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REVIEW

Engaging One Health in Heavy Metal Pollution in Some Selected Nigerian Niger Delta Cities. A Systematic Review of Pervasiveness, Bioaccumulation and Subduing Environmental Health Challenges

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Abstract

The Niger Delta environment is under serious threat due to heavy metal pollution. Many studies have been conducted on the heavy metal contamination in soils, water, seafood and plants in the Niger Delta ecosystem. However, there is a lack of clear understanding of the health consequences for people and strategies for attaining One Health, and a dispersion of information that is accessible. The study focused on investigating the contamination levels, distributions, risks, sources and impacts of heavy metals in selected regions of the Niger Delta. Prior studies revealed that the levels of certain heavy metals, including Cd, Pb, Cu, Cr, Mn, Fe and Ni, in water, sediment, fish and plants in most Niger Delta ecosystems were higher than the acceptable threshold attributed to various anthropogenic stressors. In the reviewed Niger Delta states, ecosystems in Rivers state showed the highest concentrations of heavy metals in most sampled sites. Groundwater quality was recorded at concentrations higher than 0.3 mg/L World Health Organization drinking water guideline. High concentrations of copper (147.915 mg/L) and zinc (10.878 mg/L) were found in Rivers State. The heavy metals concentrations were greater in bottom-dwelling organisms such as bivalves, gastropods and shrimp than in other fishery species. Heavy metal exposure in the region poses risks of communicable and non-communicable diseases. Diverse remediation methods are crucial to reduce contamination levels, but comprehensive strategies and international cooperation are essential to address the health hazards. Actively reducing heavy metals in the environment can achieve One Health objectives and mitigate disease and economic burdens.

Keywords Heavy metals · Environmental remediation · Risk assessment · One health · Niger Delta

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Introduction

Heavy metals are amongst the persistent organic contaminants pervasive in the environment and bioaccumulate [1]. They are naturally occurring metallic elements with atomic weights and densities greater than those of water [2, 3]. Although certain heavy metals, such as iron and zinc, are physiologically essential and play vital functions in the body, cadmium, chromium, copper and lead are not essential and have adverse effects at low concentrations that cause acute and chronic toxicities [4]. As a result of the effects it has on the ecosystem, heavy metal contamination has received more attention from the general population [5]. They pose severe risks to man and biota due to their persistence in the environment and capacity to accumulate in humans through the food chain [6–8]. Amongst these risks include impairments of the brain system, vascular system, immunological system, gastrointestinal and renal malfunction, cancer and skin lesions [2, 6].

Heavy metal diverse environmental sources may have either natural or anthropogenic origins [2, 9, 10]. However, anthropogenic sources are the primary contributors of heavy metals in diverse environmental media. They include residential and commercial sewage, urbanization, mining and oil and gas exploration. According to Ihunwo et al. [11], the Niger Delta ecosystems are extensively impacted by sewage input, exacerbated by poor waste management techniques. Most coastal communities' populations appear to dump garbage into nearby rivers, estuaries and the ocean without much or any treatment.

The Niger Delta is a fan-shaped region in southern Nigeria with a size of over 70,000 km^2 [12]. The region is rich in natural resources, particularly hydrocarbon reserves, which boost oil and gas development operations, which are crucial to the stability of the nation's economy [13]. It is amongst the richest petroleum tertiary deltas in the world, collectively making for around 5% of global oil and gas reserves [14]. The area also has vast mangrove forests, brackish swamp forests and rainforests, as well as substantial fish resources and agricultural fields [15]. Although fragile, the Niger Delta region's ecology is distinguished by various indigenous terrestrial, aquatic and animal species [16, 17]. Environmental concerns are posed by these toxic heavy metals, which are found in significant amounts in domestic and industrial effluents released into the ecosystems of the Niger Delta [18, 19]. Industrial waste discharged into rivers contributes to river pollution, threatening aquatic life, lowering water quality, resulting in ecological imbalances [20], and eventually affecting the food chain.

Furthermore, uncontrolled oil exploration operations are now a significant source of heavy metal contamination and have been the focus of various research projects in the area [21]. Given the ongoing oil and gas exploration in the area, the population of the Niger Delta are often exposed to environmentally toxic metals. The United Nations Environment Programme (UNEP) study on environmental assessment of Ogoni land, Niger Delta, revealed that heavy metal levels in the drinking water, air and agricultural soils examined in 10 settlements were higher than the permissible threshold [22]. The Niger Delta ecosystems are also affected by shipbreaking yards, gas production facilities, aquaculture facilities, untreated port waste, plastic bottles and other disposable items. The several synergistic human activities pollute water, endanger aquatic species and create long-term health risks to people.

In polluted waters, fish, crabs and other aquatic biota get contaminated and accumulate in different organs like muscles, liver and kidney. Human get exposed through inhaling gas released during gas flare-ups, consumption of contaminated food such as shellfish and vegetables and drinking contaminated water [4, 8, 23]. Since fishing for both subsistence and commercial purposes, as well as agricultural and aquaculture production is one of the primary activities of the Niger Deltans, there is a chance that infected fish or crops will be harvested. The consumption of these fish and other seafood from these waters impairs human health over the long run and may damage organs [24, 25].

According to the Lancet Commission on Pollution and Health, pollution causes an estimated 9 million premature deaths worldwide yearly. Pollution is, thus, the leading environmental cause of illness and death [26]. Also, the World Health Organization [27] stated that one of the leading environmental health concerns is water pollution, which increases the burden of illness in the kidneys, liver, lungs and brain, as well as carcinogenic risks affecting human health and the environment. Environmental Sustainable Development (ESD) may be possible with the help of emerging technology, such as bioremediation techniques, which might provide mitigating strategies for the increasing heavy metal impact on water resources. The ESD entails improving people's quality of life, enabling them to live in a healthy environment and improving socioeconomic and environmental conditions for current and future generations [28]. The 2030 Agenda for Sustainable Development calls for everyone, from individuals to stakeholders, to take action to solve the challenges highlighted in the Sustainable Development Goals (SDGs) [29]. The SDG 14, 'Life below Water', is particularly concerned with the effects of pollution on the aquatic environment. Also, people's health is pertinent, which is also affected by the environment (water, soil and air), and is related to SDGs 3 and 11.

Therefore, heavy metal and water pollutant effects and responses are interdisciplinary, necessitating the One Health perspective to support sustainable environmental management properly. So it is crucial to promote One Health as an integrated, unified strategy to balance and improve the health of humans, animals and ecosystems [30]. One Health initiative integrates human, animal and environmental health to enhance outcomes and solve the global problem [31]. Despite the World Health Organization's extensive work on environmental pollution, there are few reports on heavy metal contamination. The Niger Delta area continues to experience an upsurge in the burden of heavy metal pollution and related health risks. Although several studies on heavy metals in the Niger Delta environment have been conducted, there has not been a comprehensive synthesis of these studies covering the previous decade. This research conducts a thorough literature review to methodically evaluate the heavy metal contamination situation in the Niger Delta, focusing on the effects on the environment, plants, water, sediment, fish and human health.

Methodology

A comprehensive and extensive compilation was utilised to assess previously published research and review articles on heavy metal pollution. The studies focused on various aspects of heavy metal pollution and their routes in plants, sediment, water and soil, as well as their health effects on human health and ecosystems. The three central Niger Delta states, Bayelsa, Delta and Rivers state (Fig. 1), were the only focus of the study between 2012 and 2022. The selection of Bayelsa, Delta and Rivers states as central Niger Delta states is based on their representation of the oil-rich Niger Delta region. With abundant oil and gas reserves, these states have emerged as prominent centers for petroleum exploration and production in Nigeria over many years. As a result, they play a crucial role in contributing significantly to Nigeria's oil revenue compared to other states within the Niger Delta region.

The search item used included '*Heavy metals in sediments*', '*Heavy metals exposure*', '*Heavy metals in water of Niger Delta*', '*Trace elements in water*', '*Heavy metals in sediments*', '*Heavy metals in river sediment*', '*Heavy metal contamination in fishes*', '*Heavy metals remediation*', '*remediation of heavy metal contamination*' and '*Heavy metal effects on human health*'. The inclusion and exclusion criteria approach collected 189 research publications on heavy metals and their exposure-related studies from globally known sources such as Science Direct, Web of Science, Scopus, Springer and the World Health Organization (WHO). This review only considered studies and articles that specifically examined the presence of heavy metals in water and soil within Bayelsa, Delta and Rivers State. Studies that did not directly address this topic were excluded from the review. To ensure the relevance of the information, articles published within the last 10 years from the time of writing this manuscript were considered. Publications that were not accessible or lacked comprehensive information about the study in their abstracts were also excluded from the review. After abstracts were sorted, full-text publications and reports were reviewed to identify research that was wholly or partly related to the study's objectives. Following this, research that did not align with the purpose of the present study was excluded, leaving just the most relevant

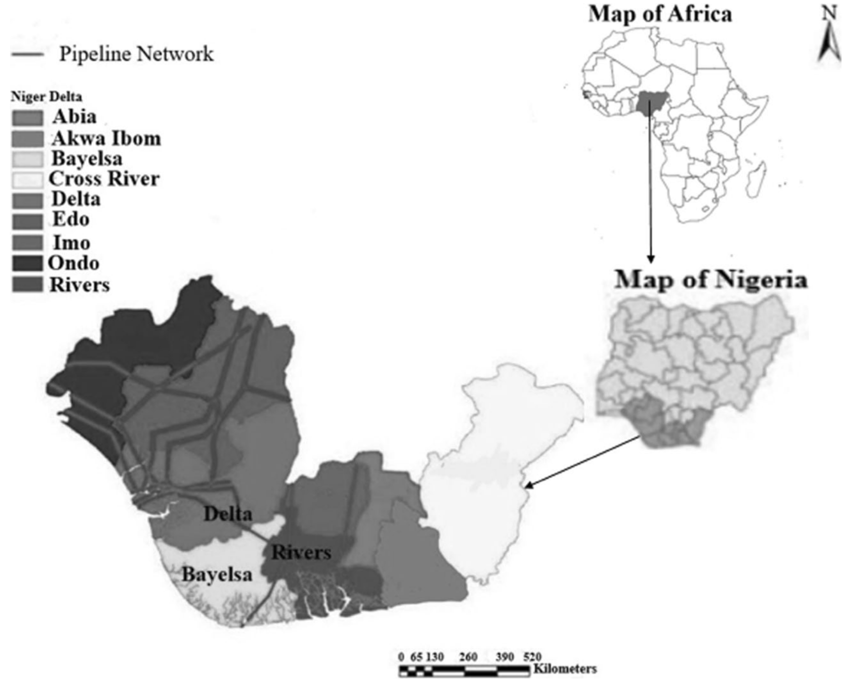

Fig. 1 The three significant hubs of petroleum exploration and production in Niger Delta, Nigeria, selected as case studies

papers for the current review. The objectives of the identified studies were classified. Finally, the results were processed and analysed to compare heavy metal concentrations from different sources.

Heavy Metal Sources in the Environment

Heavy metals in the environment may come from both natural and anthropogenic sources. Natural sources such as volcanic eruption, mineral dissolution, rock weathering, tsunami, hurricanes, forest fires, storm surges, leaching and evaporation from soil and water surfaces, droughts, flooding, erosion and earthquakes all contribute to the heavy metal pollution in the environment [32, 33]. The Niger Delta is notably inundated during the rainy season; major floods happen when rivers surge past their normal levels. The Niger Delta experienced severe flooding in 2022, and several toxins from non-point sources are expected to have been released into the environment. Anthropogenic sources are generally considered the primary causes of rising levels of heavy metal pollution, as opposed to natural sources.

Domestic sources of heavy metals in the environment include burning kerosene, burning wood, incineration of trash and refuse, crop waste (agricultural), sewage and garbage, plastic waste and electronic waste. Increased solid and liquid waste is dumped in the water due to increased human population and waste generation. Ezekwe and Edoghotu [34] and Asim and Nageswara Rao [35] stated that heavy metal-containing domestic garbage that has not been treated is continuously dumped into rivers and streams. Local communities with little or nonexistent waste management procedures are mostly affected. When dumped into the aquatic environment, these domestic wastes constitute ecosystem risks, ultimately lowering the water quality [36].

Heavy metals are one of the primary contaminants that the industrial sector releases into the environment, including the air [37]. Heavy metals, including lead, cadmium and chromium, are amongst the heavy metals in industrial waste. Heavy metals cannot be degraded; instead, they build up inside living things, impair immunological function and damage vital organs (Fig. 2). Farmers who are 'ignorant' care little about the environment's advantages or risks and exclusively focus on increasing agricultural yields and profits may utilise municipal and industrial wastewater. Heavy metal accumulation in the soil and biota may eventually arise from continuously irrigating land with industrial wastewater [38]. According to reports, industrial activity caused nickel concentrations in sediments from the northwest Persian Gulf to adversely impact aquatic organisms [39]. High levels of cadmium, lead, chromium, copper, zinc, mercury and arsenic were discovered across industrial parks and developed towns along the Yangtze River in China [40].

Another source of heavy metals is fertilizer and chemicals in agriculture. Toxic metallic and metalloid elements are also abundant in mine soil, which is a significant source for the environment on the earth's surface [41]. High metal concentrations are introduced during the oxidation of sulphide ores, especially those found near the earth's surface rich in pyrite. The numerous pollutants in the topsoil are washed away by precipitation and deposited in the environment. A significant environmental issue is also the production of acidic wastewater and water discharge from mining wastes that contain high amounts of dissolved metals [42].

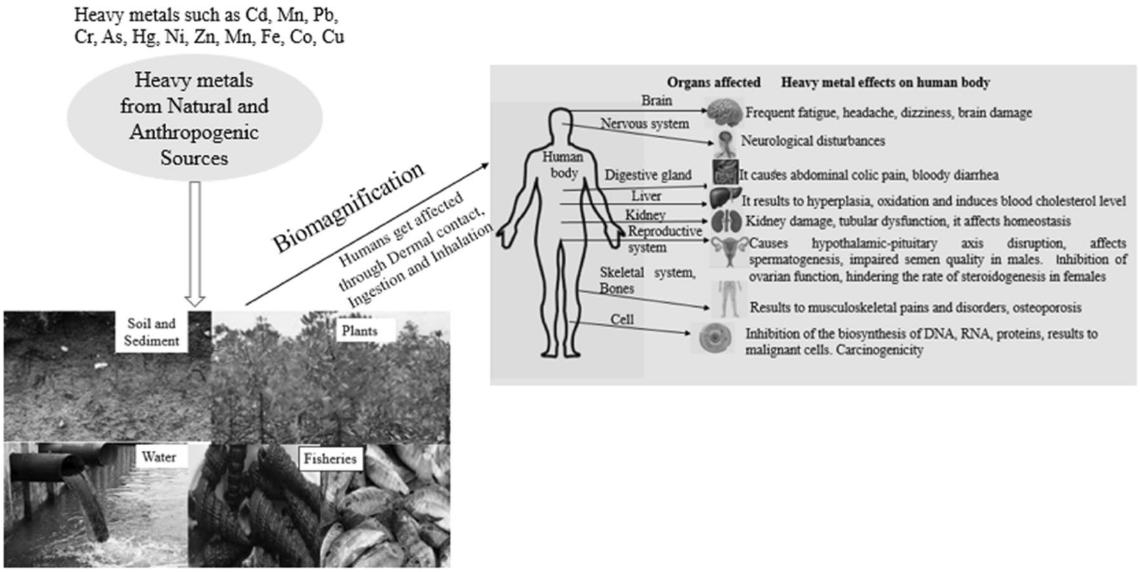

Fig. 2 Heavy metal contamination pathway and effect on humans

Similarly, oil exploration and extraction have posed a significant environmental threat to the Niger Delta for more than six decades [21]. There is significant pollutant-atmosphere interaction, and environmental pollution in the form of crude and refined oil spillages, gas flares and artisanal refining has a detrimental influence on the air, vegetation, water, arable land and aquatic ecology [43–45]. Rainwater is a significant source of small pollution particles entering rivers from the air. According to the WHO, air pollution is a significant environmental health concern linked to increased chronic and acute respiratory conditions, such as asthma and cancer [46].

Higher amounts of heavy metals exposure to receptors is a global health concern. Due to increased human activity, heavy metal concentrations and severity are increasing in the Niger Delta. Evidence shows that heavy metals adversely affect human health and the natural systems that sustain them [47, 48]. Therefore, it is vital to assess the level of heavy metal pollution of the entire ecosystem (including the surface, plants, sediment, soil and biota) to protect human life and preserve nature.

Current State of Heavy Metal Levels in Different Environmental Media of the Niger Delta Ecosystem

Heavy Metals in Waters of Niger Delta

Heavy metal contamination in water columns deteriorates water quality in Niger Delta [49–54]. Heavy metals have been identified at alarming levels in rivers in the previous decades, as shown in Table 1.

Fe concentration range in surface waters Edagberi creek 0.028 ± 0.00–0.075 ± 0.03 mg/L [67] and from Aguobiri community [93] all in Rivers state were below the allowed limit [99, 101]. Groundwater quality recorded concentrations higher than 0.3 mg/L World Health Organization drinking water guideline in the study of Olalekan et al. [72]. However, it was found to be less in the study of Oyem et al. [61]. Odekina et al. [63] discovered high Fe concentrations (36.9 mg/L) in interstitial Water from Isaka-Bundu Water Front in Rivers State above the standard specification. Ihunwo et al. [1] determined significant Cd concentrations in Woji Creek (0.146 mg/L), and 4.45 ± 2.43 mg/L in water samples was observed in Okirika Rivers state [90], which was above Standard Organization Nigeria (SON) [101] permissible limit. Copper concentrations were shown to be higher during the dry season than in the wet season and, in these cases, were above permissible limits [62, 66, 98]. High concentrations of copper (147.915 mg/L) and zinc (10.878 mg/L) were found in Isaka-Bundu Water Front in Rivers State [63]. The level of Pb found in the Okuluagu creek (3.95 mg/L) was above the WHO [100], SON [101] and NER [99] threshold limits [75]. Similarly, 2.04 ± 0.01 mg/L Pb was observed in Elebele waters [57]. In contrast, several studies recorded lower levels of Pb (0.02 ± 0.00–0.06 ± 0.00 mg/L) in Aghoro Community [56], Yenegoa Metropolis (0.036–0.098 mg/L) [53] and Elelenwon (0.428 ± 0.001 mg/L) but were still above permissible levels.

Mercury in water is harmful to man, animals and food crops. While < 0.001 mg/L of Hg was found in Sagbama creek [59], 0.02 ± 0.02 mg/L in Owubu creek Rivers and 0.05 ± 0.01 mg/L from an Imiringi Oil field in Bayelsa state [49]. However, in Andoni Rivers, Hg level ranged between 0.02 and 0.04 mg/L across the different seasons [54]. In the Oginigba river, the content of Cr (3 mg/L) was found to be much over the WHO [100] (0.5 mg/L) and SON [101] limits (0.05 mg/L) [86]. Lower Cr values were found by George and Abowei [3] and Ekweozor et al. [75]. The level of Ni discovered (0.221 mg/L) in the Bonny River (Onojake et al. (2017) and 3 mg/L in Bomu river and Oginigba river [86] in Rivers state surpassed the WHO [100] of 0.07 mg/L, and the SON [101] permitted limit (0.01 mg/L). However, an earlier study showed 16.45 ± 23.49 µg/L of Ni during the dry season and 27.51 ± 34.01 µg/L during the wet season in Bonny River Marcus et al. [92]. The Mn content in effluent from paint industries in Yenagoa Metropolis was found (0.037–1.769 mg/L) [53], which was within the National Environmental Regulations' permissible limit of 0.05 mg/L [102]. Aluminium levels were recorded in Amadi creek at 0.01–0.08 mg/L [89] and 0.88 mg/L in Soku [71], higher than NER levels of 0.2 mg/L.

The studies of Marcus and Ekpete [90], Imasuen and Egai [93] and Marcus et al. [92] also recorded concentrations of vanadium in various water samples. Cobalt concentrations were found above 0.2 mg/L in the Niger Delta [53, 70, 78, 85]. Co is good for health at lower concentrations but causes lung and heart problems and dermatitis by exposure to higher levels [102]. Edori et al.'s [70] studies observed the presence of silver 1.428 ± 0.384 in the Elelenwo River. Bekeowei and Bariweni [53] reported very high arsenic levels 1.195 to 5.022 compared to the studies of Edori and Kpee [85], which recorded (0.15 to 0.37 mg/L) and Aleru-Obogai et al. [54] that observed approximately 0.2 mg/L. These values exceeded 0.01 WHO [100] and SON [101] threshold levels. Magnesium content was found to be 23.03 ± 4.74 mg/L in Brass river [77] and 0.91 mg/L in Otuoke [60] and were significantly below the SON [101] and NER [99] acceptable limits (30 mg/L and 40 mg/L, respectively). The levels of heavy metals in the Southeast region of Nigeria have shown higher concentrations in groundwater sources from mining communities in Abakaliki, particularly in areas close to active mines [103]. A seasonal analysis revealed a decrease

Table 1 Heavy metal concentrations in water from Niger Delta (mg/l)

Area	Sampling site	No of sites	Fe	Cd	Cu	Zn	Pb	Hg	Cr	Ni	Mn	Al	V	Co	Ag	As	Mg	Ca	Reference
Bayelsa	Taylor creek	12			0.05– 0.61	0.06–0.83	0.00 to 0.48		0.02–0.42										[55]
Bayelsa	Yenagoa Metropolis	6	3.337 -17.991	0.002 - 0.528	0.345 - 1.343	0.478 - 3.302	0.036 - 0.098		0.141 - 0.733		0.037 - 1.769			0.253 - 0.447		1.195 - 5.022			[53]
Bayelsa	Aghoro Community	8	1.17 ±0.07–3.37 ±0.12		0.02 ±0.00 - 0.05 ±0.01	0.12 ±0.01-0.16 ±0.07	0.02 ± 0.00-0.06 ± 0.00			0.06 ±0.01-0.17 ±0.01									[56]
Bayelsa	Elebele	4	8.03 ±3.70			0.01 ±0.00	2.04 ±0.01		0.01 ±0.00	0 ±0.00									[57]
Bayelsa	Diebu creek	3	8.78		ND		ND							ND		ND			[58]
Bayelsa	Sagbama		5.96 ±5.01	< 0.001	0.045 ±0.0014	0.098 ±0.111	0.045 ±0.011	< 0.001			0.439 ±0.42								[59]
Bayelsa	Otuoke	14	10	NA	< 0.001	NA	< 0.001	NA	NA	NA	< 0.001	< 0.001	NA	0.001	NA		0.91		[60]
Delta	Benin river		0.14	0.01	0.02	0.01	0.18			0.42	0.06			0.14					[52]
Delta	Groundwater		0.1	ND		0.02					0.1				ND				[61]
Rivers	Ebocha-Obrikom	9	Rainy Season:	Rainy Season:0.01 ±0.02	Rainy Season:0.03 ±0.03	Rainy Season:0.66 ±0.17	Rainy Season:0.11 ±0.06		Rainy Season:0.87 ±0.89	Rainy Season:0.92 ±0.29	Rainy Season:0.03 ±0.02	NA	NA	NA	NA	NA	NA		[62]
			2.95 ±1.53	Dry Season:0.03 ±0.02	Dry Season:0.08 ±0.01	Dry Season:0.83 ±0.20	Dry Season:0.01 ±0.02		Dry Season:2.03 ±0.93	Dry Season:1.21 ±0.25	Dry Season:0.06 ±0.02								
			Dry Season season:																
			2.43 ±1.50																
Rivers	Andoni	3 seasons(Nov/April/July)	NA	Nov: 0.058 ±0.384	NA	NA	Nov:	Nov:	Nov:	Nov:	NA	NA	NA	NA	NA	Nov:	NA		[54]
				April:			0.097 ±0.009	0.373 ±0.025	-0.030 ±0.003	-0.216 ±0.026						-0.168 ±0.122;			
				-0.072 ±0.008			April:	April:	April:	April:						April:			
				July:			0.087 ±0.011	0.272 ±0.028	-0.026 ±0.006	-0.249 ±0.044						-0.205 ±0.414			
				-0.066 ±0.006			July:	July:	July:	July:						; July:			
							0.077 ±0.012	0.257 ±0.039	-0.025 ±0.005	-0.241 ±0.030						-0.203 ±0.044			
Rivers	Isaka-Bundu	3	36.91	NA	147.915	10.878	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA		[63]
Rivers	Bonny	3	5.33-8.27	NA	0.13-0.15	2.67-5.73	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA		[64]
Rivers	Port-Harcourt(NCR)	3	Station I:	Station :	Station I:	Station I:	Station I:	NA	Station I:	Station I:	Station I:	NA	NA	NA	NA	NA	NA		[65]
			1.88 ±0.05	< 0.001 ±0.00	0.03 ±0.07	2.43 ±0.02	< 0.001 ±0.02		0.03 ±0.10	0.28 ±0.05	0.34 ±0.01								
			Station II:	StationII:	Station II:	Station II:	Station II:		Station II:	Station II:	Station II:								
			3.06 ±0.02	< 0.001 ±0.00	0.05 ±0.05	6.28 ±0.08	0.06 ±0.07		0.04	0.25 ±0.01	0.02 ±0.01								
			Station III:	Station III:	Station III:	Station III:	Station III:		±0.10	Station III:	Station III:								
			3.07 ±0.08	< 0.001 ±0.00	0.03 ±0.10	3.86 ±0.02	< 0.001 ±0.00		Station III:	0.19 ±0.01	0.04 ±0.01								
									0.03 ±0.02										
Rivers	Elele-Alimini	5	NA	Wet season:	Wet season:	NA	Wet season:1.03 ±0.02	NA	Wet season:	Wet season:	NA	NA	NA	NA	NA	Wet season:	NA		[66]
				1.0E-2 ± 1.1E-2	1.08 ±0.01		Dry Season season:		0.11 ±0.01	1.86 ±0.03						2.2E-3 ±1.0E-3			
				Dry Season season:	Dry Season season:		0.09 ±0.02		Dry Season season:	Dry Season season:						Dry Season season:			
				2.2E-2 ± 1.2E-1	1.10 ±0.02				2.2E-2 ± 1.2E-1	1.80 ±0.02						3.9E-3 ±2.0E-3			
Rivers	Edagberi creek	3	0.028 ±0.00-0.075 ±0.03	ND-0.0008 ±0.00	0.004 ±0.00-0.058 ±0.02	0.016 ±0.00-0.076 ±0.00	0.0006 ±0.00-0.003 ±0.00	ND-0.0006 ±0.00	0.003 ±0.00-0.015 ±0.00	0.176 ±0.00-0.219 ±0.01	0.005 ±0.003-0.486 ±0.06	NA	NA	NA	NA	NA	NA		[67]
Rivers	Woji	5	NA	0.146	2.328	N/A	3.252	N/A	1.59	0.109	N/A	NA	NA	NA	NA	< D.L	NA		[1]
Rivers	Ekerekana creek		NA	0.39 ±0.06	0.45 ±0.06	NA	0.29 ±0.04	NA	0.23 ±0.03	NA	NA	NA	NA	NA	NA	NA	NA		[68]
Rivers	Bonny river		NA	Dry Season season: < 0.01 Wet season:			Dry Season season:			Dry Season season:	NA	NA	NA	NA	NA	NA	NA		[69]
				< 0.01			0.14-0.29			0.21-0.31									
							Wet season:			Wet season:									
							0.15-0.47			0.15-0.30									
Rivers	Elelenwon	12	5.91 ±0.008	0.251 ±0.000	0.781 ±0.003	1.324 ±0.320	0.428 ±0.001		0.139 ±0.001	0.184 ±0.000	NA	NA	NA	0.672 ±0.002	1.428 ±0.384	ND	NA		[70]
Rivers	Soku	4	1.95	0.01	NA	NA	0.64	NA	NA	NA	NA	0.88	0.08	NA	NA	NA	NA		[71]

Table 1 (continued)

Area	Sampling site	No of sites	Fe	Cd	Cu	Zn	Pb	Hg	Cr	Ni	Mn	Al	V	Co	Ag	As	Mg	Ca	Reference
Rivers	Woji creek		Aug:0.379 ±0.26 Sep:0.047 ±0.056	Aug:0.102 ±0.217	Aug:0.0102 ±0.0023	NA	Aug:0.990 ±0.855	NA	NA	Aug:0.379 ±0.259	NA	NA	NA	NA	NA	NA	NA		[72]
			Oct:0.55 ±0.37	Sep:0.0004 ±0.0009	Sep:0.031 ±0.034		Sep:1.534 ±0.103			Sep:0.047 ±0.056									
				Oct:0.062 ±0.035	Oct:0.041 ±0.044		Oct:0.229 ±0.333			Oct:0.545 ±0.369									
Rivers	Ebocha-Obrikom Groundwater(GW), Boreholewater (BW), Wellwater(WW)	8	GW:5.3 ±12.18	NA	GW:0.01 ±0.001	GW:0.3 ±0.49	GW:0.001 ±0.00	NA	GW:0.001 ±0.00	GW:0.001 ±0.00	GW:0.05 ±0.08	NA	NA	NA	NA	NA	NA		[73]
			BH:6.9 ±15.61		BH:0.001 ±0.001	BH:0.09 ±0.1	BH:0.001 ±0.00		BH:0.001 ±0.00	BH:0.001 ±0.00	BH:0.1 ±0.10								
			WW:2.4 ±3.3		WW:0.001 ±0.00	WW:0.8 ±0.8	WW:0.001 ±0.00		WW:0.001 ±0.00	WW:0.001 ±0.00	WW:0.02 ±0.01								
Rivers	Azuabie creek	3			<0.001-0.02 ±0.006	<0.001-0.132 ±0.047			<0.001mg/L	<0.001-0.129 ±0.006				NA	NA	NA	NA		[74]
Rivers	Port-Harcourt	3	1.52 ±0.34	NA	NA	1.77 ±0.53	0.19 ±0.11	NA	0.65 ±0.21	NA	NA	NA	NA	NA	NA	NA	NA		[3]
Rivers	Azuabie creek, Okrika/PH	4	NA	0.21		0.02	0.05		0.15		NA		NA	NA	NA	NA	NA		[75]
Rivers	Okuluagu creek	NA	NA	0.31	NA	0.05	3.95		0.43		N		NA	NA	NA	NA	NA		
Rivers	Rumuolumini river: iwofe creek	NA	Station 1:	NA	Station 1:	Station 1:	Station 1:	NA	NA	NA	Station 1:	NA	NA	NA	NA	NA	NA		[76]
			12.5 ±0.7		0.16 ±0.01	0.41 ±0.003	0.00 ±0.00				0.35 ±0.07								
			Station2:		Station 2:	Station 2:	Station 2:				Station 2:								
			13.14 ±0.014		0.10 ±0.00	0.18 ±0.01	0.00 ±0.00				0.24 ±0.001								
			Station 3:		Station 3:	Station 3:	Station 3:				Station 3:								
			0.41 ±0.001		0.08 ±0.00	0.34 ±0.01	0.00 ±0.00				0.32 ±0.005								
			Station 4:		Station 4:	Station 4:	Station 4:				Station 4:								
			2.42 ±0.28		0.00 ±0.00	0.15 ±0.001	0.00 ±0.00				0.11 ±0.001								
			Station 5:		Station 5:	Station 5:	Station 5:				Station 5:								
			0.31 ±0.002		0.05 ±0.01	0.05 ±0.01	0.00 ±0.00				0.08 ±0.00								
Bayelsa	Brass river		0.12 ±0.02	0.02 ±0.01	0.01 ±0.01	0.03 ±0.01	0.07 ±0.05		BDL	0.13 ±0.02	BDL						23.03 ±4.74		[77]
Rivers	Bonny/New Calabar river	3	1.375	0.089	0.465	2.811	0.23		1.388	0.221	NA	NA	NA	0.239	NA	NA	NA		[78]
Rivers	Bonny river	NA	NA	NA	0.0001-0.04	0.04-0.09	NA				NA	NA	NA	NA	NA	NA	NA		[79]
Rivers	Gokana LGA	30		0.03			0.1		0.17	0.19	0.86		NA	NA	NA	NA	NA		[80]
Rivers	Port-Harcourt(NCR)	3	2	0.01	NA	1.35	1.03	NA	0.13	NA	1.74	NA	NA	NA	NA	NA	NA		[81]
Rivers	Bonny(ferry terminal)	NA		0.41			0.24		< 0.001	0.012				NA	NA	NA	NA		[82]
Rivers	Iwofe			0.13			0.31		< 0.001	< 0.001				NA	NA	NA	NA		
Rivers	Nembe			0.43			0.36		< 0.001	< 0.001				NA	NA	NA	NA		
Rivers	Umuechem	5	Station 1:	ND	Station 1:	Station 1:	Station 1:	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA		[83]
			0.167 ±0.01		0.478 ±0.02	1.23 ±0.01	0.02 ±0.00												
			Station 2:		Station 2:	Station 2:	Station 2:												
			0.156 ±0.01		0.925 ±0.03	2.00 ±0.13	0.03 ±0.00												
			Station 3:		Station 3:	Station 3:	Station 3:												
			0.294 ±0.02		1.288 ±0.01	2.51 ±0.21	0.025 ±0.01												
			Station 4:		Station 4:	Station 4:	Station 4:												
			0.246 ±0.00		1.304 ±0.11	1.33 ±0.30	0.035 ±0.01												
			Station 5:		Station 5:	Station 5:	Station 5:												
			0.177 ±0.10		1.158	3.04 ±0.23	3.04 ±0.23												
					±0.00														
Rivers	Gokana: Bodo Creek	3	Station 1:	Station 1:	NA	NA	Station 1:	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA		[84]
			1.30 ±0.19	0.03 ±0.00			1.63 ±0.37												
			Station 2:	Station 2:			Station 2:												
			1.40 ±0.18	0.06 ±0.00			1.33												
			Station 3:	Station 3:			±0.17												

Table 1 (continued)

Area	Sampling site	No of sites	Fe	Cd	Cu	Zn	Pb	Hg	Cr	Ni	Mn	Al	V	Co	Ag	As	Mg	Ca	Reference
			0.56 ± 0.73	0.037 ± 0.00			Station 3: 1.03 ± 0.15												
Rivers	Port Harcourt	3	Iwofe:0.007 ± 0.00 Agip:0.03 ± 0.00 Mile III:0.007 ± 0.00	Iwofe:< 0.001 Agip:< 0.001 Mile III:< 0.001	Iwofe:0.027 ± 0.00 Agip:0.031 ± 0.00 Mile III:0.069 ± 0.01	Iwofe:4.40 ± 0.01 Agip:3.37 ± 0.01 Mile III:6.59 ± 0.04	Iwofe:0.02 ± 0.00 Agip:0.01 ± 0.00 Mile III:0.03 ± 0.00	NA	Iwofe:0.037 ± 0.00 Agip:0.024 ± 0.00 Mile III:0.051 ± 0.00	Iwofe:0.027 ± 0.01 Agip:0.012 ± 0.00 Mile III:0.047 ± 0.00	Iwofe:0.049 ± 0.01 Agip:0.051 ± 0.00 Mile III:0.054 ± 0.01	NA	NA	Iwofe:0.37 ± 0.03 Agip:0.34 ± 0.00 Mile III:0.42 ± 0.02	NA	Iwofe:0.15 ± 0.00 Agip:0.25 ± 0.01 Mile III:0.37 ± 0.04	NA		[85]
Rivers	Bomu river	NA	NA	ND	1.282 ± 0.557	2.086 ± 0.999	0.697 ± 0.134		3.106 ± 0.675	3.069 ± 0.801	NA	NA	NA	NA	NA	NA	NA		[86]
Rivers	Oginigba river	NA	NA	NA	1.229 ± 0.083	1.311 ± 0.092	0.472 ± 0.053		3.164 ± 0.075	3.119 ± 0.946	NA		NA	NA	NA	NA	NA		
Rivers	Andoni	NA	Station 1:0.45 Station 2: 0.61 Station 3: 1.54 Station 4: 0.46 Station 5: 0.45	Station 1: 0.05 Station 2: 0.03 Station 3: 0.05 Station 4: 0.5 Station 5: 0.02	NA	Station 1: 0.17 Station 2: 0.08 Station 3: 0.08 Station 4: 0.08 Station 5: 0.06	Station 1: 0.44 Station 2: 0.25 Station 3: 0.36 Station 4: 0.3 Station 5: 0.14	NA	Station 1: < 0.02 Station 2: < 0.02 Station 3: < 0.02 Station 4: < 0.02 Station 5: < 0.02	Station 1: 0.09 Station 2: 0.08 Station 3: 0.08 Station 4: 0.11 Station 5: 0.1	Station1: 0.16 Station 2: 0.15 Station 3: 0.15 Station 4: 0.04 Station 5: 0.08	NA	NA	NA	NA	NA	NA		[34]
Rivers	Sombreiro		0.099 ± 0.104	0.002 ± 0.001	0.056 ± 0.075	0.04 ± 0.024	0.003 ± 0.011		0.055 ± 0.067	0.091 ± 0.132			NA	NA	NA	NA	NA		[87]
Rivers	Imonite creek, Ndoni	5	ND	NA	NA	ND	Station 1:0.006 Station 2:0.006 Station 3:0.006 Station 4:0.006 Station 5:0.006	NA	NA	NA	Station 1: 0.034 Station 2: 0.062 Station 3: 0.256 Station 4: 0.17 Station 5: 0.147	NA	NA	NA	NA	NA	NA		[88]
Rivers	Amadi creek	NA	0.30-1.43		0.07-0.5				0.00-0.06"		NA	0.01-0.08	NA	NA	NA	NA	NA		[89]
Rivers	Okrika		NA	4.45 ± 2.43			21.66 ± 11.65	ND	NA	38.84 ± 32.15	NA	NA	0.15 ± 0.29	NA	NA	NA	NA		[90]
Rivers	New Calabar river	NA	0.4 ± 0.1	0.05 ± 0.0			0.1 ± 0.1				NA	NA	NA	NA	NA	NA	NA		[91]
Rivers	Bonny river/Okrika creeks	ug/L	NA	Dry Season season: 1.87 ± 3.52 Wet season: 7.03 ± 7.57			Dry Season season: 16.45 ± 23.49 Wet season: 27.51 ± 34.01			Dry Season season: 46.48 ± 68.19 Wet season: 31.8 ± 53.69	NA	NA	Dry Season season: 0.11 ± 0.24 Wet season: 0.20 ± 0.34	NA	NA	NA	NA		[92]
Bayelsa	Aguobiri community	15	0.01-0.68	NA	0.01 - 0.62	NA	0.001 - 0.48	NA	0.002 - 0.042	0.001 - 0.06	0.001 - 0.176	NA	0.002 - 0.07	NA	NA		NA		[93]
Rivers	Okrika river	2	NA	Downstream: 0.41 ± 0.07 Upstream: 0.413 ± 0.05			Downstream: 0.24 ± 0.01 Upstream: 0.226 ± 0.03		Downstream: 1.05 ± 0.01 Upstream: 1.79 ± 0.08	Downstream: 0.16 ± 0.01 Upstream: 0.159 ± 0.01			NA	NA	NA	NA	NA		[94]
Rivers	Owubu creek, Ahoada	3	0.03 ± 0.21	0 ± 0.01	2.85 ± 0.40	NA	0.35 ± 0.14	0.02 ± 0.02	NA	NA	NA	NA	NA	NA	NA	NA	NA		[95]
Rivers	Sombreiro river	7	NA	< 0.001-0.0625	< 0.001-0.0772	0.1139-6.1168	< 0.0002-0.0012	NA	0.0632-0.1836	NA	NA	NA	NA	NA	NA	NA	NA		[96]
Rivers	Elechi creek		NA	Station 1: 0.21 ± 0.08 Station 2:		Station 1: 0.21 ± 0.04 Station 2:	Station 1: 1.04 ± 0.01 Station 2:			Station 1: 0.48 ± 0.04 Station 2:	Station 1: 0.12 ± 0.02 Station 2:	NA	NA	NA	NA	NA	NA		[97]

Table 1 (continued)

Area	Sampling site	No of sites	Fe	Cd	Cu	Zn	Pb	Hg	Cr	Ni	Mn	Al	V	Co	Ag	As	Mg	Ca	Reference
				0.10 ±0.30		0.18 ±0.02	0.59 ±0.02			0.30 ±0.12	0.09 ±0.02								
Rivers	Kalabari Creek	5	Rainy Seasony season:		Rainy Seasony season:		Rainy Seasony season:			Rainy Seasony season:				NA	NA	NA	NA		[98]
			1.63 ±2.19		0.002 ±0.001		0.02 ±0.02			0.01 ±0.01									
			Dry Season season:		Dry Season season:		Dry Season season:			Dry Season season:									
			2.64 ±2.20		0.28 ±0.29		0.04 ±0.05			0.43 ±0.46									
Bayelsa	Imiringi Oil field	5	1.3 ±0.2	0.07 ±0.003			0.06 ±0.004	0.05 ±0.01								ND	4.2 ±0.4	8.3 ±0.5	[49]
	NER [100]		0.05	0.005	0.001	0.01	0.01	0.001	0.5	0.01		0.2				0.05	40	180	
	WHO [101]		0.3	0.02	1	5	0.1		0.05	0.01	0.05			0.05		0.04			
	SON [99]		0.3	0.003	1	0.2	0.01		0.05		0.2			0.05		0.01			

NA Not Available; *ND* Not Detected; *BDL* Below Detection Limit; *GW* Ground water; *BW* Borehole Water; *WW* Well water

in the concentration of chemical constituents during the rainy season compared to the dry season [103]. Similarly, in Northwest Nigeria, the water samples obtained from artisanal and local mining sites exhibited concentrations of heavy metals above the permissible limits [104]. The water in the Niger Delta communities is potentially hazardous due to its high concentration of hydrocarbons and other pollutants, which can cause serious health risks if ingested directly or indirectly.

Heavy Metals in Soil and Sediment of Niger Delta

Given the anthropogenic activities and impacts of oil industries and artisanal refining during the past six decades in the Niger Deltas, ecological restoration of contaminated soils has been a significant concern [21]. As a result, the soils of the Niger Delta (Table 2) are contaminated with heavy metal concentrations [105, 109, 117, 122].

Sediment is a significant and dynamic component of aquatic ecosystems, including various ecosystems and conditions. Since sediments are typically sinks for various anthropogenic stressors, sediments are widely used to evaluate environmental contamination levels [1]. Due to dissolution, precipitation, sorption and other complex processes, heavy metals in sediment experience considerable speciation changes as they travel through the river system [125]. Heavy metal concentrations in sediment are significantly higher than in the water column as metals accumulate in the substratum [1, 126]. Sediments in aquatic ecosystems may be contaminated by leachates transporting chemicals from various urban, industrial and agricultural activities, traffic emissions, terrestrial runoff and effluent disposal [53, 84]. Gijo and Alagoa [127] stated that the leading causes of heavy metal contamination in sediment include domestic wastes, industrial effluents, fertilisers and pesticides.

High levels of heavy metals are found in sediment and water due to the significant amounts of heavy metals emitted by industrial and urban effluents. Cadmium contamination was found in sediment from Bodo creek [84], Okuluagu creek [75], Kolo creek [71, 128] and Woji creek [1] (Table 3). In contrast, heavy metal concentrations in sediments from the Ethiope river [134] and Diebu creek [58] were all reduced and within DPR permissible limit [124]. However, the continuous use of crops, water and fisheries from the Niger Delta could negatively affect public health. Elevated concentrations of heavy metals have been observed in various ecosystems beyond the area under review [138]. These high concentrations are primarily attributed to mining and industrial activities, and other anthropogenic contributions such as the direct discharge of used-lubricant oil, scrap metals, tire wear and emissions from traffic [139].

Table 2 Heavy metal concentrations in soil from Niger Delta (mg/kg)

Area	Sampling site	No of sites	Fe	Cd	Cu	Zn	Cr	Pb	Ni	As	Co	Mn	Ba	V	Mg	Hg	References
Bayelsa	Yenagoa and southern ijaw-Plantain plantation	12	25.09	1.31	6.37	17.71	3.63	2.57	0.63			8.85		0.13	NA	NA	[108]
	Virgin Land		13.18	0.83	4.04	8.23	2.66	1.63	0.4			5.61		0.08			
	Fallow Land		18.67	1.13	5.54	11.57	3.63	2.22	0.54			7.64		0.11			
Bayelsa	Kolo creek river	3	6.71-68.55	NA	0.95-2.77	0.63-4.40	NA	2.28-4.47	NA		NA	7.86-12.67		NA	NA	NA	[109]
Bayelsa	Kolo		5970 ± 0.69	< 0.001	17.5 ± 0.13	53.7 ± 0.16	< 0.001	3.80 ± 0,000	< 0.001		< 0.001	322.76 ± 0.41		< 0.001	NA	NA	[110]
Bayelsa	Okako Otuoke		4490 ± 2.22	< 0.001	10.9 ± 0.36	78.3 ± 0.29	< 0.001	3.81 ± 0.01	< 0.001		< 0.001	57.6 ± 0.26		< 0.001	NA	NA	
Delta	Ozoro, Dump-site		39.20 - 43.23	1.04 - 2.05	NA	NA			2.89-6.9								[111]
Delta	Agbor - Asaba Express-way	1	142.93 ± 42.16	NA	NA	59.34 ± 42.16	14.27 ± 5.39	13.63 ± 5.41	24.98 ± 15.57								[106]
Delta	Workshop Abraka		40.05	NA	0.66	16.74						34.39					[112]
Delta	Cassava Process-ing Mill	1	1746.4 - 2839.6	0.01 - 1.60	21.9 - 97.3	0.01 - 1.60	3.7 - 29.5	< 0.01 - < 0.01	4.0 - 11.3			0.1 - 383.2					[113]
Rivers	Bdere, Ogoni	3	NA	0.02 ± 0.03	NA	1.66 ± 2.39	NA	0.55 ± 1.02	NA	NA	NA	2.15 ± 3.41	NA	NA	NA	NA	[114]
Rivers	Ogoni	3	1700.6 ± 87.4-4780.9 ± 78.3	0.01 ± 0.001	NA	NA	0.29 ± 0.08-8.92 ± 1.84	0.01 ± 0.002-6.53 ± 1.19	0.01 ± 0.001-2.52 ± 0.14	NA	NA	7.33 ± 1.04-63.7 ± 3.27		NA	NA	NA	[115]
Rivers	Ebubu & Alimini	2	Ebubu:3094.55 ± 39.59; Alimini:3035.98 ± 51.52	Ebubu:0.77 ± 0.05 ; Alimini:0.19 ± 0.02	NA	Ebubu:6.67 ± 0.45; Alimin:15.14 ± 0.16	Ebubu:5.98 ± 0.11; Alimini:5.29 ± 0.09	Ebubu:7.69 ± 0.49; Alimini:2.27 ± 0.04	Ebubu:1.62 ± 0.08 ; Alimini:0.69 ± 0.45	NA	NA	NA	NA	NA	NA	NA	[116]
Rivers	Elele & Ogale		NA	Elele:0.2 ± 0.02; Ogale:0.8 ± 0.1	NA	Elele:15.1 ± 0.2; Ogale:55 ± 0.3	Elele:5.3 ± 0.1 ; Ogale:10.3 ± 1	Elele:2.3 ± 0.04; Ogale:17 ± 1	Elele:1.02 ± 0.13; Ogale:1.7 ± 0.1	NA	NA	NA	NA	NA	NA	NA	[117]
Rivers	Port Harcourt	4	15.3	4.47	0.2	3.13	0.38	5.21	10.05	0.1	NA	NA	NA	NA	10.15	NA	[118]
Rivers	Alakhaia & Eleme	4	NA	0 ± 0.00-0.80 ± 0.21	0.55 ± 0.05-1.11 ± 0.09	NA	0.78 ± 0.24-1.60 ± 0.06	0.37 ± 0.02-0.69 ± 0.07	0.52 ± 0.05-0.90 ± 0.17	0.01 ± 0.00-0.03 ± 0.00	NA	NA	NA	NA	NA	0.00-0.00	[107]
Rivers	Kokori & Kolo creek	40	NA	Kokori:0.84 ± 0.60 ; Kolo:0.70 ; Control:0.34 ± 0.12	NA	Kokori:45.65 ± 12.7 ; Kolo:46.97 ± 11.32 ; Control:13.12 ± 2.56	Kokori:6.91 ± 1.67 ; Kolo:12.33 ± 6.85; Control:2.51 ± 0.62	Kokori:5.49; Kolo:1.38 ± 0.56; Control:2.82 ± 2.30	Kokori:1.99 ± 1.03; Kolo:7.4 ± 1.71; Control:2.26 ± 1.20	NA	NA	NA	NA	NA	NA	NA	[119]
Rivers	Gokana		256 ± 0.26	0.01 ± 0.00		1.22 ± 0.01	0.04 ± 0.00	0.14 ± 0.00	NA	NA	NA	4.07 ± 0.00	NA	NA	NA	NA	[120]
Rivers	Diobu		847.82	NA	NA	39.58	0.03	0.03	0.05	NA	NA	17.39	NA	NA	NA	NA	[121]
Rivers	Diobu		816.33	NA	NA	32.7	0.02	0.02	0.04	NA	NA	13.96	NA	NA	NA	NA	
Rivers	Eleme	4	NA	0.16 ± 0.01-0.26 ± 0.04	1.55 ± 0.37-4.25 ± 1.38	4.07 ± 0.87-11.69 ± 3.03	NA	2.69 ± 0.74-6.92 ± 2.51	NA	NA	NA	NA	NA	NA	NA	NA	[122]
Rivers	Bodo city	20	7.7	NA	1.8 ± 0.3	NA	0.3	NA	3.1	NA	NA	NA	102.4	6.8	NA	NA	[105]

Table 2 (continued)

Area	Sampling site	No of sites	Fe	Cd	Cu	Zn	Cr	Pb	Ni	As	Co	Mn	Ba	V	Mg	Hg	References
Rivers	Rumuolumeni	5	NA	0.056 ±0.033	1.426 ±1.124	3.995 ±1.922	NA	1.472 ±1.314	NA	NA	NA	NA	NA	NA	NA	NA	[123]
		DPR [171]	Tar. Value	100	0.3		20	35	140	200	36					85	
			Inter Value	380	10		240	210	720	625	190					530	

NA Not Available; *Tar. Value* Target Value; *Inter Value* Intervention Value

Heavy Metals in Fish and Shell Fishes of the Niger Delta

Toxic heavy metals can bioaccumulate and biomagnify in seafood, subsequently transmitted to humans through the food chain [6, 8]. Ingestion of chemically contaminated foods generates anthropogenic foodborne diseases [140]. Fish and fishery products are essential components of a healthy diet [141, 142]. They contain several essential nutrients, including omega-3 fatty acids, are low in saturated fat and are a cheap source of animal protein in developing countries [143, 144]. The diverse ecosystems of the Niger Delta are potential hotspots for numerous species and economic trends, with local and rural communities engaging in commercial fishing [1]. Since fish is the primary source of animal protein in the Niger Delta, heavy metals in the aquatic diet have become the principal pollutant in this region, as detailed in Table 4 for the various heavy metal pollution.

Heavy metals have become the principal pollutants in fish diets due to the increased entry of heavy metals into the aquatic environment from anthropogenic activities such as oil extraction, industrial waste and metal effluent discharge [18, 19]. Untreated industrial waste, discarded battery particles, painting paints derived from Pb sources, gasoline from cargos, motorised boat transit routes and inappropriately discharged domestic wastes all contribute to the accumulation of heavy metals in the environment [145]. The use of polluted seafood poses serious health risks worldwide [146]. As a result, heavy metal contamination in food is considered one of the most severe risks to human health [91].

Heavy metals enter the aquatic environment via natural and anthropogenic sources, posing significant hazards to aquatic biota and humans [32, 33]. Absorption of particulate particles in sediment-to-water interactions, types of feed ingestion, adsorption on tissue and skin surfaces and ion exchange into lipophilic tissues are significant pathways of heavy metal fish accumulation [5]. These heavy metals absorbed in fish are transported to humans through the food chain and deposited in various tissues and vital organs [84, 86]. Many food safety studies have been linked to the risk of consuming heavy metal-contaminated foods [147, 148], particularly concerning metal accumulation in fish [1, 149]. The presence of metal concentrations in fish implies environmental contamination that threatens human health and is highlighted in Table 4.

In the Woji Creek Rivers state, *Mugil cephalus* was discovered to have a mean concentration of Cu higher than the national and international food safety standard limits at 33.48 ± 15.54 mg/kg [1]. Moslen [150] states that *Mugil cephalus* recorded levels of 4.12 ± 1.07 mg/kg at

Table 3 depicts various heavy metal concentration in sediment of Niger Delta

Area	Sampling site	No of site	Fe	Cd	Cu	Zn	Pb	Hg	Cr	Ni	Mn	Al	V	Co	Ag	As	Mg	Ca	References
Bayelsa	Taylor creek	10	3500	0.38	5.8	18	7.8		10	5									[130]
Bayelsa	Nun river	3	0.138 – 0.314	0.005 – 0.012		0.082 – 0.126	0.007 – 0.017		0.001 – 0.003	0.001 – 0.032				0.001 – 0.002					[131]
Bayelsa	Nun river	12	441.48- 6,674.34	0.25 -0.91	0.25-14.64	11.57 -33.67	3.66-7.18		7.04-15.38	8.63 -88.29									[9]
Bayelsa	Diebu creek	3	1812.31 ± 190.31		1.56 ± 1.16		0.94 ± 0.87							0.66 ± 0.76		ND			[58]
Bayelsa	Kolo creek		15499.02 ± `1454	2.22 ± 2.48	7.39 ± 4.75	35.19 ± 22.15	6.00 ± 4.47												[126]
Bayelsa	Pennington river	4	Dry season: 26.82 ± 22.19 Wet season: 26.65 ± 24.79		Dry season: 2.43 ± 5.06 Wet season: 2.07 ± 4.35	Dry season: 1.22 ± 1.19 Wet season: 1.11 ± 1.00	Dry season: 0.69 ± 1.10 Wet season: 0.61 ± 1.08	NA	NA	NA	NA	NA	NA	Dry season: 0.39 ± 0.35 Wet season: 0.37 ± 0.60		Dry season: 0.14 ± 0.17 Wet season: 0.11 ± 0.18	NA	NA	[132]
Delta	Fish farm-River Anwai			1.156–3.329	26.71–121.82	87.68–371.06	0.34–1.54		9.439–14.373		3.14–37.20								[133]
Delta	Benin river	5	1.88 – 12.73		0.24 – 1.75	2.0 – 6.38	0.15 – 1.10		0.25 – 1.68	0.14 – 0.75	0.63 – 3.79								[50]
Delta	Benin river			0.08 ± 0.09		92.1 ± 170	53 ± 57		4.1 ± 2.0	0.14 ± 0.17									[134]
Delta	Ethiope	5		0.00- 0.11	0.34-0.60	0.84-2.24	0.27— 0.72		ND		0.21-0.46		0.00-0.05						[127]
Rivers	Isaka-Bundu	3	1696	NA	533.65	223.63	NA	NA	NA	NA	NA	NA	NA	NA		NA			[63]
Rivers	Elele-Alimini	5	NA	Wet season: 0.04 ± 0.01 Dry season: 0.04 ± 0.02	Wet season: 3.52 ± 0.05 Dry season: 2.99 ± 0.04	NA	Wet season: 3.21 ± 0.07 3.39 ± 0.05	NA	Wet season: 3.69 ± 0.02 Dry season: 2.59 ± 0.01	Wet season: 3.57 ± 0.03 Dry season: 2.95 ± 0.03	NA	NA	NA	NA		Wet season: 2.3E-2 ± 2.0E-3 Dry season: 1.6E-2 ± 2.0E-3			[66]
Rivers	Woji	5	NA	8.91	21	NA	140.93	NA	29.98	37.48	NA	NA	NA	NA		< D.L			[1]
Rivers	Soku	4	6608.63	2.16	NA	NA	2.84	NA	NA	NA	NA	2.54	1.9	NA		NA			[71]
Rivers	Woji creek/ Bonny river	10	20148.92	0.06	12.38	52.15	11.58		34.79	10.17	126.24	NA	NA	6.71		6.39			[18]
Rivers	Bonny river	NA	NA	Dry season: < 0.01 Wet season: < 0.01	NA	NA	Dry season: 0.21-0.35 Wet season: 0.37-0.50	NA	NA	Dry season: 0.31-0.64 Wet season: 0.25-0.28	NA	NA	NA	NA		NA			[69]
Rivers	Port-Harcourt	3	87.43 ± 6.57	NA	NA	7.90 ± 2.56	2.23 ± 0.61	NA	1.94 ± 0.81	NA	NA	NA	NA	NA		NA			[3]
Rivers	PH(NCR)	NA	650.3	5.65	18.77	25.82	11.11	NA	2.06	NA	8.37	NA	NA	NA		NA			[81]
Rivers	Azuabie creek, Okrika/PH	4	NA	0.3	NA	178.8	18.75		14.27	NA	NA	NA	NA	NA		NA			[75]
Rivers	Okuluagu creek	NA	NA	8.65	NA	27.57	ND	NA	2.8	NA	NA	NA	NA	NA		NA			
Rivers	Bonny river	20	15.07 ± 5.93	NA	1.31 ± 0.31	9.11 ± 0.94	3.95 ± 0.95	NA	NA	NA	31.54 ± 9.37	NA	NA	NA		NA			[135]
Rivers	Bomu river		NA	ND	66.301 ± 38.152	203.513 ± 63.101	60.301 ± 29.122	NA	129.731 ± 30.483	148.919 ± 84.793	NA	NA	NA	NA		NA			[86]
Rivers	Oginigba	NA	NA	ND	74.61 ± 27.152	213.315 ± 60.214	43.307 ± 21.521	NA	109.297 ± 21.843	151.219 ± 34.473	NA	NA	NA	NA		NA			
Rivers	Bodo Creek Gokana	3	Station 1: 1425.00 ± 52.04 Station 2: 1623.35 ± 102.70 Station 3: 1696.70 ± 103.36	Station 1: 2.83 ± 0.33 Station 2: 1.65 ± 0.43 Station 3: 2.70 ± 0.12	NA	NA	Station 1: 2.00 ± 0.32 Station 2: 1.87 ± 0.07 Station 3 2.47 ± 0.26	NA	NA	NA	NA	NA	NA	NA		NA			[84]
Rivers	Bonny/New Calabar river		25.6 ± 7.4 29.9 ± 5.9	0.06 ± 0.02 0.1 ± 0.03	0.9 ± 0.3 0.5 ± 0.09	NA	0.6 ± 0.1 0.3 ± 0.06	NA	1.1 ± 0.2 2.0 ± 0.3	0.4 ± 0.09 13.8 ± 3.2	NA	NA	NA	NA		NA	NA	NA	[124]
Rivers	Sombreiro river	NA	340.66 ± 106.21	0.022 ± 0.006	0.628 ± 0.495	5.37 ± 1.918	0.474 ± 0.401		4.27 ± 1.675	1.693 ± 0.957	NA	NA	NA	NA		NA			[87]

Table 3 (continued)

Area	Sampling site	No of site	Fe	Cd	Cu	Zn	Pb	Hg	Cr	Ni	Mn	Al	V	Co	Ag	As	Mg	Ca	References
Rivers	New Calabar River		160204 ±456	0.41 ±0.6	NA	NA	43.2 ±4.4	NA	NA	NA	NA	NA	NA	NA		NA			[91]
Rivers	Kalabari creek	5	Wet season: 6557.14 ±9702; Dry season: 7777.1 ±8172.63	Wet season: Dry season:	Wet season: 5.66 ±8.02 Dry season: 23.72 ±13.98	NA	Wet season: 1.24 ±1.23 ; Dry season: 2.04 ±1.89	NA		Wet season: 20.77 ±15.51; Dry season: 24.42 ±10.72	NA	NA	NA	NA		NA			[136]
Rivers	Okrika		NA	0.13	NA	NA	23.218	0.273	57.194	NA	NA	0.06	NA	NA		NA			[90]
Rivers	Bonny(NCR)	NA	29.9 ±5.9	0.1 ±0.03	0.5 ±0.09	2.8 ±0.7	0.3 ±0.06	NA	2 ±0.3	13.8 ±3.2	NA	NA	NA	0.5 ±0.06		NA			[137]
Rivers	Owubu creek, Ahoada	3 (ppb)	674 ±12.31	0.01 ±0.01	8.31 ±0.31	NA	6.22 ±0.16	0 ±0.00	NA	NA	NA	NA	NA	NA		NA			[95]
Rivers	Sombreiro river, Abonnema	7	< 0.001-0.053	0.13-0.31	1.054-7.10	0.0075-0.0520	NA	0.0762-0.3071	NA	NA	NA	NA	NA	NA		NA			[96]
Rivers	Elechi creek	mg/g	NA	Station 1: 0.24 ±0.02; Station 2: 0.06 ±0.12	NA	Station 1: 7.04 ±0.35 Station 2: 6.54 ±0.33	Station 1: 2.39 ±0.03 Station 2: 1.46 ±0.72	NA	NA	Station 1: 0.15 ±0.06 Station 2: 0.23 ±0.42	Station 1: 0.88 ±0.12 Station 2: 0.70 ±0.57	NA	NA	NA		NA			[97]
	DPR [171]	Tar. Value		100	0.3		35	85	20	140				36		200			
		Inter Value		380	10		210	530	240	720				190		625			

NA Not available; *Tar. Value* Target Value; *Inter Value* Intervention Value

Azuabie Creek in Rivers State and 1.49 ± 0.06 mg/kg at Forcados Terminal in Delta State [151]. Copper is essential for health, especially in synthesising many enzymes, including haemoglobin [152]. However, excessive copper consumption has been linked to altered liver and renal function [153]. *Tympanotonus fuscatus* and *Pachymelania aurita* from Bayelsa, in contrast, observed higher Cu concentration values of 33.3 ± 1.43 mg/kg and 57.0 ± 4.0 mg/kg, respectively [154].

The maximum permitted limit of lead contaminants in fish is 0.5 mg/kg, according to FSANZ [155]. Mean Pb values of 10.59 ± 9.12 mg/kg in *Mugil cephalus* [1] and 0.74 ± 0.002 mg/kg in *Calamichthys carabaricus* [156] were above the safety guidelines. According to Patrick-Iwuanyanwu et al. [156], the mean concentrations of seafood from the three Bayelsa markets (Swali, Mbiama and Kpansha) ranged from 0.016–0.741 mg/kg for Pb, Cd, Ni and Cr, 0.044 to 0.385 mg/kg for Cd, 0.430 to 2.283 mg/kg for Ni, and 1.504 to 4.943 mg/kg for Cr. While Ni and Cr exceeded the threshold level established by the World Health Organization [157], Pb and Cd were below the permissible limits. Dietary chromium regulates lipid and glucose metabolism [5]. However, excessive Cr can cause severe respiratory issues and liver, lung and kidney damage [158].

Tympanotonus fuscatus from freshwater ecosystems have been shown to have higher iron and zinc contents in their tissues than those from marine environments, perhaps due to the higher dissolved mineral content of the former [159]. Tissue concentrations of Hg, Zn, Fe and Pb also exceeded the WHO/FAO maximum levels for seafood. Acute lead (Pb) exposure can cause nausea, headaches, hypertension, stomach pain, renal failure, lethargy, sleeplessness, arthritis, psychosis and vertigo [160]. Mercury exposure causes acrodynia disease and can alter brain structure, causing tremors, cognitive loss, anger and optical or hearing impairment [161]. The heavy metal concentrations in most of the selected Niger Delta States were found to be higher compared to studies conducted in the Lagos Lagoon [162, 163]. In contrast, a comparative study by Onyena and Udensi [142] in Imo State, Nigeria, revealed that *Clarias gariepinus* (catfish) harvested from rivers and fish ponds accumulated high levels of Hg concentrations (> 1.40 mg/kg) in their sample sites, while the concentrations recorded in the Niger Delta states reviewed were generally lower. Furthermore, catfish sampled from the Nworie River exhibited a high Cd concentration (8.33 mg/kg). The elevated levels of heavy metals in the fishes were attributed to the discharge of waste products from industries, institutions, breweries and automobiles into the sampled rivers. The concentration of Fe recorded in the study was above 4 mg/kg, with the highest concentration being 30.8 mg/kg, which was lower than the values obtained from the ecosystems in the Niger Delta.

Table 4 The concentrations of heavy metals in several fish species from the Niger Delta

Area	Sampling site	Fishery	*Specie name*	No of sites	Fe	Cd	Cu	Zn	Pb	Hg	Cr	Ni	Mn	Al	V	Co	Ag	As	Mg	Ca	References
Bayelsa	Oporoma in Eker-emiv L.G.A	Prawn (mg/g)		3	NA	0.001 ± 0.00	NA	NA	0.001 ± 0.00	0.001 ± 0.00	NA	NA	NA	NA	NA	NA	NA		NA		Johnson et al. (2022)
Bayelsa	Sangana in Brass LGA	Oyster		3	NA	0.001 ± 0.00	NA	NA	0.001 ± 0.00	0.001 ± 0.00	NA	NA	NA	NA	NA	NA	NA		NA		
Bayelsa	River Nun		*Petrocephalus bane*			0.123 ±0.077			0.0056 ±0.0045		0.017 ±0.015	0.03 ±0.026									Alagoa et al. (2021)
Bayelsa	River Nun		*Chrysichthys aluuensis*			0.46 ±0.098			0.043 ±0.0153		0.036 ±0.037	0.26 ±0.163									
Bayelsa	River Nun		*Chrysichthys autatus*			0.526 ±0.241			0.086 ±0.0153		0.036 ±0.021	0.37 ±0.320									
Bayelsa	Swali Market	Open market	*Clarias gariepirus*			0.097 ± 0.002			0.564 ± 0.006		2.852 ± 0.001	0.430 ± 0.001									Patrick-Iwuanyanwu et al. (2020)
			Calamichthys carabaricus			0.265 ± 0.002			0.741 ± 0.002		2.521 ± 0.002	1.470 ± 0.002									
			Physella acuta			0.044 ± 0.001			0.089 ± 0.001		3.284 ± 0.001	2.151 ± 0.002									
			Scombrus linnaeus			ND			0.039 ± 0.001		1.736 ± 0.003	1.691 ± 0.002									
			Caretta caretta			0.052 ± 0.001			0.030 ± 0.002		1.544 ± 0.001	0.851 ± 0.001									
	Mbiama Market		*Clarias gariepirus*			0.061 ± 0.001			0.398 ± 0.001		4.943 ± 0.002	1.344 ± 0.001									
			Calamichthys carabaricus			0.169 ± 0.001			0.528 ± 0.002		3.169 ± 0.001	1.892 ± 0.002									
			Physella acuta			0.077 ± 0.001			0.052 ± 0.004		2.514 ± 0.001	2.283 ± 0.002									
			Scombrus linnaeus			0.062 ± 0.002			0.016 ± 0.002		2.176 ± 0.001	1.743 ± 0.002									
			Caretta caretta			ND			0.130 ± 0.001		2.283 ± 0.002	1.403 ± 0.001									
	Kpansha Market		*Clarias gariepirus*			0.160 ± 0.001			0.683 ± 0.007		3.086 ± 0.001	0.869 ± 0.001									
			Calamichthys carabaricus			0.385 ± 0.001			0.656 ± 0.001		3.276 ± 0.002	1.202 ± 0.002									
			Physella acuta			0.083 ± 0.002			ND		1.816 ± 0.001	1.623 ± 0.003									
			Scombrus linnaeus			0.174 ± 0.001			0.437 ± 0.003		1.504 ± 0.002	0.725 ± 0.002									
			Caretta caretta			0.088 ± 0.002			ND			1.273 ± 0.003									
Bayelsa	Ikoli creek		*Chrysichthys nigrodigitatus* (marine catfish)		66.36 ±0.10	ND		32.61 ±0.14	0.83 ±0.04		1.02 ±0.05										Ighariemu et al. (2019)
Bayelsa	Ikoli creek		Clarias gariepinus (African catfish)		88.23 ±0.09	ND		23.74 ±0.03	ND		ND										
Bayelsa	Ikoli creek		*Schibe mystus* (silver catfish)		85.54 ±0.26	ND		32.58 ±0.23	ND		0.5 ±0.11										
Bayelsa	Diebu creek	Freshwater		3	284.22		0.75		2.3							1.08		ND			Elijah et al. (2018)
Bayelsa	3 Local Government Bayelsa		*T. fuscatus*		1985 ± 4.89	NA	33.3 ± 1.43	77.7 ±9.19	NA	NA	NA	NA	NA	NA	NA	NA	NA		NA		Markmanuel et al. (2017)
			Pachymelania aurita		1260 ±159.2		57.0 ± 4.0	63.8 ± 9.6													
Bayelsa	Ikoli creek		*Clarias Gariepinus*		110.33 ±46.99	0.37 ±0.15	3.21 ±0.15	26.86 ±8.24	1.60 ±1.55												Elijah et al. (2016)
Bayelsa	Nembe	Brackish	Tympanotonus fuscatus			0.010-0.036					0.020-0.023	0.048-0.823							6.447-8.800	10.717-14.533	Ogamba et al. (2016)
Bayelsa	Brass Island River		*Tympanotonos fuscatus* var. *radula*			0.042			0.36	2.02								1.54			Obasi et al. (2015)
Bayelsa	Bayelsa	giant land snail	*A. achatina*		2358.3 ±35.67		33.8 ±6.25	75.3 ±4.87	29.5 ±4.42												Markmanuel and Horsfall (2015)
Bayelsa	Bayelsa	Garden snail	*L.flammea*		900 ±303.56		23.7 ±2.62	138.7 ±4.49	8 ±0.82												
Delta	Fish farm-River Anwai	Fish	*C. gariepnus*			0.73–1.41	175.88–245.32	248.19–292.33	0.22–0.26		0.59–1.69		ND-3.33								Ehiemere et al. (2022)
Delta	Forcado terminal		I. africana		13.74 ±1.57	0.05 ±0.00	1.34 ±0.02	3.46 ±0.17	1.44 ±0.09		0.04 ±0.01							0.54 ±0.02			Oyibo et al. (2017)

Table 4 (continued)

Area	Sampling site	Fishery	*Specie name*	No of sites	Fe	Cd	Cu	Zn	Pb	Hg	Cr	Ni	Mn	Al	V	Co	Ag	As	Mg	Ca	References
			Scomber scrombru (Mackerel)		46.59 ±0.34	0.01 ±0.00	5.95 ±0.03	4.75 ±0.01	3.85 ±0.29		0.57 ±0.02							0.01 ±0.00			
			Cololabis saira (Barracuda)		16.92 ±29.3	0.025 ±0.01	3.49 ±0.05	10.56 ±0.18	1.73 ±0.02		0.47 ±0.02							0.01 ±0.00			
			Tylosurus crocodilus (Needle fish)		10.92 ±1.89	0.07 ±0.01	2.43 ±0.1	8.46 ±0.01b	1.55 ±0.01		0.14 ±0.02							ND			
			Oreochromis niloticus (Tilapia fish)		38.73 ±0.13	0.68 ±0.01	1.54 ±0.12	5.44 ±0.01b	4.77 ±0.02		2.69 ±0.06							0.01 ±0.00			
			Trichiurus lepturus (Cutlass fish)		21.56 ±0.18	0.46 ±0.02	1.15 ±0.03	2.43 ±0.01	2.45 ±0.02		1.16 ±0.15							ND			
			Mugil cephalus (Mullet)		20.48 ±0.02	0.05 ±0.00	1.49 ±0.06	5.54 ±0.02	5.54 ±0.02		0.45 ±0.01							ND			
Delta	Benin river	shrimp	*Macrobrachium macrobrachion*		114.78	0.93	60.83	84.02	22.39			33.03	24.78			18.01					Ezemonye et al. (2019)
		Fish	*Brycinus longipinnis*		66.13	0.98	7.05	51.64	36.04			53.57	39.45			31.14					
Rivers	Bonny	Crab	*Callinectes amnicola*	3	7.05-10.67	NA	0.15-0.21	4.45-9.22	NA	NA	NA	NA	NA				NA	NA			Akankali and Davies (2021)
Rivers	Eagle Island River Mgbu-oshi-mini	Periwinkle	*Tympanotonos fuscatus*	25	Salt water:			Salt water:	Salt water:	Salt water:	NA	NA	NA				NA	NA			Chioma et al. (2021)
					3. 3 Fresh water:			0.92	0.89	0.54											
					3.08			Fresh water:	Fresh water:	Fresh water:											
								0.57	0.75	0.46											
Rivers	Isaka-Bundu	Fish	*Periophthalmus papillio*	3	11.973	NA	0.716	104.814	NA	NA	NA	NA	NA				NA	NA			Odekina (2021)
Rivers	Woji creek	Bivalve	*Mugil cephalus*	5	NA	24.62 ±12.11	33.48 ±15.54	NA	10.59 ±9.12	NA	0.43 ±0.66	NA	NA				NA	NA			Ihunwo et al. (2020)
Rivers	New Calabar river	Periwinkle	*Callinectus amnicola*	5	NA	Dry:	Dry:		Dry:	NA	Dry:	Dry:	NA				NA	Dry:			Uwah et al. (2020)
						0.002mg/kg	16.3		6.88		7.37	5.63						0.012			
						Wet:	Wet:		Wet:		Wet:	Wet:						Wet:			
						0.002	12.4		7.49		5.54	7.48						0.006			
Rivers	New Calabar river	Crab	*Tympanotonus fuscatus*	5	NA	Dry:	Dry:	NA	Dry:	NA	Dry:	Dry:	NA				NA	Dry:			
						0.02	20.5		7.34		11	9.1						0.28			
						Wet:	Wet:		Wet:		Wet:	Wet:						Wet:			
						0.17	14.7		8.16		9.36	7.24						0.01			
Rivers	Bonny river	Crab	*Callinectes amnicola*	NA	NA	Dry season: < 0.01	NA	NA	Dry season:	NA	NA	Dry season:	NA				NA	NA			Akankali et al. (2019)
						Wet season:			0.17-0.34			0.31-0.54									
						< 0.01			Wet season:			Wet season:									
									0.22-0.27			0.24-0.38									
Rivers	Buguma creek	Oysters	*Crassostrea gasar*	NA	NA	Fresh:	Fresh:	Fresh:	Fresh:	NA	NA	NA	NA				NA	NA			Abu and Eli (2018)
						0.04 ±0.01	0.98 ±0.09	0.11 ±0.05	0.20 ±0.02												
						Smoked:	Smoked:	Smoked:	; Smoked:												
						0.21 ±0.06 (ppm).	1.32 ±0.02	0.86 ±0.07	0.50 ±0.03												
Rivers	Buguma creek	Shrimp	*Penaeus notialis*	NA	NA	Fresh:	Fresh:	Fresh:	Fresh:	NA	NA	NA	NA				NA	NA			
						0.9 ±0.02	1.04 ±0.01	0.25 ±0.02	0.50 ±0.05												
						Smoked:	Smoked:	Smoked:	; Smoked:												
						0.30 ±0.06	1.13 ±0.04	0.11 ±0.04	0.12 ±0.03												
Rivers	Ebubu &Ali-mini	Catfish			Ebubu:25.58 ± 1.12	Ebubu:0.15 ±0.02	NA	Ebubu:15.80 ±0.69	Ebubu:1.43 ±0.06;	NA	Ebubu:ND;	Ebubu:0.53 ±0.04	NA				NA	NA			Ogunka-Nnoka et al. (2018)
					; Alimini:51.63 ±0.92	Alimini:0.17 ±0.03		Alimini:29.89 ± 1.68	Alimini:2.88 ±0.14		Alimini:1.82 ±0.23	; Alimini:0.59 ±0.03									
Rivers	Azuabie creek, Okrika/PH	Fish		4	NA	0.4 mg/kg	NA	31.6	3.49	NA	3.6		NA				NA	NA			Ekweozor et al. (2017)

Table 4 (continued)

Area	Sampling site	Fishery	*Specie name*	No of sites	Fe	Cd	Cu	Zn	Pb	Hg	Cr	Ni	Mn	Al	V	Co	Ag	As	Mg	Ca	References
Rivers	Okuluagu creek	Fish			NA	0.74	NA	43.56	3.95	NA	2.79						NA	NA			
Rivers	Azuabie creek	Fish	*Mugil cephalus*	3	NA	0.33 ±0.09	4.12 ± 1.07	NA	2.96 ±0.67	NA	1.96 ±0.81	1.82 ±0.40	NA				1.2 ±0.33	NA			Moslen (2017)
Rivers	Ogoni	Shellfish	*C. Pallidus*	2	Bodo:1768.6 ±5.11 B-dere:2593.2 ±2.48	Bodo:0.96 ±0.63 B-Dere:1.54 ±0.03			Bodo:2.12 ±0.12 B-Dere:1.68 ±0.02	NA	Bodo:1.84 ±0.42 B-Dere:2.76 ±0.02	Bodo:4.35 ±0.06 B-Dere:5.28 ±0.03	NA				NA	Bodo:2.13 ±0.02 B-Dere:2.73 ±0.05			Nkpaa et al. (2017)
Rivers	Ogoni	Shellfish	*T. fucastus*	2	Bodo:2257.6 ±1.67 B-Dere:2004.6 ±3.58	Bodo:1.43 ±0.05 B-Dere:2.12 ±0.02			Bodo:3.12 ±0.09 B-Dere:2.56 ±0.05	NA	Bodo:4.49 ±1.09 B-Dere:3.97 ±0.23	Bodo:8.24 ±1.03 B-Dere:5.98 ±0.65	NA				NA	Bodo:2.67 ±0.11 B-dere:2.45 ±0.00			
Rivers	Ogoni	Shellfish	*U. tangeri*	2	Bodo:1868.2 ±2.86 B-Dere:1256.2 ±4.79	Bodo:3.82 ±0.08 B-Dere:2.54 ±0.01			Bodo:3.67 ±0.22 B-Dere:3.42 ±0.14	NA	Bodo:2.57 ±1.24 B-Dere:2.23 ±0.12	Bodo:6.67 ±0.09 B-Dere:8.34 ±0.05	NA				NA	Bodo:4.89 ±0.03 B-Dere:3.76 ±0.07			
Rivers	Ogoni	Shellfish	*C. gasar*	2	Bodo:2074.0 ±3.69 B-Dere:2468.0 ±6.68	Bodo:1.20 ±0.03 B-Dere:1.46 ±0.02			Bodo:2.28 ±0.05 B-Dere:1.64 ±0.06	NA	Bodo:3.46 ±0.08 B-Dere:2.76 ±0.04	Bodo:8.23 ±0.14 B-Dere:7.56 ±0.06	NA				NA	Bodo:2.36 ±0.06 B-Dere:2.97 ±0.02			
Rivers	Ogale stream	African catfish	*Clarias gariepinus*	15	NA	Elele:0.2 ±0.02 Ogale:0.32 ±0.03	NA	Elele:30 ±2 Ogale:30 ±1	Elele:3 ±0.10 Ogale:3 ±0.14	NA	Elele:2 ±0.2; Ogale:4 ±0.1	Elele:0.4 ±0.03 ; Ogale:0.6 ±0.03	NA				NA	NA			Abarikwu et al. (2017)
Rivers	Azuabie creek	Fish	*Sarotherodon melanotheron*		NA	0.38 ±0.08	5.59 ±1.06		5.12 ±1.23	NA	2.69 ±1.44	1.94 ±0.34	NA				1.02 ±0.34	NA			Moslen and Mie-baka (2017)
Rivers	Azuabie creek	Crab	*Callinectes amnicola*	Ug/g	NA	0.73 ±014	12.94 ±3.53	NA	5.67 ±1.03	NA	2.32 ±0.71	2.76 ±0.71	NA				1.83 ±0.71	NA			
Rivers	Bonny river	Fish	*Genyonemus lineatus*	2 (ug/g)	102.00-216.03	0.00-1.50	3.50-45.00	14.00-49.90	0.20-0.50	NA	NA	5.33-9.60	9.34-11.02				NA	NA			Abarshi et al. (2017)
Rivers	Finima creek	Fish	*Genyonemus lineatus*		646.25-801.50	0.00-1.50	15.75-52.64	124.50-166.50	3.63-6.38	NA	NA	30.00-76.50	202.50-323.00				NA	NA			
Rivers	Bomu river	Crab	*Callinectes gladiator (ug/g)*	NA	NA	Egg: ND Exoskelecton: ND Flesh: ND	Egg: 45.215 Exoskeleton: 37.217 Flesh: 64.392	Egg: 19.823 Exoskeleton: 13.807 Flesh: 56.421	Egg: ND Exoskeleton: 44.036 Flesh: 31.12	NA	Egg: 64.222 Exoskeleton: 13.874 Flesh: 54.354	Egg: 47.501 Exoskeleton: 16.824 Flesh: 51.973	NA				NA	NA			Marcus and Edori (2016)
Rivers	Oginigba	Crab	*Callinectes gladiator(ug/g)*	NA	NA	Egg: ND Exoskelecton: ND Flesh: ND	Egg: 40.111 Exoskeleton: 15.203 Flesh: 66.58	Egg: 197.783 Exoskeleton: 17.68 Flesh: 87.51	Egg: 5.555 Exoskeleton: 3.055 Flesh: 7.65	NA	Egg: 28.131 Exoskeleton: 21.333 Flesh: 78.442	Egg: 33.402 Exoskeleton: 41.053 Flesh: 101.62	NA				NA	NA			
Rivers	Andoni river	Oyster	*Crassostrea gasar*	ug/g	NA			42.69 ±1.81	0.53 ±0.02	NA	NA		NA				NA	NA			Woke et al. (2016)
Rivers	Gokana Bodo creek	Crab	*Callinectes amnicola*	3	Station 1: Leg-68.27 ±4.00; Carapace- 1285.68 ±85.69 ; Muscle-138.73 ±19.81; Gill-1033.25 ±33.25	Station 1: Leg:0.43 ±0.13 Carapace: 2.40 ±0.26 Muscle: 0.03 ±0.03 Gill: 0.38 ±0.44	NA	NA	Station 1: Leg:1.13 ±0.09 ; Carapace: 0.47 ±0.20 ; Muscle: 0.62 ±0.02 ; Gill: 0.42 ±0.02	NA	NA	NA	NA				NA	NA			Abu and Nwokoma (2016)
Rivers	Gokana Bodo Creek	Crab	*Callinectes amnicola*	3	Station 2: Leg: 182.35 ±16.20; Carapace: 161.90 ±1.90 ; Muscle:	Station 2: Leg: 2.81 ±0.16 ; Carapace: 2.40 ±0.26; Muscle: 1.13 ±1.19			Station 2: Leg: 0.30 ±0.25 Carapace: 0.00 ±0.00 Muscle: 0.00 ±0.00	NA	NA	NA	NA				As	NA			

Table 4 (continued)

Area	Sampling site	Fishery	*Specie name*	No of sites	Fe	Cd	Cu	Zn	Pb	Hg	Cr	Ni	Mn	Al	V	Co	Ag	As	Mg	Ca	References
					101.08 ±0.95; Gill: 318.73 ±33.16	; Gill: 2.02 ±0.02			Gill: 0.70 ±0.10												
Rivers	Gokana Bodo Creek	Crab	*Callinectes amnicola*	3	Station 3: Leg: 475.31 ±6.05; Carapace: 771.68 ±34.86 ; Muscle: 48.77 ± 1.49 ; Gill: 1440.02 ±30.57	Station 3: Leg: 3.78 ±0.15 ; Carapace: 5.43 ±0.31; Muscle: 0.00 ±0.00; Gill: 1.48 ±0.27			Station 3: Leg: 0.33 ±0.33 Carapace: 0.00 ±0.00 Muscle: 0.00 ±0.00 Gill: 0.00 ±0.00	NA	NA	NA	NA				NA	NA			
Rivers	Azuabie creek	Mudskipper	*Periophthalmus sp.*	ug/g	NA	NA	1.92	NA	3.09	NA	3.16	2.91	NA				2.57	NA			Moslen and Miebaka (2016)
Rivers	Ogoni	Seafood species	*T.guineensis*	3	Kaa:625 ± 1.22 B-Dere:862 ±0.79 Bodo:1080 ± 2.33	Kaa:0.65 ±0.09 B-dere:0.76 ± 0.56 Bodo:1.00 ±0.23		Kaa:29.5 ± 0.34 B-Dere:46.0 ±0.30 Bodo:30.9 ±0.25	Kaa:13.0 ±0.18 B-Dere:17.5 ±0.11 Bodo:16.0 ±0.27	NA	Kaa:3.75 ±0.11 B-Dere:5.65 ±0.02 Bodo:9.98 ±0.12	NA	Kaa:54.9 ± 1.23 B-Dere:53.1 ±0.15 Bodo:60.9 ±0.23				NA	NA			Nkpaa et al. (2015)
Rivers	Ogoni	Seafood species	*L.falcipinis*	3	Kaa:293 ± 1.22 B-Dere:1039 ±0.89 Bodo:762 ± 2.43	Kaa:0.52 ±0.05 B-Dere:1.50 ± 0.34 Bodo:0.83 ±0.20		Kaa:23.1 ± 0.13 B-Dere:26.1 ±0.36 Bodo:30.8 ±0.39	Kaa:10.8 ±0.24 B-Dere:7.88 ± 2.20 Bodo:9.89 ±0.23	NA	Kaa:1.95 ±0.05 B-Dere:6.18 ±0.18 Bodo:6.75 ± 1.04	NA	Kaa:10.1 ± 2.33 B-Dere:8.67 ±0.20 Bodo:12.0 ±0.54				NA	NA			
Rivers	Ogoni	Seafood species	*P. notialis*	3	Kaa:1040 ± 1.29 B-Dere:1283 ± 1.76 Bodo:1522 ± 2.33	Kaa:0.90 ±0.05 B-Dere:0.96 ±0.17 Bodo:1.37 ±0.11		Kaa:33.2 ± 0.25 B-Dere:32.1 ±0.09 Bodo:33.9 ±0.28	Kaa:24.8 ± 0.26 B-Dere:31.3 ±0.12 Bodo:7.01 ± 1.34	NA	Kaa:2.90 ±0.14 B-Dere: 4.85 ±0.12 Bodo:6.54 ±0.02	NA	Kaa:22.2 ± 0.48 B-Dere:25.1 ±3.54 Bodo:26.9 ±0.29				NA	NA			
Rivers	Ogoni	Seafood species	*C. Pallidus*	3	Kaa: 860 ±0.33 B-dere:1038 ± 1.18 Bodo:1287 ± 1.23	Kaa:0.78 ±0.13 B-Dere:1.80 ±0.22 Bodo:1.65 ±0.21		Kaa:30.9 ±0.18 B-Dere:43.0 ±0.45 Bodo:31.0 ±0.17	Kaa:21.6 ± 0.06 B-Dere:23.1 ±0.18 Bodo:26.0 ± 2.43	NA	Kaa:3.75 ±0.01 B-Dere:6.26 ±0.10 Bodo:4.20 ±0.01	NA	Kaa:39.2 ± 0.01 B-Dere:27.4 ± .0.76 Bodo:15.4 ±0.19				NA	NA			
Rivers	Sombreiro river	Crab	*Callinectes*		123.42 ±7.35	0.003 ±0.00	45.31 ±2.92	52.47 ±3.18	0.24 ±0.04	NA	41.74 ±2.17	39.43 ± 1.77	NA				NA	NA			Wokoma (2015)
Rivers	Soku, mangrove	Periwinkle:mg/kg	*Tympanotonous fascatus*	NA	NA	NA	Shell: <0.10 Soft tissue: <0.10	Shell: 56.6 Soft tissue: 1.612	NA	Shell: < 1.00 Soft tissue: < 1.00	NA	Shell: < 1.00 Soft tissue: < 1.00	NA				Shell: 1.8 Soft tissue: 2.4	NA			Nwoko et al. (2014)
Rivers	Owubu creek, Ahoada	Fish	*Tilapia zilli*	3 (ppb)	Tissue:72.12 ± 10.69; Digestive:0.00 ±0.00	Tissue:0.00 ±0.00; Digestive:0.00 ±0.00	Tissue:4.29 ± 1.22; Digestive:2.55 ± 1.38	NA	Tissue:0.12 ±0.13; Digestive: 0.13 ±0.11	Tissue:0.00 ±0.00 ; Digestive:0.00 ±0.00	NA	NA	NA				NA	NA			Friday et al. (2013)
Rivers	Ogoni	Fish	*Tilapia queneesis*	3	Kaa:627 ± 1.89; B-dere:860 ±0.99 ; Bodo:1079 ± 4.33	Kaa:0.64 ±0.00; B-Dere:0.77 ±0.01 ; Bodo:0.97 ±0.01		Kaa:28.7 ±0.12 ; B-Dere:45.5 ±0.28; Bodo:31.1 ±0.33	Kaa:12.9 ± 0.11; B-Dere:16.2 ±0.13; Bodo:15.7 ±0.31	NA	Kaa:3.72 ±0.07; B-Dere:5.63 ±0.08; Bodo:9.97 ±0.10	NA	Kaa:55.4 ± 0.24 ; B-Dere:52.9 ±0.08 ;Bodo:61.2 ±0.11				NA	NA			Nkpaa et al. (2013)
Rivers	Ogoni	Mullets	*Liza falcipinis*	3	Kaa:290 ±0.97; B-Dere:1037 ± 1.01 ; Bodo:760 ±4.62	Kaa:0.50 ±0.00 ; B-Dere:1.48 ±0.01; Bodo:0.85 ±0.01		Kaa:22.5 ±0.20 ; B-Dere:25.8 ±0.47; Bodo:32.1 ±0.09	Kaa:10.1 ±0.18 ; B-Dere:7.45 ±3.67 ; Bodo:9.99 ±0.01	NA	Kaa:1.94 ±0.08 ; B-Dere:6.18 ±0.08; Bodo:6.78 ±0.02	NA	Kaa:9.83 ± 0.13 B-Dere:8.63 ± 0.19 Bodo:11.8 ±0.06				NA	NA			
Rivers	Ogoni	Crabs	*Callinectes pali*	3	Kaa:857 ±0.12 ; B-Dere:1038 ± 1.10; Bodo:1285 ±2.74	Kaa:0.78 ±0.01; B-Dere:1.79 ±0.01 ; Bodo:1.64 ±0.39		Kaa:31.4 ±0.12 ; B-Dere:42.6 ±0.66; Bodo:30.8 ±0.11	Kaa:20.9 ±0.27 ; B-Dere:22.9 ±0.08 ; Bodo:27.2 ±0.05	NA	Kaa:3.77 ±0.02 ; B-Dere:6.27 ±0.05; Bodo:4.18 ±0.29	NA	Kaa:38.9 ±0.57 B-Dere:27.6 ±0.03 Bodo:15.5 ±0.16				NA	NA			
Rivers	Ogoni	Shrimps	*Penaeus notialis*	3	Kaa:1038 ± 1.37; B-Dere:1281 ± 1.24; Bodo:1520 ± 1.62	Kaa:0.86 ±0.02 ; B-Dere:0.95 ±0.04; Bodo:1.38 ±0.01		Kaa:30.8 ±0.21 ; B-Dere:31.7 ±0.07; Bodo:34.3 ±0.04	Kaa:23.5 ±0.35; B-Dere:30.6 ± 0.27 ; Bodo:6.91 ±0.06	NA	Kaa:2.92 ±0.03 ; B-Dere:4.84 ±0.04 ; Bodo:6.52 ±0.09	NA	Kaa:21.9 ±0.76 B-Dere:24.7 ± 3.49 Bodo:26.6 ±0.29				NA	NA			

Table 4 (continued)

Area	Sampling site	Fishery	*Specie name*	No of sites	Fe	Cd	Cu	Zn	Pb	Hg	Cr	Ni	Mn	Al	V	Co	Ag	As	Mg	Ca	References
Rivers	Ekerekana creek/ Okpoka-Toru river	Periwinkle	*Pachymelania aurita*	10 (ug/g)	NA	0.391 ± 0.393			1.241 ± 0.012	NA	NA	11.058 ± 12.509	NA				NA	NA			Marcus et al. (2013)
Rivers	Ekerekana creek/ Okpoka-Toru river	Oysters	*Crassostrea rhizophorae*	10	NA	0.094 ± 0.041			1.193 ± 0.697	NA	NA	19.923 ± 27.036	NA				NA	NA			
Rivers	Ekerekana creek/ Okpoka-Toru river	Shellfish	*P.koelreuteri*	10		0.093 ± 0.090			0.212 ± 0.228	NA	NA	11.131 ± 16.817	NA				NA	NA			
Rivers	Ekerekana creek/ Okpoka-Toru river	Fish	*Mugil cephalus*	10	NA	ND			1.904 ± 1.944	NA	NA	16.591 ± 18.132	NA				NA	NA			
Rivers	Ekerekana creek/ Okpoka-Toru river	Fish	*Sardinella marderensis*	10	NA	ND			0.815 ± 0.932	NA	NA	8.039 ± 18.007	NA				NA	NA			
Rivers	Ekerekana creek/ Okpoka-Toru river	Fish	*Tilapia guianeensis*	10		ND			0.627 ± 1.110	NA	NA	0.567 ± 0.658	NA				NA	NA			
Rivers	New Calabar river	Periwinkle	*Tympanuotonus fuscatus*	5	Rainy season: 439.60 ± 264.31 Dry season: 1472.22 ± 937.28	ND	Rainy season: 4.54 ± 3.55 ; Dry season: 11.10 ± 2.76		Rainy season: 0.57 ± 0.78 ; Dry season: 0.34 ± 0.19	NA	NA	Rainy season: 15.01 ± 10.49; Dry season: 12.55 ± 3.79	NA				NA	NA			Kpee (2012)
Rivers	Elechi creek	Fish	*S. melanotherun*	2	NA	Station 1: 0.10 ± 0.04; Station 2: 0.09 ± 0.00	NA	Station 1: 4.23 ± 0.01 Station 2: 4.02 ± 0.15	Station 1: 1.58 ± 0.03 Station 2: 1.33 ± 0.18	NA	NA	Station 1: 0.45 ± 0.01 ; Station 2: 0.40 ± 0.03	Station 1: 1.15 ± 0.01 ; Station 2: 0.23 ± 0.2				NA	NA			Vincent-Akpu and Mmom (2012)

NA Not available; *ND* Not detected

Table 5 The concentrations of heavy metals in several plants from the Niger Delta

Area	Sampling site	Plant Part	Species name	Fe	Cd	Cu	Zn	Pb	Hg	Cr	Ni	Mn	Al	V	Co	Ag	As	Mg	Ca	Se	References
Bayelsa	Amasoma Community	Edible part/ vegetable	*Carica papaya*		5.990 ± 0.06	NA	1.317 ± 0.02	1.090 ±0.01	NA	NA	0.212 ±0.03	NA	NA	NA	NA	NA		NA			[179]
Bayelsa	Amarata Yelya	Bark, Fruits, Leaves, Roots	*Carica papaya*	NA	0.26 ± 0.039	NA	NA	0.97 ± 0.18	NA	ND	0.49 ± 0.154		NA			NA	0.23 ± 0.003	NA			[183]
Bayelsa	Otuoke	Root	*Talinum triangutare*	1350 ± 0.32	<0.001	10.9 ±0.16	24.1 ± 0.16	1.43 ± 0.02	NA	<0.001	<0.001	74.04 ± 0.44	NA	<0.001	<0.001	NA	<0.001	NA			[110]
		Shoot		346 ± 0.41	<0.001	14.2 ± 0.32	14.3 ± 0.33	3.81 ±0.01	NA	<0.001	<0.001	40.9 ±0.28	NA	<0.001	<0.001	NA	<0.001	NA			
Bayelsa	Kolo Creek	Root		4290 ± 0.52	<0.001	14.2 ± 0.16	147.3 ± 0.24	1.43 ± 0.02	NA	<0.001	<0.001	249.2 ± 0.18	NA	<0.001	<0.001	NA	<0.001	NA			
		Shoot		3580 ±0.49	<0.001	20.9 ±0.16	181.3 ±0.32	1.43 ±0.03		<0.001	<0.001	293.5 ±0.53		<0.001	<0.001		<0.001				
Bayelsa	Kpanahia and Swali market	Vegetable	16 Vegetable samples	NA	0.028 - 1.487	NA	NA	0.016 -1.387	NA	0.893 - 2.478	0.093 - 3.625	NA	NA	NA	NA	NA		NA			[180]
Delta State	Warri refining Petrochemical company, Ugbokodo and Jeddo	Vegetables	*Telfairia accidentalis* (fluted pumpkin), *Vernonia amygdalina* (bitter leaves), *Ocimum gratissmum* (scent leaves), *Amaranthus hybridis* (green african spinach), *Amaranthus viridis* (red african spinach)	NA	0.010 - 0.230	NA	NA	0.019-0.178	NA	0.383-2.331	0.411 - 2531										[184]
Delta	Agbor- Asaba express way	Dry Cassava leaf and Tuber		21.70 ±3.45 and 9.62 ±3.93	NA	NA	4.15 ±7.01 and 1.15 ±0.44	3.46 ±1.58 in leaves	NA	5.12 ± 2.75 and 0.37 ± 0.63											[106]
Delta	Asaba	Fresh Tomatoes friuts	From 3 sample points	6.38, 5.09, 6.00	NA	0.41, 1.35, 1.44	3.33, 2.98, 3.73	2.96, 3.01, 3.92	0.01, 0.15, 0.01	0.63	1.35, 1.88, 1.82	3.83, 3.01, 3.05									[185]
Rivers	Onelga LGA	Edible parts	V. amygdalina, T.triangula, reA. esculentus, T.occidentalis	61.589-101.520	0.364-2.977	12.033-46.536		0.168-4.908	NA	NA	2.780-10.241	NA			NA		0.157-2.633	NA		NA	[178]
Rivers	Ebubu & Alimini	Pumpkin	*Telfairia accidentalis*	Ebubu:121.39 ±1.21; Alimini:5318.34 ±120.95	Ebubu:0.38 ±0.03 ; Alimini:0.75 ±0.06	NA	Ebubu:22.38 ±0.89 ; Alimini:34.22 ±0.32	Ebubu:5.13 ±0.17 ; Alimini:9.75 ±0.25	NA	ND	Ebubu:2.39 ±0.14 ; Alimini:3.09 ±0.17	NA			NA		NA	NA		NA	[116]
Rivers	Choba, Kpean, and Bodo City	Root tubers	*Manihot esculenta*, *Colocasia esculenta*, and *Dioscorea alata*	6.3 ±1.18-118.6 ±0.19		NA	NA	0.01 ±0.001-0.09 ±0.02	NA	0.2 ±0.01-0.84 ±0.04	0.01 ±0.002-0.63 ±0.04	2.11 ±0.03-11.8 ±2.12			NA		NA	NA		NA	[115]
Rivers	Ogale & Elele	Edible vegetable	*Telfairia accidentalis*	NA	Elele:0.3 ±0.03; Ogale:0.8 ±0.1	NA	Elele:1.2 ±0.03; Ogale:34.2 ±0.3	Elele:3.03 ±0.10; Ogale:10 ±0.30	NA	Elele:<0.05; Ogale:<0.05	Elele:ND; Ogale:3.1 ±0.2	NA			NA		NA	NA		NA	[117]
Rivers	Alakahia & Eleme	Vegetables & root tubers		NA	0.00-0.46	0.03-0.93	NA	0.00-0.55	NA	0.00-1.26	0.11-2.78	NA			NA		NA	NA		NA	[107]

Table 5 (continued)

Area	Sampling site	Plant Part	Species name	Fe	Cd	Cu	Zn	Pb	Hg	Cr	Ni	Mn	Al	V	Co	Ag	As	Mg	Ca	Se	References
Rivers	Port-Harcourt	Forest leafy vegetable	Ocimum gratissimum(L) Lamiacea	8.87	0.022	0.218	0.044	0.725	0	0.022	0.416	0.45			0.343		0.003	1.63		0.03	[186]
			Ocimum bassilicum (L) Lamiacea	7.63	0.032	0.97	0.055	0.38	0.01	2.615	0.665	0.5			0.118		0.015	1.308		0.06	
			Pterocarous soyauxii (Jacq.) Fabaceae	6.72	0.028	0.375	0.053	0.777	0.01	1.464	0.527	0.74			0.197		0.009	0.805		0.02	
			Piper guineense (L) Piperaceae	5.8	0.025	0.936	0.068	1.004	0.02	3.792	0.614	0.54			0.18		0.025	1.235		0.03	
			Gongronema latifolia (Benth.) Aslepiadaceae	8.97	0.056	0.718	0.046	0.648	0.01	1.959	0.388	4.29			0.091		0.006	1.556		0.02	
			Liasanthera africana (P.Beauv.) Icacinaceae	7.18	0.057	0.629	0.057	0.603	0.01	2.106	0.496	6.03			0.104		0.008	0.609		0.05	
			Heinsia crinata (Afzel.) Rubiaceae	4.69	0.076	1.165	0.061	0.468	0.01	0.409	0.516	1.08			0.097		0.012	1.321		0.07	
			Gnetum africana (Welw.) Gnetaceae	6.88	0.058	0.995	0.045	0.172	0.01	3.743	0.519	4.05			0.058		0.008	1.33		0.05	
Rivers	Gokana	Bitter leaf	*Vernonia amygdelina*	0.82 ± 0.00	0.08 ± 0.00	NA	0.21 ± 0.01	0.24 ± 0.00	NA	0.2 ± 0.01	NA	3.05 ± 0.01			NA		NA	NA		NA	[120]
Rivers	Gokana	Waterleaf	*Talinum triangulare*	1.35 ± 0.00	0.07 ± 0.00	NA	0.13 ± 0.00	0.22 ± 0.00	NA	0.11 ± 0.00	NA	1.92 ± 0.00			NA		NA	ND		NA	
Rivers	Gokana	Cassava	*Manihot esculenta*	< 0.0001	< 0.0001	NA	0.1 ± 0.00	< 0.0001	NA	< 0.0001	NA	0.89 ± 0.01			NA		NA	NA		NA	
Rivers	Gokana	Cocoyam	*Xanthotosoma sagittifolium*	10.5 ± 0.01	0.02 ± 0.00	NA	1.58 ± 0.06	0.11 ± 0.00	NA	0.02 ± 0.00	NA	0.67 ± 0.00			NA		NA	NA		NA	
Rivers	Port-Harcourt	Vegetable	*Vernonia amygdalina*	NA	1.25-1.50	7.75-11.00	79.75-186.95	6.25-8.00	NA	1.50-10.25	15.75-19.25	9.75-62.75			1.75-3.00		NA	NA		NA	[187]
			Ocimum gratissimum																		
			Talinum triangulare																		
			Telfairia occidentalis																		
Rivers	Kaani, Bori	Fruits: avocado pear, orange,pawpaw pineapple		25.7	0.13	2.31	7.54	5.01	NA	NA	3.34	1.5			2.07		NA	NA		NA	[188]
		DPR [171]	Tar. Value		100	0.3		35	85	20	140				36		200				
			Inter Value		380	10		210	530	240	720				190		625				

NA Not available

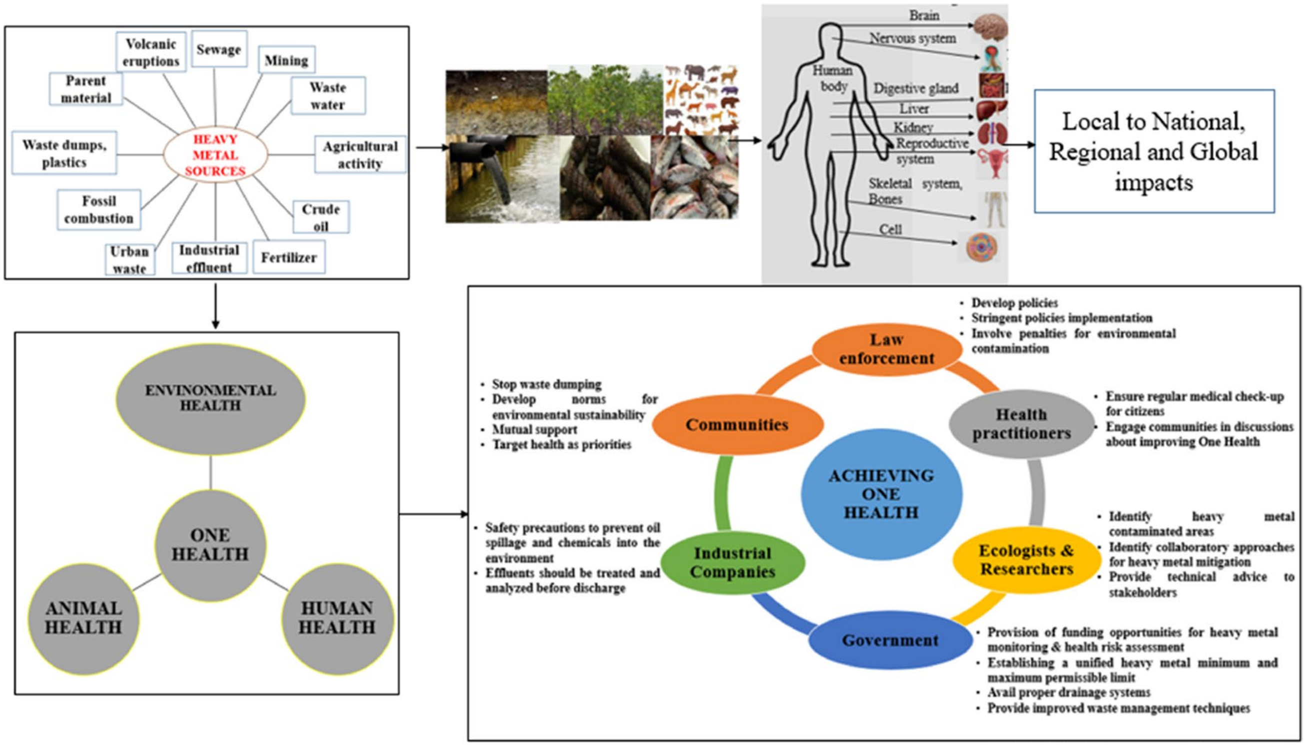

Fig. 3 Collaborative pathway towards achieving One Health objectives

Heavy Metals in Plants of Niger Delta

Increased metal accumulation in plants occurs after long-term exposure to soils contaminated by heavy metal deposition because of direct interactions between sediment and plants. Studies have been conducted on heavy metals in plant species (Table 5) [113, 164, 169]. Iron, cadmium zinc, lead and nickel levels in *Telfairia accidentalis* were higher in Alimini than in Ebubu city in Rivers state [114]. Root tubers of *Manihot esculenta* in Choba, Kpean and Bodo City exhibited elevated amounts of heavy metals, and the heavy metal hazard index values for children were > 1. Thus, it was determined that the heavy metal contamination of root tubers cultivated in Ogoni land Rivers state poses a serious health concern to the local population, particularly children who constantly consume the tubers [113].

Similarly, Patrick-Iwuanynwu and Chioma [166] found high levels of heavy metals in 16 vegetables purchased from Kpanahia and Swali markets in Bayelsa state, leading them to conclude that market-bought vegetables may be a significant component in the heavy metal load of consumers. High quantities of Fe, Zn, and Cr were found in dried cassava leaves and tubers from farms along a major highway in Delta state [109], even more significant than those found in crops grown in an oil-polluted area of Gokana Rivers state [119]. Omeka and Igwe [173] conducted a study at mining sites in Nigeria, which revealed that heavy metals have a higher tendency to accumulate in the leaves of plants rather than in the tubers. In the case of Challawa in Kano State, Nigeria, the concentration of Cd and Cr in vegetables exceeded the permissible limits, posing a significant health risk for the residents who consume these vegetables [174].Therefore, bioaccumulating these heavy metals in plants from contaminated water, soils and sediments poses a significant human health risk.

Heavy Metals and Health Risks Assessments: Implications for the Niger Deltans

Communicable diseases (CDs) are caused by pathogens and the disease severity depends on several factors such as the prevalence, virulence of the pathogen, transmission and host response [175]. Heavy metal deficiencies or toxicities and CDs contribute significantly to the global burden of morbidity and death. The global disease burden (GDB) from zinc deficiency was 9.14 million disability-adjusted life years (DALYs) in 2010 [176]. Iron (Fe) depletion from hemolytic malaria and parasitic and bacterial diseases such as hookworm, trichuriasis, amoebiasis and schistosomiasis causes Fe-deficiency anaemia [175]. Also, human immunodeficiency virus (HIV)-infected persons from the

USA exhibited higher concentrations of cadmium, lead and mercury than non-HIV-infected individuals [177]. Xu et al. [177, 178] concluded that HIV-infected people had more chronic ailments, such as cardiovascular disease, due to cadmium exposure. Folorunso et al. [179] found that HIV-positive patients had decreased serum zinc levels and higher blood lead, cadmium and mercury levels.

Malaria is reported to be prevalent in several gold-mining sites, a major source of heavy metal contamination and global disease burden [180]. Malaria and gold mining exposure were linked in the Brazilian Amazon community study. This study found that the chances of reporting a prior malaria infection amongst those exposed to mercury (Hg) through fish ingestion were four times greater for those who also worked with Hg in mining [181], indicating that Hg exposure may increase the risk of infection. Small-scale gold miners in Tapajos watersheds in Amazonian Brazil were coexposed to high rates of infective mosquito bites and high levels of methyl-mercury from the fish diet [182, 183]. Miners from downstream communities exposed to methyl-mercury had higher malaria risks than miners in comparable areas that did not utilise mercury. According to Douine et al. [180], malaria cases were linked to deforestation (Brazil, Colombia), gold extraction (Colombia), gold prices (Guyana) and mining regions (Peru, Colombia, Venezuela, Guyana).

Comparatively, a range of non-communicable diseases (NCDs), including neurobehavioral disorders (lead, mercury), cardiovascular disease (lead, cadmium), renal disease (lead, cadmium) and malignancies (arsenic, chromium), have progressively been linked to environmental exposures to heavy metals [184–186]. Other diseases include congenital anomalies, autoimmune disorders, diabetes, mental health issues and endocrine, gastrointestinal and cardiac diseases [27, 187, 188]. Heavy metal intake has also been linked to metabolic disorders such as obesity, insulin resistance and dyslipidemia [189]. Their exposure has also been linked to an increased risk of non-lymphoma Hodgkin's [185] and hormone-responsive malignancies such as those of the breast, ovary and prostate [190–192].

These diseases kill around 41 million people annually, 74% of global human deaths [27] and over 14 million people under 70 die prematurely [193, 194]. The Global Burden of Disease research found that NCDs caused 21 of the top 30 causes of age-standardized years lived with disability in 2019 [188]. The leading causes of disability include headache, low back pain, osteoarthritis, melancholy, anxiety, diabetes, asthma and vitamin A deficiency. Cardiovascular diseases kill 17.9 million people yearly, followed by cancer (9.3 million), chronic respiratory diseases (4.1 million) and diabetes (2.0 million, including diabetes-related kidney disease mortality) [27]. The epidemiologic transition from infectious diseases to NCDs has been documented since the twentieth century, and 86% of premature NCD deaths occur in low- and middle-income countries [27, 195, 196]. There is a substantial economic loss on the global economy as NCDs will cost the global economy $47 trillion between 2010 and 2030, averaging over $2 trillion yearly [194]. NCDs impede economic growth and impoverish millions in emerging nations. The burden of NCDs continues to increase significantly in low- and middle-income nations as NCD research, prevention and treatment are grossly underfunded compared to their population burden [197].

Numerous studies conducted in various regions have provided insights into the potential health consequences associated with heavy metal exposure. China's rapid industrialization and urbanization have resulted in extensive heavy metal pollution, with lead, cadmium and mercury exposure in contaminated areas linked to adverse health effects, including neurological disorders, respiratory problems and developmental issues [186, 198, 199]. In India, urban areas have also encountered substantial heavy metal pollution due to industrial activities, vehicular emissions and improper waste disposal [200]. Notably, elevated levels of lead and chromium have been identified in soil, water and food sources, contributing to increased risks of kidney damage, impaired cognitive function and various cancers. Bangladesh faces a significant health risk with excessive levels of arsenic in groundwater, leading to conditions such as skin lesions, cardiovascular diseases and various cancers, including those affecting the skin, lungs, bladder and kidneys [145]. In Mexico, industrial activities and mining operations have resulted in heavy metal contamination in specific regions, causing heightened rates of respiratory problems, gastrointestinal issues and adverse neurological effects amongst communities residing near contaminated sites. These effects are primarily associated with exposure to heavy metals like lead, arsenic and mercury [201, 202]. Moreover, artisanal small-scale gold mining in Ghana has led to mercury pollution in water bodies and their surroundings, posing health risks such as neurological disorders, kidney damage and developmental issues in children [203, 204].

Yet, heavy metals have been identified in practically every environment studied in the Niger Delta. When heavy metals proliferate across ecosystems, human exposure becomes unavoidable and ubiquitous. Heavy metal assessments in animal and human tissues indicate widespread disease burdens. The amounts of certain heavy metals vary depending on geography, age, dietary patterns and accumulation potentials. Human health risk assessment is regarded as one method of assessing the possible adverse health impacts of environmental risks on people [205]. This procedure utilizes scientific and statistical techniques to identify and quantify a hazard, establish possible routes of exposure and finally calculate a numerical number to reflect the potential risk [205].

Olawoyin et al. [206] observed the greatest cancer risk values for lead (2.62×10^{-2}) and chromium (1.50×10^{-2}) in soil obtained from Bonny and Delta State, Nigeria. *Telfairia occidentalis* and *Achatina achatina* fish samples from the Ogale River State in the Niger Delta revealed carcinogenic hazards, particularly for lead and cadmium [115]. The presence of nickel (Ni), cadmium (Cd), chromium (Cr), lead (Pb) and copper (Cu) in the tissues of grey mullet (*Mugil cephalus*) from the River State were highlighted to pose a threat to the health of adults and children who consume them. The hazard index (HI) for males and females (adults) was 7.612 and 7.840, while the HI for males and females (children) was 9.567 and 10.842, both exceeding > 1 USEPA standard. Hazard index values for vegetables harvested in Bayelsa were greater than 1, suggesting a possible health concern [166]. The studies indicate significant health concerns linked with eating fisheries and vegetables harvested from the Niger Delta, and it is alarming that children are at the most significant risk. These findings emphasize the need for comprehensive measures and international collaboration to mitigate heavy metal-related health risks in affected regions. One Health co-participatory approach should be conducted to address this issue to lower the heavy metal contaminants prevalent in the Niger Delta region.

The NCDs and CDs in the Niger Delta are not currently researching the impacts of the environment to enhance the health and well-being of adults and children and to increase knowledge of the role of various factors in health and disease. Relevant factors are the impacts of the air, water, nutrition, community and cultural factors and genetics on the growth, development and health of children in the Niger Delta. There is a need for further evidence to determine potential comorbidities owing to exposure to heavy metals. Monitoring terrestrial and aquatic populations may offer early warnings of environmental hazards to human health professionals.

Remediation Approaches of Heavy Metal Contamination

Remediation involves restoring contaminated land, water or air to its original condition [207]. Heavy metal pollution has become a global environmental problem [208, 209]. Globally, 5 million soil pollution sites spanning 500 million hectares of land are polluted by heavy metals at concentrations greater than the geo-baseline or regulatory thresholds [210].

Remediation of heavy metal-contaminated soil may be done in various ways, and these techniques have proven effective over time. When utilised exclusively, the traditional approaches including chemical and physical methods, typically produce by-products (toxic sludge or pollutants) and are costly. At the same time, the biological process is exceedingly slow and time-consuming [211].

Physical Remediation

Soil Replacement

The process of substituting or partially removing polluted soil with non-contaminated soil is known as soil replacement. This approach reduces the concentration of heavy metals in the soil, enhancing the soil's efficiency. The soil may be replaced by spading and fresh soil importation, which dilutes the heavy metal content [212].

Soil Isolation

Soil isolation involves separating soil polluted with heavy metals from uncontaminated soil. This technique limits heavy metals and other pollutants transport in a restricted area. When alternative remediation approaches are not economically or physically feasible, soil isolation technology is used to avoid additional heavy metal pollution of groundwater [208, 213].

Vitrification

High-temperature treatment of polluted ecosystems lowers heavy metal mobility in soil by forming vitreous material [214]. Mercury and other metals are volatilized during vitrification and collected for disposal or treatment. For example, heating zinc and lead-rich ceramic debris to 1850 °C effectively remediates heavy metal-contaminated sites [215]. The temperature during vitrification immobilizes heavy metals and remediates heavy metal-contaminated waste and large amounts of soil. In Spain, vitrification immobilized Zinc, Manganese, Iron, Copper, and Nickel at 1350 °C and mobilized them at 1050 °C [216]. However, in situ vitrification method is more cost-effective and energy-efficient than ex-situ [208].

Chemical Remediation

Immobilization Technique

Immobilizing chemicals in soil reduces metal mobility, bioavailability and bioaccessibility of heavy metals. Binding, precipitation and adsorption processes transfer heavy metals from soil solution to solid particles, limiting soil transport and bioavailability. Cement, clay, zeolites, phosphates, minerals, microorganisms and organic soil amendments are used to immobilize heavy metals [217, 218]. Studies show that low-cost industrial wastes such termitaria, industrial eggshell, red mud and manure byproducts may immobilize heavy metals in polluted soil [38, 208, 219, 220].

Encapsulation

Encapsulation combines polluted soils with other materials, such as asphalt, concrete or lime. This procedure renders the polluted soil immobile, so preventing the spread of contamination. Cement is a binding material due to its accessibility, flexibility, and affordability [221].

Phytoremediation

Phytoremediation utilizes plants to restore polluted ecosystems. The method grows metal hyperaccumulators in polluted soil to recover heavy metals [222]. Phytoremediation is environmentally safe, non-invasive, energy-efficient and cost-effective for areas with low-to-moderate heavy metal levels [223]. This method can be used with other remediation methods and depends on many plant and soil factors, such as soil physicochemical properties, the bioavailability of metals in soil, microbial and plant exudates and living organisms' ability to uptake, accumulate, sequester, translocate and detoxify metals [224].

Phytoremediation cleans up polluted sites using plant processes and traits from energy from the sun. Given that plants absorb heavy metals, therefore, plant-based metal remediation methods sound more promising [225]. Phytoremediation of crude oil-impacted soil in Niger Delta, Nigeria, indicated that *Axonopus* sp. could phytoremediate hydrocarbon concentration in soil [226]. *Eleusine indica* combined with cow manure effectively reduced the amount of PAH and led in crude oil-contaminated soil in the Niger Delta [227]. Heavy metals accumulate in the root and plant parts throughout remediation process [228]. The bioavailability of heavy metals in soil and plant nutrition determines the plant absorption rates. Techniques for phytoremediation include phytovolatilization, phytostabilization and phytoextraction [229].

Phytovolatization

Phytovolatilization converts soil heavy metals into less lethal vapours that plants discharge into the atmosphere through transpiration. Phytovolatization converts metals into volatile organic chemicals released into the atmosphere as biomolecules [230]. *Arabidopsis thaliana*, *Brassica juncea* and *Chara canescens* can absorb heavy metals and release them into the environment [231]. Plant enzymes and genes help to convert heavy metals into volatile forms [208, 232].

Phytostabilization

Plants stabilize soil heavy metals, reducing their bioavailability and mobility [228]. Phytostabilization prevents heavy metals from spreading off-site but does not reduce soil concentration. Roots or rhizosphere precipitation prevent heavy metals from entering the unsaturated zone. Unlike other phytoremediation approaches, phytostabilization minimizes media/area pollution rather than soil remediation [233]. Phytostabilization is utilised for soils that cannot be phytoextracted. Plants may prevent metal migration by reducing leaching, soil erosion and runoff through transpiration, root stability and above-ground vegetation [233]. Phytostabilization increases soil fertility without producing secondary waste. These plants are effective phytostabilizers but limited potential as metal extractors [228].

Phytoextration

Plants can absorb heavy metals from soil using the phytoextraction method. This method employs energy from the sun and is based on the ability of plant roots to ingest, translocate and concentrate heavy metals from soil to harvestable plant parts. Phytoextraction effectively removes metals from contaminated areas, although most plant species cannot survive in highly polluted environments [219, 234].

Transgenic Plants

Transgenic plants containing bacterial genes (merA and merB) can volatilize 100–1000 times more Mercury than native plants [235, 236]. Plants can be engineered to adjust their rhizosphere to increase target metal mobility, modify metal speciation for better root-to-shoot translocation, increase metal tolerance, transfer metals into less toxic forms by binding with organic acids and thiol-rich chelators and sequester heavy metals in vacuoles [237]. Targeted genes that absorb, transport and accumulate heavy metals from an efficient source to the host improve host tolerance. Heavy-metal-binding peptides such as phytochelatins, glutathione and metalothionones detoxify and sequester heavy metals [238]. The vacuole stores or detoxifies harmful metal ions bound to organic or sulfur-rich peptide complexes [239]. Volatilized heavy metals in the atmosphere are difficult to manage, but studies show that volatile substances are diluted and diffused and provide little environmental risk [240].

Nanotechnological Approach to Remediation

In recent years, nanotubes, nanosheets and nanolayers have remediated soil, soil sediments, solid waste and wastewater in situ and ex-situ [241]. Researchers have synthesized surface-functionalized nanoparticles (less than 50 nm) to adsorb heavy metals, organic pollutants and pigments from contaminated streams [242].

Nanoremediation uses nanomaterials to transform, remediate, stabilize and detoxify pollutants [239]. Nanoparticles are prominent recently due to their size, large surface area to unit mass ratios, short intra-particle diffusion distance, magnetic properties, surface modifiability, biocompatibility, tunable surface chemistry, increased adsorption sites, reusability, increased porosity, higher gas permeability, ease of separation, enhanced catalytic activity, greater dispersion degree and comparative cost [243].

Nanotechnology's adaptability and development show great promise for the environmental remediation of contaminants and heavy metals [244]. These approaches are fast, versatile and cost-effective [239].

Newer Approaches to Remediation

Metagenomics allows direct access to microbial communities in polluted environments regardless of their culturability, metabolomics measures all metabolites at a specific time point, reflecting all regulatory occurrences responding to external environmental conditions and proteomics identifies and quantifies differentially expressed proteins [239]. They are essential tools for identifying all unknown microbial communities that digest heavy metals and the numerous metabolites organisms make to withstand stress. Thus, merging both 'omics' will provide a complete picture of microbial populations and biodegradation mechanisms [229].

Challenges Faced in Optimal Remediation in the Niger Delta

In the Niger Delta, heavy metal pollution is gaining significant attention from the environmental pollution field. Environmental contamination in the area continues to rise due to inconsistent environmental management rules, which result in lax enforcement and compliance with waste disposal, resource exploitation and environmental degradation. Additionally, several regulatory bodies with conflicting regulatory responsibilities provide various interpretations of the law, confusing those involved in environmental management.

More research is urgently needed to understand the distribution and remediation of heavy metals in Nigeria due to the growing human population, industrialization and associated rising levels of heavy metals in the environment [245]. On the other hand, it is still unclear how heavy metals get into the sediment, water, fish and plants. Future research will need to pay more attention to this issue. Given the possible effects of these contaminants on aquatic life and human health, there is ignorance underlying their environmental behaviour and the absence of adequate analytical and sampling methodologies [246]. In economically significant species, monitoring and study on the combined health impacts of concurrent chronic and acute exposures are only emerging. Contamination mechanisms must be carefully investigated to measure the number of toxic substances that might enter our food and become biomagnified.

Organisms and genes may withstand heavy metal ingestion more efficiently with the aid of physiological, genetic and new developments in researching biotechnological approaches based on sediment, water, fish and plant treatments. Research on the incorporation of advanced remedial approaches is still in its development. The Niger Delta's potential for large-scale remediation (including nanoremediation, transgenic techniques, metabolomics analyses and omics technology) is untapped. Another difficulty is that, whereas ambient environments include a variety of contaminants, current approaches tend to concentrate on a particular pollutant [239].

The long-term remediation of heavy metal contamination in the Niger Delta is a significant concern and is lacking. The efficacy of plants in removing heavy metals from the environment may be improved through transgenic plants that express efficient genes from other species [247]. In transgenic plant cells, specific proteins and natural chelators are overexpressed [208, 248–250]. In order to assist plants in adapting to increased heavy metal concentrations and hyper-accumulators, foreign genes may be injected into plant genomes. Transgenic techniques produce hybrid plants that can remove certain metals from the environment [250]. One of the most promising options for eliminating chemical and biological pollutants and heavy metals from wastewater or coastal waters is the systematic integration of bioremediation, nanoremediation, and molecular approaches.

Improving the health of humans, animals and the environment is the goal of a One Health approach to public health [251]. Everyone who eats or lives in a polluted environment may have one health concern. To maintain One Health, partnerships and dialogue amongst specialists in ecological, human and environmental health are required. It is necessary to develop workable strategies, discuss objectives and progress, develop a collaborative mitigation strategy and participate to have the highest expected influence on improving the health of both people and the environment (Fig. 3).

Research Gaps and Future Perspectives

Several studies reveal the effects of heavy metals in the Niger Delta [1, 115, 206]. Bioremediation is a viable option for mitigating heavy metal-contaminated sites since it improves the ecosystem and leaves tiny environmental footprints. Although large-scale field applications of developing nanoremediation technologies have not yet been achieved in Nigeria, as research advances, there will be less uncertainty about their potential applications. Future development and widespread use of these remedial strategies for heavy metals face several challenges, calling for more in-depth study. Intensive field studies with process optimization and improvements in the suitability of methods in particular environments should be carried out successfully. This will reduce heavy metal contamination in the food chain and ensure sustainability and widespread applicability for future generations and resources.

In order to determine the overall effect that risk factors for a disease have on human health, public health professionals need to conduct a burden of disease assessment. It may be possible to accomplish the anticipated decrease in disease burden and economic burden by lowering or removing exposure to the risk factor (for example, reducing different heavy metal sources) [175]. Future studies should be influenced by a collaborative global effort to reduce the high disease burden related to communicable and non-communicable diseases that are attributed to the deficiency and toxicity of trace metals.

More pertinent is the poor knowledge of rural and coastal community members on the health risks associated with heavy metals and ESD. Communities may be more willing to actively participate in preserving and protecting human life if they are aware of the risks that specific actions (such as dumping of wastes in rivers) entail. There is also little understanding of the One Health perspective's importance as a criterion for addressing the significant issues with heavy metal contamination. It is necessary to provide a sustainable platform for heavy metal pollution mitigation measures and a sustainable aquatic environment due to the rise in the concentration and accumulation of heavy metals in different types of soil, sediment, water, fisheries and plants. In order to reduce health risks from heavy metals and implement One Health, the WHO could take a holistic approach to attain the Sustainable Development Goals (SDGs) by including health professionals, coastal communities, ecologists and researchers and industrial companies. Without a One health framework, it will be challenging to attain One Health in areas where pollution mitigation measures are insufficient, given the nature of water and ecosystem depletion [30, 31].

Conclusions and Recommendations

This review study thoroughly examined the presence of heavy metals in the Niger Delta and their threats to human and environmental health. This study establishes that the levels of specific heavy metals, such as Cd, Pb, Cu, Cr, Mn, Fe, and Ni, in water, sediment, fish, and plants within the majority of Niger Delta ecosystems exceeded acceptable threshold values. These elevated concentrations can be attributed to various human activities. Notably, Rivers State exhibited the highest concentrations of heavy metals. Furthermore, macroinvertebrates, being sedentary organisms, accumulated higher concentrations of heavy metals compared to other fish species in the region. The analysis of this review showed the considerable risks that heavy metal pollution presents to the general population, particularly children, in terms of carcinogenic effects. Surface water, soil parent materials and erosion contribute less to the accumulation of heavy metals; instead, wastewater, solid waste, crude oil spills and agricultural inputs were the main primary sources of heavy metals in the Niger Delta. The contamination of cultivated soils and seafood by the deposition or discharge of heavy metals increases the amounts of toxic compounds in food chains. Intake of contaminated foods may lead to various diseases in life forms.

However, modern and sustainable heavy metal abatement techniques are currently lacking in the region. The necessity for epidemic surveillance, vigilance for endemic and pandemic diseases and overall ecosystem deterioration cannot be ignored as we continue to explore our environment and all the natural resources that nature has provided us. The Niger Delta requires appropriate remediation methods due to the high incidence of heavy metals due to increased oil exploratory activities. Effective remediation of polluted areas uses a variety of remedial approaches. While chemical remediation methods are quick, straightforward, simple to apply, have high public acceptability and are relatively inexpensive, physical remediation methods can completely remove heavy metals from contaminated soil.

Nevertheless, physical remediation is destructive and costly and can only be applied to small soil areas. However, these remediation techniques are not environmentally friendly since they restrict the number of toxins they may release into the environment. Combining phytoremediation with other conventional remediation methods like chelate-assisted, microbial-assisted and transgenic plants may be quite efficient. A particularly successful technique to support this technology for an application is using genetically modified plants with beneficial remediation traits tailored to the needs of contaminated sites. Transgenic techniques have effectively increased the phytoextraction capability of hyperaccumulators through metal transporters and improved the production of antioxidant enzymes and metal-detoxifying chelators. Nanoabsorbents, phytoremediation and genetic techniques are improved and advanced, effective, efficient and commercially feasible remediation technologies. However, the range of applications for these techniques is currently limited, and the Niger Delta lacks in-depth field research.

Therefore, practical and cost-effective restoration, remediation strategies and co-participatory framework are urgently required to attain One Health. In the Niger Delta's poor communities and overburdened economy, bioremediation offers a sustainable alternative at the very least due to its low net emissions and environmental footprints. However, combining biological and physicochemical remedial techniques with the One Health paradigm might address different kinds and quantities of heavy metal pollution. Additional study is required to evaluate the large-scale application of developing technologies in the Niger Delta environment.

The existing One Health challenges in the Niger Delta and the possibility for additional heavy metal contamination in the area need a comprehensive evaluation in the future based on the proposed sustainable approach. Different stakeholders could implement the following key recommendations:

- A standardized minimum and maximum permitted heavy metal limit
- Regular monitoring of heavy metal-contaminated water, sediments, and soils
- Comprehensive policy implications for managing contaminated areas effectively
- Coordinating global mitigation measures for long-term heavy metals remediation in the interest of environmental sustainability
- Going transdisciplinary and cross-sectoral to benefit from cross-linked sciences
- Establishing national and regional research agencies on heavy metal-related diseases
- Mapping areas for heavy metals mitigation prioritization
- Improved and stringent policies implementation and operationalization
- Industrial companies should ensure that effluents are within discharge permissible limits before discharge into the environment
- Companies should strictly observe safety precautions to prevent accidental oil spill discharges or ship breakages
- The comprehensive understanding of heavy metal accumulation in the food chain and their toxicity in cells
- Ecologists and researchers should identify models for tracking heavy metal pollution and give technical advice for preventive measures
- Provision of funding opportunities to continue heavy metal and health risk monitoring
- Routine medical examinations are essential to guarantee that people's health is protected
- Coastal communities should help protect waters by not exploiting them as landfills for garbage, plastics, and other household waste
- Proper drainage systems are essential to reduce the severity of floods during the rainy season
- Continuous seminars and workshops could achieve heavy metal awareness for One Health
- Heavy metals source reduction is pertinent to prevent heavy metals from entering the food chain

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