that the *Mugil cephalus* was unsafe for human consumption since all the HI for adults and children are greater than 1. Specifically, they reported the highest THQ value such as 7.49 adult male and 7.72 adult female, and 9.41 children male and 10.7 children female for Cd, respectively (Table 4).

Similarly, Ekere et al. (2018) reported an unsafe value for Cd via the consumption of Nile tilapia and sharptooth by children, and Nile tilapia by an adult. With their findings, the potentially hazardous risk is associated with the

Table 4 THQ for the consumption of fish from surface water in Nigeria

Fish type	Category of person	Cr	Cd	Pb	Cu	Mn	Ni	Fe	Co	Zn	Reference
<i>Mugil cephalus</i>	Adult (male)	4.0×10^{-3}	7.49	9.2×10^{-2}	2.5×10^{-2}	–	–	–	–	–	Ihunwo et al. (2020)
	Adult (female)	4.0×10^{-3}	7.720	0.100	3.0×10^{-2}	–	–	–	–	–	
<i>Palaemon hastatus</i>	Adult	3.391×10^{-1}	3.6634×10^{-1}	6.411×10^{-2}	6.439×10^{-2}	3.88×10^{-3}	–	1.77×10^{-2}	–	1.476×10^{-2}	Adebiyi et al. (2020)
Nile tilapia	Adult	2.3×10^{-4}	1.42	–	–	–	–	–	–	3.1×10^{-2}	Ekere et al. (2018)
Sharptooth catfish	Adult	4.8×10^{-4}	9.8×10^{-1}	–	–	–	–	–	–	3.1×10^{-2}	
<i>Brycinus longipinnis</i>	Adult	–	2.10×10^{-1}	1.93	3.78×10^{-2}	3.79×10^{-2}	5.74×10^{-1}	4.72×10^{-2}	3.34×10^{-1}	3.69×10^{-2}	Ezemonye et al. (2019)
<i>Clarias gariepinus</i>	Adult	0.158×10^{-3}	188×10^{-3}	374.57×10^{-3}	1.66×10^{-3}	–	–	0.89×10^{-3}	–	–	Matouke and Abdullahi (2020)
<i>Mugil cephalus</i>	Child (Male)	5.0×10^{-3}	9.414	1.16×10^{-1}	3.2×10^{-2}	–	–	–	–	–	Ihunwo et al. (2020)
	Child (Female)	1.0×10^{-2}	10.700	1.30×10^{-1}	4.0×10^{-2}	–	–	–	–	–	
<i>Palaemon hastatus</i>	Child	1.48356	1.60274	2.8047×10^{-1}	2.8171×10^{-1}	1.699×10^{-2}	–	7.758×10^{-2}	–	6.46×10^{-2}	Adebiyi et al. (2020)
Nile tilapia	Child	5.1×10^{-5}	2.2	–	–	–	–	–	–	4.8×10^{-2}	Ekere et al. (2018)
Sharptooth catfish	Child	6.4×10^{-4}	1.52	–	–	–	–	–	–	4.8×10^{-2}	
<i>Clarias gariepinus</i>	Child	0.033×10^{-3}	40×10^{-3}	78.29×10^{-3}	0.35×10^{-3}	–	–	0.19×10^{-3}	–	–	Matouke and Abdullahi (2020)
<i>Oreochromis aureus</i> (28)	Not specified	3.84	1.21	2.6×10^{-1}	–	–	–	–	–	1.0×10^{-2}	Edogbo et al. (2020)
<i>Oreochromis niloticus</i> (52)		1.88	1.92	1.9×10^{-1}	–	–	–	–	–	1.0×10^{-2}	
<i>C. nigrodigitatus</i>	Not specified	6.9×10^{-1}	–	4.5×10^{-1}	7.3×10^{-1}	1.0×10^{-1}	–	4.3×10^{-1}	–	1.8×10^{-1}	Okogwu et al. (2019)
<i>C. angularis</i>		6.6×10^{-1}	–	4.2×10^{-1}	7.3×10^{-1}	1.0×10^{-1}	–	5.5×10^{-1}	–	2.1×10^{-1}	
<i>T. zilli</i>		8.0×10^{-1}	–	5.1×10^{-1}	7.7×10^{-1}	1.2×10^{-1}	–	1.09	–	2.6×10^{-1}	
<i>M. rume</i>		7.2×10^{-1}	–	4.1×10^{-1}	7.4×10^{-1}	1.0×10^{-1}	–	5.7×10^{-1}	–	1.8×10^{-1}	
<i>T. crocodilus</i>	Not specified	1.0×10^{-4}	1.0×10^{-1}	7.43×10^{-1}	3.4×10^{-3}	–	–	2.32×10^{-2}	–	4.8×10^{-2}	Oyibo et al. (2018)
<i>S. scombrus</i>		6.0×10^{-4}	0.00	1.85	8.4×10^{-3}	–	–	9.9×10^{-2}	–	2.66×10^{-2}	
<i>C. saira</i>		4.0×10^{-4}	0.00	8.28×10^{-1}	4.9×10^{-3}	–	–	3.58×10^{-2}	–	5.96×10^{-2}	
<i>I. africana</i>		4.0×10^{-4}	8.3×10^{-3}	5.71×10^{-1}	1.9×10^{-3}	–	–	2.91×10^{-2}	–	1.96×10^{-2}	
<i>O. niloticus</i>		3.0×10^{-3}	1.0×10^{-1}	2.31	2.2×10^{-3}	–	–	8.22×10^{-2}	–	3.1×10^{-2}	
<i>T. lepurus</i>		1.3×10^{-3}	7.8×10^{-1}	1.20	1.6×10^{-3}	–	–	4.59×10^{-2}	–	1.36×10^{-2}	
<i>M. cephalus</i>		1.0×10^{-4}	8.5×10^{-2}	2.68	2.0×10^{-3}	–	–	4.35×10^{-2}	–	3.14×10^{-4}	

The age of the fishes was not considered for the THQ analysis; highlighted bold are THQ greater than 1

consumption of fish across different age groups. Also, Adebisi et al. (2020) demonstrated that the consumption of *Palaemon hastatus* poses a health risk for children since the THQ values for Cr and Cd were greater than 1. The THQ in Cd and Cr were greater than 1 in the muscle of the *Oreochromis aureus* and *Oreochromis niloticus* (Edogbo et al. 2020). Cd as a toxic HM is associated with chronic renal failure and skeletal damage (Ahmad and Al-Mahaqeri 2015). Therefore, carcinogenic occurrence in human kidney and lung damage, stomach irritation, vomiting, as well as diarrhea have been related to long-term exposure to Cd (Ukoha et al. 2014). Also, deleterious effects, such as cancer, contact dermatitis, and premature dementia, among others, are associated with long-term exposure to Cr (Basketter et al. 2000).

The cancer risk (CR) of Pb was raised by Adebisi et al. (2020) and Abalaka et al. (2020) indicating the concern for the consumption of *Palaemon hastatus* and *Clarias gariepinus* in Nigeria, respectively. Okogwu et al. (2019) reported the carcinogenic risk values for Pb (2.96 to 4.78×10^{-4}) and Cr (9.85×10^{-4} to 1.12×10^{-3}) in commercially important fish species greater than the permissible limit (Varol et al. 2017). Finally, from Table 4, the THQ showed that the concentrations of the investigated potential HMs such as Cr, Cd, and Pb pose a threat to health.

Future research needs

The behavior and fate of HMs in Nigeria's freshwater fishes are still very much unknown. As such, HM pollution is still a serious, persistent, and threatening problem to aquatic environments. Hence, more precise and sophisticated research is needed in this area. Aquatic vertebrates such as fishes absorb HMs through ingestion of water and contaminated food. HMs are transferred to humans through the dietary consumption of fish and other aquatic organisms. It is important to note that the current toxicity experiments in Nigeria are not designed in a way to explore the similarities and dissimilarities in the modes of actions of HMs in aquatic bio-indicators resembling those in humans, rather general and established test systems and traditional organisms are used based on the assessment of the traditional endpoint such as bioaccumulation, biomagnification, and trophic transfer. Due to this, sophisticated toxicological data are still lacking. Also, the majority of fish species studied so far are exposed to HM pollution over a short period. Information on the continuous exposure of fishes to HM pollution over a long period or even throughout their entire life cycle is lacking. Hence, such data is needed for an accurate ecotoxicological and risk assessment over a short- and long-term period of exposure. These data can aid to proffer key recommendations to the government in crucial policymaking for the proper monitoring and

management of HMs in fishes and other aquatic organisms in freshwaters.

Conclusion

This study reviewed the level of HM contamination in freshwaters, in different parts of fish (such as intestine, gills, fin, intestine, muscles/tissues, kidney, heart, and bones) and associated hazards via dietary intake of fishes in Nigeria. It is observed that most freshwaters are highly contaminated by anthropogenic activities (e.g., burning of fossil fuels, mining, use of fertilizers and pesticides, industrial effluent discharge). It was also noticed that the concentration of most HMs in freshwaters exceeds the permissible limit prescribed by WHO and NSDWQ. Considering the mean concentration of HMs, only Mn and Hg did not significantly exceed NSDWQ limits. The major HMs pollutants are Zn (9.02 mg/L), As (7.25 mg/L), Cu (4.35 mg/L), Fe (1.77 mg/L), and Pb (1.46 mg/L). From the synthesis of the literature, it was observed that the major HMs in Nigerian freshwater fishes from polluted freshwaters are Mn (180.9 mg/kg) and Fe (129.5 mg/kg). The other heavy metals were also an insignificant amount in fish (10–45 mg/kg). Since fish is a popular source of food protein in Nigeria, this study demonstrated considerable health risks associated with some HMs such as Cr, Cd, and Pb due to their high bioaccumulation in fish organs from contaminated surface water. Hence, to protect the lives of people, especially the most vulnerable ones who rely on fish from polluted freshwater sources, this review suggests that strict government regulations should be enforced on the indiscriminate discharge of industrial wastes/wastewater. Finally, grassroots sensitization should be provided by relevant environmental and health authorities in the country.

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Author contribution OAA: conceptualization, data curation, investigation, methodology, writing—original draft, writing—review and editing. MRO: investigation, visualization, writing—original draft, writing—reviewing and editing. TFA: investigation, visualization, writing—original draft, writing—reviewing and editing. FOA: conceptualization, resources, supervision, validation, visualization, writing—original draft, writing—review and editing. BA: investigation, visualization, data curation, writing—original draft, writing—reviewing and editing. JOI: data curation, formal analysis, writing—reviewing and editing. MOA: investigation, writing—reviewing and editing. PK: investigation, data curation, writing—reviewing and editing. HD: investigation, writing—reviewing and editing. AYU: investigation, writing—reviewing and editing. IDS: investigation, writing—reviewing and editing. LFOS: resources, investigation, visualization, supervision, writing—reviewing and editing.

Declarations

Consent to participate We affirm that all authors have participated in the review work and are fully aware of ethical responsibilities.

Consent to publish We affirm that all authors have agreed to the submission of the paper to ESPR and are fully aware of ethical responsibilities.

Conflict of interest The authors declare no competing interests.

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