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Heavy Metal Contamination in Soils, Water, and Food in Nigeria from 2000–2019: A Systematic Review on Methods, Pollution Level and Policy Implications

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Abstract Heavy metal pollution is a silent killer and has become a pervasive issue in various regions worldwide, particularly within developing nations such as Nigeria. This study undertook a thorough examination of 120 scholarly articles published from 2000 to 2019, aimed at evaluating the prevalence of heavy metal pollution in soils, aquatic environments, and food sources including crops, meat, and dairy products. Methodologies employed for sample collection and metal quantification were critically assessed, alongside an extensive discussion on the concentrations, sources, and levels of contamination observed. The investigation revealed elevated concentrations of cadmium (Cd), copper (Cu), nickel (Ni), lead (Pb), zinc (Zn), cobalt (Co), chromium (Cr), iron (Fe), and arsenic (As) across all examined locales, with average metal concentrations surpassing World Health Organization/Food and Agriculture Organization (WHO/FAO) guidelines for soil. Furthermore, higher metal concentrations were detected in surface and well waters, whereas borehole groundwaters were relatively pollution-free. Analysis of food crops, meat, and milk demonstrated metal concentrations exceeding WHO/FAO standards across all urban areas studied. Contrary to expectations of lithogenic toxicity, the primary sources of contamination were identified as anthropogenic, stemming from dumpsites, landfill sites, mining operations, runoff and seepage from automotive repair workshops, petroleum hydrocarbon spills, and effluents from industrial plants. The geo-accumulation index (Igeo) analysis revealed significant soil contamination with Fe and Cd, classified under extremely serious and moderate contamination levels, respectively. This comprehensive review highlights the necessity for viable and clear policy interventions to mitigate heavy metal pollution and advocates for the rigorous monitoring and control of industrial activities.

Keywords Heavy metals · Environmental contamination · Geo-accumulation index · Industrial emissions · Anthropogenic sources

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1 Introduction

Heavy metal pollution remains a topical issue across most informed gatherings across the globe due to its health and socioeconomic implications. Heavy metals are naturally occurring metals and metalloids with relatively high atomic weight and a specific gravity greater than 5.0 g/cm^3. Some common examples of such metals are cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), mercury (Hg), and zinc (Zn), etc. (Masindi & Muedi, 2018). Metalloids such as arsenic (As), selenium (Se), and antimony (Sb) are sometimes grouped as heavy metals because they share comparable physical and chemical properties with heavy metals, including high density, melting point, insolubility or slight solubility in water, reactivity, and toxicity (Morais et al., 2012). In general, heavy metals are transition or post-transition metals within groups 3 to 16 and period 4 and above of the periodic table (Hawkes, 1997). In contrast to Cd, Hg, As, and Pb, which are heavily toxic and deleterious, Cu, Co, Fe, and Zn, within standard limits, offer essential benefits to flora and fauna (Masindi & Muedi, 2018; Morais et al., 2012). Heavy metals can be emitted into the environment through industrial processes, such as mining and manufacturing, or through natural sources, such as volcanic eruptions (Stankovic & Stankovic, 2013; Wuana & Okieimen, 2011). Because heavy metals are covert and insidious; not easily detected by sight or smell, they can go unnoticed and accumulate in the environment over time, causing long-term health and environmental damage (Asrari, 2014; Gupta, 2020).

1.1 Heavy Metal Pollution Publications: Number of Publications and Journal Distribution

Heavy metal studies in Nigeria context is numerous and widely covered. Google Scholar search engine was explored to identify peer-reviewed literature related to heavy metals in Nigeria published between 2000 and 2019. The search phrase "heavy metals pollution in Nigeria", restricted to each year was used and included only articles from peer-reviewed journals in the search. Figure 1 generated using OriginPro V 2019b illustrates the number of papers published as a function of years using all the resulting articles the search returned. It can be seen that the interest in metal pollution has indeed increased over the last two decades. The number of publications grew from 713 in the year 2000 to 9,130 in 2019 with a total sum of 66,778 and a mean of 3,339 per year. However, this number did not exclude articles in duplicated versions because the interest was to show the trend and semi-quantitative data. Stricter inclusion and exclusion criteria were applied for the selection of primary studies before their critical appraisal as discussed in Sect. 1.4.

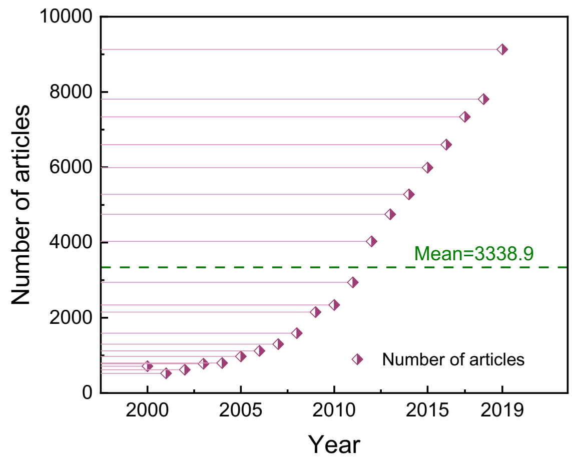

Fig. 1 Trend of number of publications on heavy metals studies in Nigeria. (Source: Google Scholar (2020)

Similarly, the Web of Science (WoS; previously known as Web of Knowledge) was utilized to acquire papers published on heavy metals related to Nigeria. A search was conducted using the keywords 'heavy metals' and 'Nigeria'. The search was limited to publications published between 2000 and 2019. The results were then sorted by journal name, and the total number of articles published in each journal was counted. Figure 2 shows a summary of these statistics. Large portion of the papers were published in journals related to the environment and public health which is not counterintuitive. It is interesting to see publications in core science, technology, engineering, and mathematics (STEM) journals, including Engineering, Ocean, Energy fuels, and Mathematics which suggest the multidisciplinary expediency of heavy metals pollution. Nonetheless, it is also startling that public policy, art and humanities journals were absent, perhaps only STEM researchers were funded for heavy metal-related research or the non-STEM authors were oblivious to their connectedness to heavy metal research. Organizing multidisciplinary

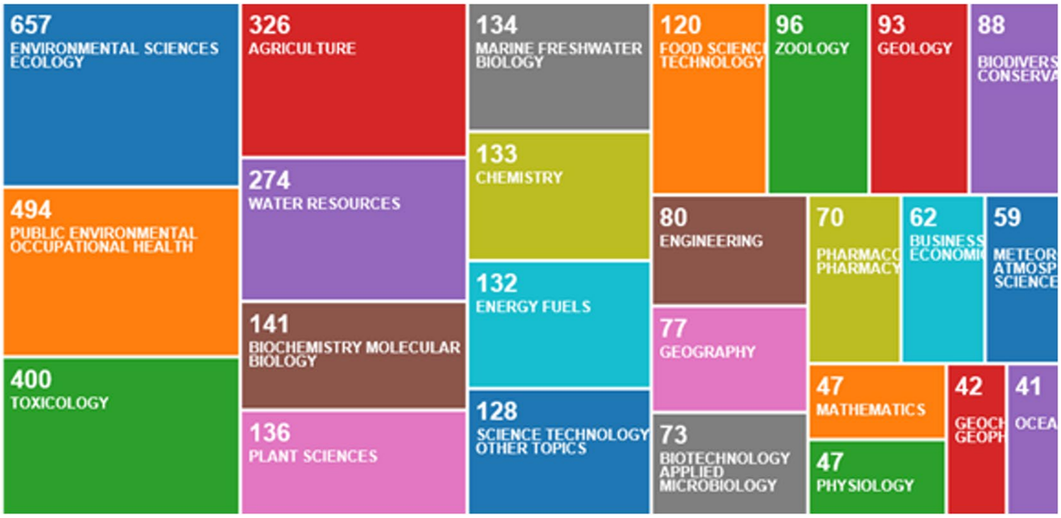

Fig. 2 Journal distribution and number of publications related to heavy metals in Nigeria

colloquiums can help resolve the latter. Moreover, it is evident there is a disparity in quantitative values between the two multidisciplinary databases, this could be related to the difference in their algorithms (Mikki, 2009), the main takeaway is that the plethora of open literature available indicates that heavy metal is a major topic of discussion among the academy of health, medical, chemical, nutritional, and environmental science researchers in Nigeria.

These enormous efforts and attention were partly justified owing to the exponential sprawling population of the nation requiring thorough monitoring of the health status drivers. With the current 2.6% annual growth rate, Nigeria is predicted to become the third most populated country in the world by 2050 representing over 400 million people (DESA, 2019). Today, one out of every eight persons in the world lives in Africa, and the population of Africa is growing faster than any other continent on Earth today. The rate of growth is three times the rate in North America, and ten times the rate in Europe (Engelman, 2016; UNFPA, 2022; Van Bavel, 2013). Thus, these statistics are sufficient reasons to listen to African voices and pay attention to occurrences in Africa. The studies were also prompted due to the numerous episodes of metal poisoning which accounted for thousands of mortalities; reported cases included lead poisoning in northwestern Nigerian claiming no fewer than 400 lives (Dooyema et al., 2012; Plumlee et al., 2013).

1.2 Keyword Evolution Analysis

In recent decades, the study of heavy metal pollution and food poisoning has seen a marked advancement in Nigeria. Data obtained in Sect. 1.1 were fed to a bibliometric analyzer. Figure 3 reflects the keyword evolution related to heavy metals, as obtained by CiteSpace bibliometric analysis software (Pan et al., 2018). It is obvious that early in the millennium, heavy metals in soil and speciation sediments were highly investigated, and the term 'trace metals' was interchangeably used for 'heavy metals'. It is important to note that, there is a thin line between the two terms. While 'trace metals' refer to metals present in very low concentrations (less than 100 parts per million (ppm)) in the environment, 'heavy metals' are metals present in relatively high concentrations (greater than 100 ppm). Additionally, 'trace metals' are referred to as 'heavy metals' due to their greater density and higher atomic mass, making them more toxic than other metals (Ishak et al., 2015). Certain trace metals, such as Pb, Hg, and As, pose an especially severe hazard to human health, which is why 'heavy metals' are universally used in research on the subject.

Furthermore, it can be inferred that research has also focused on the determination of metal levels in dust, soil, and plants around industrial areas. Studies have also been conducted on animals, including aquarium products, cattle, and bovine products.

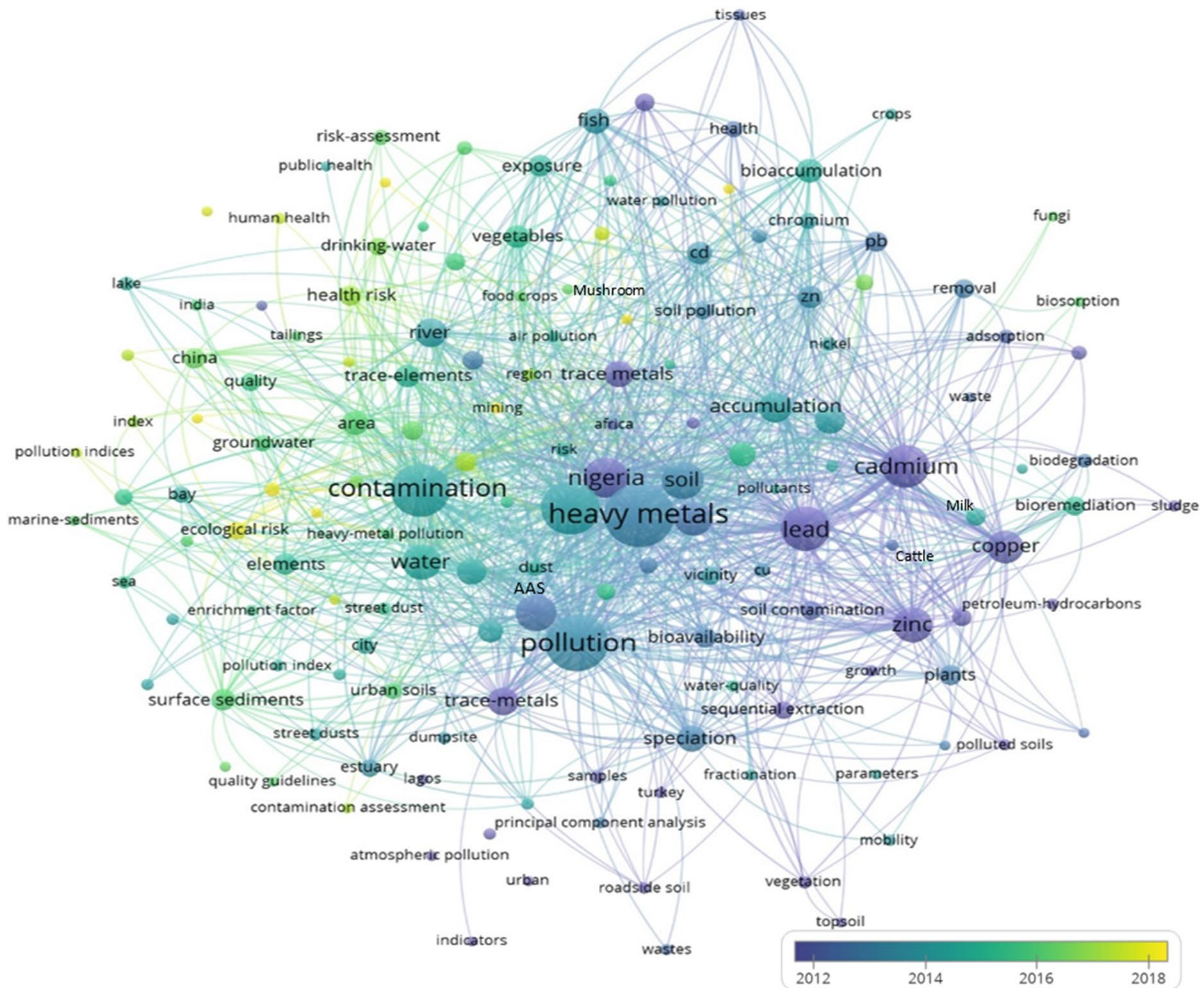

Fig. 3 The context of keyword evolution and distribution related to heavy metals in Nigeria

Additionally, agricultural soil, surface water, river, borehole groundwater, and wastewater pollution have become the focus of many authors in the middle of the last decade. While atomic absorption spectrophotometer (AAS) remains the primary method of metal analysis, recent studies have incorporated new analyses such as exposure rate, emission factor, hazard index analysis, dietary toxicity, cluster analysis, and plant remediation methods (Latinwo et al., 2015; Oyebamiji et al., 2011). Additionally, studies have been conducted on the biosorption of biomass (Latinwo et al., 2015; Oyebamiji et al., 2011), chromium adsorption on activated carbon (Taiwo & Chinyere, 2016), and the measurement of heavy metals in humans breast milk and serum (Adejumo et al., 2013; Akintujoye et al., 2013), and other rarely studied foods (edible wild mushrooms) (Ndimele et al., 2017; Wirnkor et al., 2019). Through such multidisciplinary collaborations, the study of heavy metal pollution is becoming more commonplace, with advances being made in the detection and mitigation of heavy metals.

1.3 Heavy Metals Sources and Accumulation Mechanism

Though heavy metals occur in nature but at very low concentrations, the global predominant sources are anthropogenically based which include industrial emissions, mining, pesticides and fertilizers, waste disposal, and vehicular emission as described in

Fig. 4 (Bartrem et al., 2014; Lar et al., 2013; Saxena et al., 2019). In Nigeria, several reports indicate direct exposure to high concentrations of metals through unregulated mining activities, runoff from auto mechanic workshops, direct ingestion, and contact with polluted soil (Dooyema et al., 2012; Iwegbue et al., 2009; Nworu et al., 2018; Orosun et al., 2016). Other sources peculiar to Nigeria via the food chain are spatially distributed among water, soil, plant, animal, and man (Olajire et al., 2003; Olowu et al., 2010). Numerous casualties have been reported from metal poisoning in Nigeria (Dooyema et al., 2012). Recent work suggested that an average of 2 million people in Southwestern Nigeria are at risk of lead (Pb) and mercury (Hg) poisoning from illicit mining activities (Vanguard, 2021). Metal pollution is therefore considered a silent killer.

In brief, Nigeria soil sinks large concentrations of heavy metals released from precious metals mining (gold, uranium, iron ore, wolframite, bitumen, etc.) (Dooyema et al., 2012; Olubunmi & Olorunsola, 2010), spillage of crude oil and petrochemicals (Ogoko, 2014), fertilizers (animal manures and inorganic) (Abah et al., 2009), pesticides among others. Rather than degrading over a long period in the soil, they speciate into their inorganic forms of which few are bioavailable (Osakwe, 2010). Only a few plants can metabolize them but to certain limits while most plants suffer adverse effects such as stunted growth, low yield, and death as a result of their toxicity (Saxena et al., 2019). This also introduces phytotoxicity into the human food chain from direct consumption of the contaminated plants or animals that grazed on the plants (Milam et al., 2015) as can be seen in Fig. 4.

1.4 Purpose of this Review

During the past two decades, heavy metal contamination in soil, water, air and foods has discretely been studied across towns, cities, and regions in Nigeria. Nonetheless, the levels of heavy metal pollution in environmental samples (agricultural soils, portable water, ambient air and public foods) and sources of the metal pollution are yet to be systemically collected together and intercompared. Furthermore,

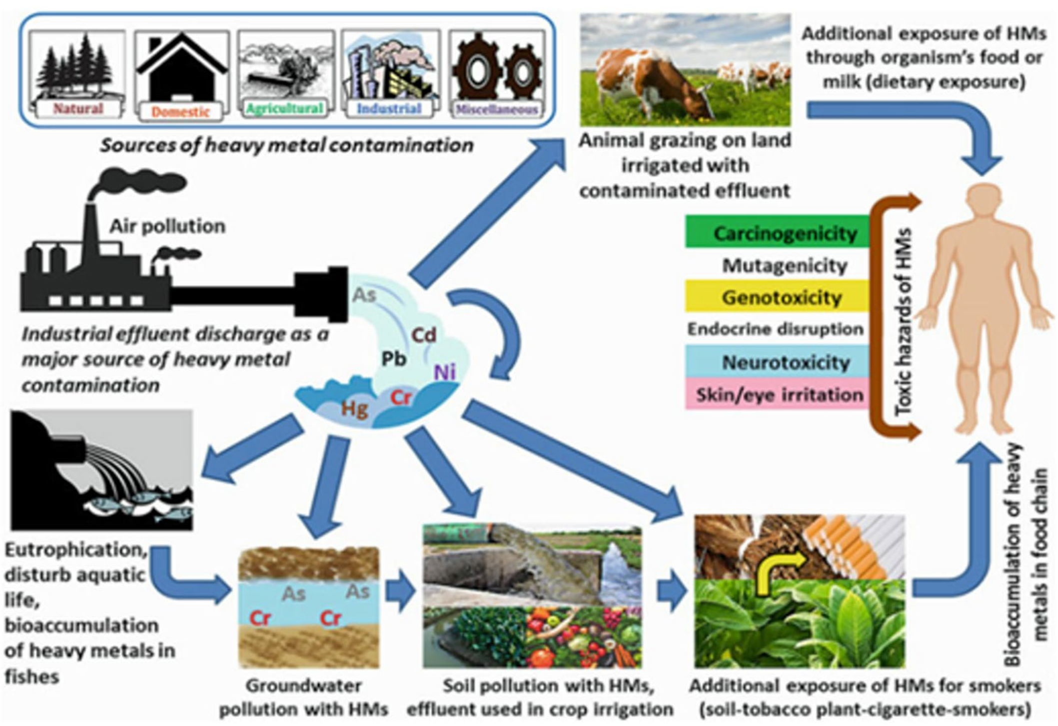

Fig. 4 Mechanism of heavy metal transfer routes to human (Saxena et al., 2019)

no study has monitored the trend of pollution levels in these samples across a given period of time, nor delineated into the present six geopolitical zones in order to ascertain reduction or increase in metal pollution in the country. Also lacking is information on the existing policy and technical strategies to combat heavy metal pollution rise in the country. The core goal of this review is to increase the awareness and understanding of heavy metal pollution levels in Nigeria and highlight the areas with need for more research efforts and policy making. In this wise, an up-to-date reference material for researchers, practitioners, civil societies and other concerned bodies on pollution assessment is made available. This could result in improved quality research and better decision making for policymakers. However, this review is delimited to the chemistry and human health risks of heavy metals since they were explicitly covered elsewhere (Wuana & Okieimen, 2011). The remainder of this paper is organized to describe the search strategy used in our review, followed by an examination of the sampling methods and analytical techniques employed in the selected literature. We then provide a detailed discussion on the concentrations of heavy metals identified in the study, explore national regulations concerning heavy metal remediation, and offer recommendations based on our findings. The paper concludes with a summary of our recommendations for future research and policy development.

1.5 Search Strategy

In this research, twelve heavy metals— Li (Lithium), Ar (Argon), V (vanadium), Ba (Barium), Manganese (Mn), Ag (Silver), As, Cd, Co, Cr, Cu, Fe, Ni, Pb, and Zn were studied but only the last eight heavy metals—were examined for concentration analysis. These eight heavy metals are all USEPA-designated priority heavy metal pollutants (USEPA, 2003). The literature search was conducted using the terms heavy metals, trace metals, pollution, contamination, and Nigeria in four databases (Google Scholar, Web of Science, Scopus, and PubMed). Keywords paired with Boolean operators ("AND" and "OR") were used to identify all relevant articles for inclusion.

To select the suitable articles, the articles were subjected to inclusion and exclusion criteria. A total of 67,778 items were found throughout the search. Following the removal of duplicates ($n = 8{,}005$), the authors examined and screened article titles and abstracts, excluding another 35,201 research, reducing the literature to 24,572. Initially, the authors reviewed abstracts of papers and removed 10,707 pieces of content owing to the targeted heavy metals. Further reading of left papers ruled out another 10,508 journals as being ineligible for the study. After retrieving the reference lists of the included papers ($n = 3{,}237$) were excluded with justification. In the end, 120 articles met all the requirements for a final evaluation. Supplementary file S. 1 (PRISM flow diagram) contains further information regarding the procedure. These criteria were peer-reviewed, English full-text papers, and articles published between January 2012 and December 2019. Due to political structure of the country, the data were analyzed across the six geopolitical zones in Nigeria namely; north-central (NC), north-east (NE), North-west (NW), south-east (SE), south-south (SW) and south-west (SW) as depicted in Fig. 5.

2 Sampling Methods and Analytical Techniques

The method of sampling, analytical tools and the investigated heavy metals from relevant literatures are presented in Tables 1, 2, 3 and 4 for soil, water, crops, and meat and milk products respectively.

2.1 Sampling Methods

In general, the soil samples were collected from the topsoil to a depth of 2.5 (Olajire et al., 2003), 10, 15, 20, 30, 40, 50, 60, and 200 (Ajah et al., 2015) cm with depth of 15 cm as the most predominant. The soil samples were from industrial sites such as automobile mechanic workshops, mining sites, cement factories, roadsides, dumpsites and agricultural sites mainly farms and garden from communities of the six geopolitical zones. Few of the soil samples were composite samples obtained by mixing thoroughly different samples from each sampling site. The roadside soil samples were usually taken from 0–5 cm topsoil at about 200 to 500 cm from the edge of the road (Abechi et al., 2010; Onianwa, 2001) and sieved through a 150 µm sieve. The samples from dumpsites and other industrial sites were usually topsoil taken at points of operation to few (Orisakwe et al., 2006) meters and kilometers away while soil samples from

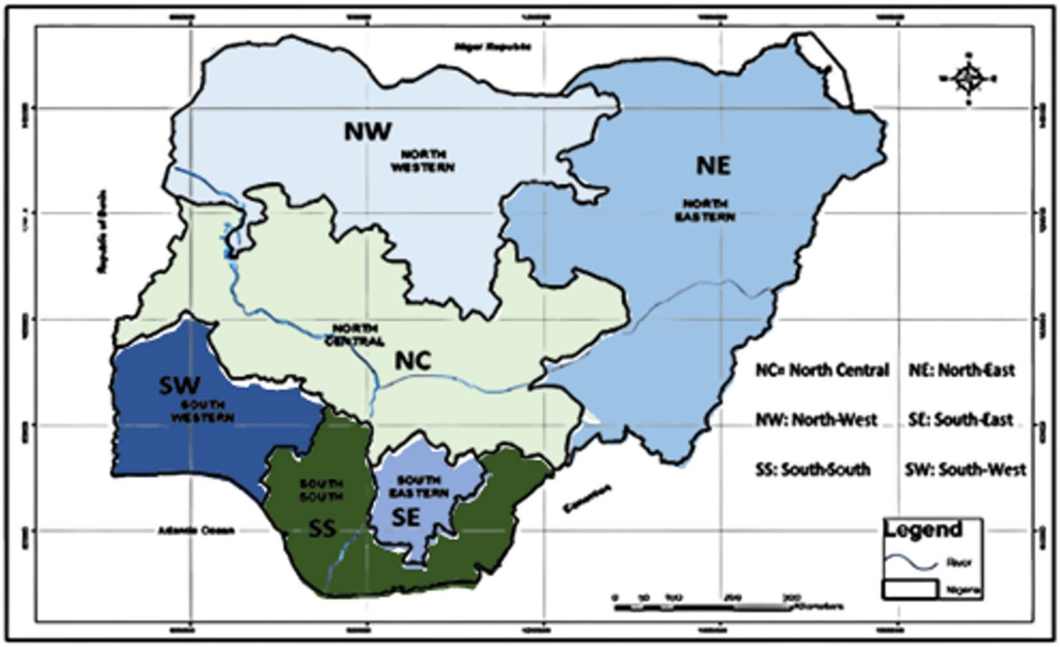

Fig. 5 Map of Nigeria showing the six geopolitical regions

farms and gardens were randomly selected (Bello et al., 2016; Iwegbue et al., 2006). The topsoil and subsoil were mostly collected using a soil auger into polythene bags (Adekiya et al., 2018).

For water samples, the number of samples collected by each researcher varies from 1 to 106 across the six geopolitical zones. Borehole water samples were collected into clean polyethylene bottles from an average of 40 m depth to about 8–12 m (Tahir et al., 2019). Deep wells, river and stream water which were few meters radially away from polluting sites (50, 80 and 100 m) were also collected (Dusa et al., 2017). Other samples including sachet and bottle water bought randomly from street hawkers were also obtained for metal analysis.

Across the six geopolitical zones, crops are grown within the vicinity of pollution sites; roots and tubers (cassava, yam, sweet potato and cocoyam), vegetables (pumpkin, lettuce, spinach, garden egg, okra, onion, cabbage, tomato, and water leaf), cereals (rice, maize, beans), fruits (mango, pawpaw, orange, pineapple, watermelon, and avocado peas) have been studied for heavy metal pollution (Ogunkunle et al., 2014; Orisakwe et al., 2012). Meats (meat or offal of cow, sheep, camel, chicken, turkey, goat, fish and shrimps) and milk products have also been analyzed for metal contamination. Distances away from the anthropogenic sites were similar to that of soil and water. Some were collected concurrently in the same location with the soil or water samples (Akan et al., 2010; Iwegbue et al., 2008; Okoye et al., 2011; Oloruntoba & Nathaniel, 2019).

2.2 Analytical Techniques

While some of the soil samples were sieved, all the soil samples were prepared by digestion with mixture of acids which may include, HF, HCl, $HClO_4$, HNO_3, H_2O_2, and H_2SO_4. The most frequently analyzed heavy metals were Cd, Cu, Ni, Pb, Zn, Co, Cr, and Fe. Only 11.3% of the studies investigated As and Hg concentrations in the soil. Atomic absorption spectroscopy (AAS) (which can either be Flame atomic absorption spectroscopy, FAAS, or Graphite furnace atomic absorption spectroscopy, GFAAS) was used by 76.1% of the researchers, only about 5% of the studies determined the metals by other methods such as; Inductively Coupled Plasma-Atomic Emission Spectroscopy (ICP-AES) and X-ray fluorescence (XRF).

All of these processing strategies and analytical systems are acceptable for soil samples. For example,

Table 1 Materials and analytical tools of heavy metals in soil in Nigeria

Year	City	Region	Type	Depth (cm)	No of Samples	Digestion	Analysis method and metals	Ref
2000	Abeokuta	SW	C	x	20	$HNO_3 + HClO_4$	FAAS(Cu,Zn,Cd,Pb,Fe)	(Odukoya et al., 2000)
2001	Ibadan	SW	A	0–5	45	HNO_3	FAAS(Pb,Zn,Cd,Cu,Cr,Co,Ni)	(Onianwa, 2001)
2002	Lagos	SW	A	15	5	HNO_3	FAAS (Cd, Cr, Cu, Pb, Ni)	(Adeniyi & Afolabi, 2002)
2002	Oyo	SW	A	0–2.5	4	$HNO_3 + HClO_4 + HCl$	FAAS (Cd, Pb, Cu, Ni, Zn)	(Olajire et al., 2003)
2003	Osun	SW	B	0–30	10	HCl	FAAS (Pc, Cd, Ni, V, Zn)	(Amusan et al., 2003)
2004	Niger delta	SS	B	0–30	2	$H_2O_2 + HNO_3/H_2SO_4$	FAAS(Ni,V,Cu)	(Osuji and C.M, 2004)
2005	Ile Ife	SW	C	0–15	2	$HNO_3 + HClO_4 + HCl$	FAAS(Zn,Fe, Co, Cu,Pb,Cd)	(Amusan et al., 2005)
2006	Port Harcourt	SS	C	0–30	6	$HF + HNO_3 + HClO_4 + H_2SO_4$	FAAS(Cd,Cr,Cu,Pb,Ni,Zn)	(Iwegbue et al., 2006)
2006	Port Harcourt	SS	C	0–60	5	$HF + HNO_3 + HClO_4 + H_2SO_4$	FAAS(Cd,Cr,Cu,Pb,Ni,Zn)	(Iwegbue et al., 2006)
2007	Onitsha	SE	C	0–15	9	$HNO_3 + HCl + HF$	FAAS(Ar,Ba,Cd,Cr,Mn,Pb,Li)	(Nwajei et al., 2007)
2008	Zaria	NW	C	x	10	$HCl + HNO_3 + HF$	FAAS(Pb,Cu,Cd,Zn,Mn)	(Uba et al., 2008)
2008	Ile Ife	SW	C	0–15	5	$HNO_3 + HCl + HF$	FAAS(As,Cd,Co,Cr,Fe,Mn,Ni,Pb,Zn)	(Oluyemi et al., 2008)
2009	Niger delta	SS	B	0–30	x	$HCl + HNO_3$	FAAS(Cd,Cu,Cr,Pb,Mn,Ni,Zn)	(Iwegbue et al., 2009)
2010	Abraka	SS	A	10	8	$HCl + HNO_3$	FAAS (Cd, Pb, Zn, Cr, Ni, Fe, Cu, Co)	(Akpoveta et al., 2010)
2010	Jos	NC	C	x	21	$HNO_3 + HCl$	FAAS(Pb,Zn,Cd, Cu,Mn,Fe)	(Abechi et al., 2010)
2010	Agbabu	SW	A	5	34	$HNO_3 + HCl$	FAAS(Fe,Cu,Mn,Zn,Hg,Pb,Cd,Ni,V)	(Olubunmi & Olorunsola, 2010)
2011	Kaduna	NW	B	x	10	$HCl + HNO_3 + HF$	FAAS (Cd, Cr, Zn, Cu, Fe, Ni, Pb)	(Achi et al., 2011)
2011	Niger delta	SS	B	0–30	12	HF	FAAS(Cd,Cu,Cr,Pb,Mn,Ni,Zn)	(Iwegbue, 2011)
2012	Owerri	SE	B	x	5	$HNO_3 + HClO_4$	FAAS(Pb,Cd,Ni)	(Orisakwe et al., 2012)
2012	Akure	SW	B	0–30	4	$HCl + HNO_3 + H_2SO_4$	AOAC, 2000(Cu,Pb,Ag,Hg)	(Akinbile, 2012)
2012	Suleja	SW	A	x	7	$HCl + HClO_4$	FAAS(Pb,Cu,Cr,Zn,Ni,Cd)	(Yisa et al., 2012)
2013	Benue	NC	B	0–40	2	$HNO_3 + HClO_4$	FAAS (Pb, Cu, Zn, Mn, Ni, Cd)	(Pam et al., 2013)
2013	Sagamu	SW	A	0–15	21	$HNO_3 + HClO_4$	FAAS(Pb,Cu,Cr,Cd,Zn)	(Ogunkunle & Fatoba, 2013)
2013	Okundi	SE	B	0–15	12	HNO_3	FAAS(Cu,Pb,Zn,Cd,Mn)	(Aikpokpodion et al., 2013)
2013	Southeast	SE	A	x	16	$HClO_4 + HF$	FAAS(Cd,Cr,Cu,Fe,Ni,Pb,Zn,Hg)	(Uwah et al., 2013)
2013	Enyigba	SE	A	x	x	x	XRF(Pb,As,Cd,Cu,Cr,Zn,Mn,Ni)	(Wilberforce & Nwabue, 2013)

Table 1 (continued)

Year	City	Region	Type	Depth (cm)	No of Samples	Digestion	Analysis method and metals	Ref
2014	Aba	SE	A	0–30	3	HNO_3+HClO_4+HCl	FAAS(Pb,Cd,As,Hg,Cu,Zn); GC–MS	(Ogoko, 2014)
2014	Minna	NC	B	0–20	25	$HCl+HNO_3$	FAAS(Ni,Cd,Cr,Pb,Zn,Ag,Hg,As,Cu)	(Ahaneku & Sadiq, 2014)
2014	Zaria	NW	B	0–15	x	x	FAAS(Pb,Fe,Cr,Zn)	(Funtua et al., 2014)
2015	Enugu	SE	C	50–200	164	$HNO_3+H_2O_2$	FAAS(Cu,Zn,Pb,As,Cr,Cd,Fe, Co,Mn,Ni)	(Ajah et al., 2015)
2016	Ughelli	SS	B	0–20	6	$HCl+HNO_3$	FAAS(Cd,Zn,Ni,Cu,Cr)	(Nwaichi et al., 2016)
2016	Katsina	NW	C	0–20	9	HNO_3+HClO_4	FAAS(Ni,Cu,Cd,Cr,Pb,Zn)	(Bello et al., 2016)
2017	Ewekoro	SW	A	0–15	27	$HCl+HNO_3$	FAAS(Mn,Fe,Cu,Zn,Cr,Pb)	(Okoro et al., 2017)
2017	Uyo	SS	C	10–15	10	HNO_3+HF	FAAS (Cd, Zn, Pb, Ni, Mn, Fe, Cr)	(Ihedioha et al., 2017)
2017	Port Harcourt	SS	A	10	3	HNO_3+HCl	FAAS(Fe,Zn,Pb,Co,Cu,Cr,Ni, Mn,As,Cd)	(Simeon & Friday, 2017)
2018	Odo-Oba	SW	B	x	10	$HNO_3+HF+HClO_4$	ICP-MS (Cu,Pb,Cr,As,Zn,Cd,Ni,Sb,Co,V)	(Adagunodo et al., 2018)
2018	Ile Ife	SW	B	0–30	30	$H_2SO_4+HNO_3$	FAAS(As,Cd,Co,Cr,Cu,Ni,Pb,Zn)	(Adekiya et al., 2018)
2019	Zamfara	NW	A	0–15	3	$HClO_4+HNO_3+H_2SO_4$	FAAS (Cd, Cu, Mn, Pb, Ni, Cr)	(Sulaiman et al., 2019)
2019	Katsina	NW	B	0–20	55	$HCl\text{-}HNO_3$	FAAS(Mn,Zn,Pb,Cd,Ni,Fe,Cr)	(Yaradua et al., 2019)
2019	Ogun	SW	B	0–15	15	$HClO_4+HNO_3+H_2SO_4$	FAAS(Pb,Fe,Zn,Mn,Ni)	(Osobamiro et al., 2019)

x: Not reported, *SS* South-South, *SW* South-West, *SE* South-East, *NC* North Central, *NW* North-West, *NE* North-East, A-Industrial Land, B-Agricultural Land, C-Dump sites

Blaser et al. (2000) using X-ray fluorescence spectrometry found out heavy metals decreased with increase in soil depth especially for As, Cr, Zn, Pb, Cu and Ni. In addition, they concluded that heavy metals concentration in top soils originated from anthropogenic and atmospheric deposition rather than due to natural geology. Metals also tend to have strong binding to the soil organic matter in the mineral or human layer (topsoil) (Saeedi et al., 2018; Silveira et al., 2003). Therefore, for agrarian soils, evaluating the topsoil for pollution indicators is valid.

However, the analysis of metals using AAS has its pitfalls. Multi-elemental determination of heavy metals at a time is lacking especially in liquid samples. Each metal has its own discrete hollow cathode lamp which has to be changed during the analysis of different metals (McComb et al., 2014; Senila et al., 2014). This accounts for why many authors eliminated As and Hg from their investigation because the lamps are expensive and scarce. In Addition, extremely large values from metals could also be due to using the wrong lamps. Studies have further shown that certain metals (especially Hg and As) easily form stable oxides and in effect are not easy for AAS to analyze, however, GFAAS (nowadays known as electrothermal AAS (ET-AAS) and FAAS have been found to be resistant to spectral interference (Zhu et al., 2013). XRF can be more advantageous for multi-elemental analysis; however, it is costly and may not be able to detect lighter elements (Vähäoja et al., 2008). The lack of the use of modern analytical devices for heavy metal research in Nigeria could be attributed to inadequate funding, which is supported by Akinyemi and Bassey (2012) analysis demonstrating the underfunding of research in Nigerian tertiary institutions. Furthermore, sampling could be prehistoric, thus introducing contaminations that could impede accuracy of results, but the advent of advanced measurement technologies has minimized these possibilities to a negligible point (Morais et al., 2012).

Table 2 Materials and analytical tools of heavy metals analysis in water in Nigeria

Year	City	Region	Type	No of Samples	Digestion	Analysis method and metals	Ref
2003	Benin	SS	River	4	x	FAAS(Cd,Cr,Cu,Fe,Pb,Mn, Ni,Zn)	(Oguzie, 2003)
2003	Ilorin	NC	Irrigation River	8	x	FAAS(Ni,Mn,Zn,Cd)	(Dosumu et al., 2003)
2006	Enugu	SE	Sachet water	6	HNO_3+HNO_3	FAAS(Pb,Cd,Cu,Ni)	(Orisakwe et al., 2006)
2006	Otuocha	SE	River	3	x	FAAS(Pb,Cd,Cu,Ni)	(Igwilo et al., 2006)
2008	Adamawa	NE	Well	10	HNO_3	FAAS(Cd,Cu,Fe,Zn,Pb,Ni)	(Alexander, 2008)
2010	Lagos	SW	River Surface	x	HCl	FAAS(Zn,Ni,Fe)	(Olowu et al., 2010)
2010	Itaogbolu	SW	Well	10	HNO_3 + HCl	FAAS(Zn,Cr,Pb,Cd,Cu,Ni,Fe)	(Adefemi & Awokunmi, 2010)
2010	Delta	SS	River	1	HNO_3	FAAS(Cd,Cr,Mn,Ni,Pb)	(Ekeanyanwu et al., 2010)
2010	Afikpo	SE	River	3	$HClO_4$ + HF	FAAS(Fe,Zn,Cu,Mn,Pb,Cr)	(Nwani et al., 2010)
2011	Makurdi	NC	River	10	x	FAAS(Cd,Cu,Mn,Ni,Pb,Zn)	(Rapheal & Adebayo, 2011)
2011	Warri	SS	Surface	24	HNO_3	FAAS(Fe,Mn,Zn,Cu,Ni,V,Cr, Cd,Pb)	(Wogu & Okaka, 2011)
2011	Bayelsa	SS	Surface	5	x	FAAS(Fe,Pb,Cd,Hg,As)	(Meindinyo & Agbalagba, 2011)
2012	Nassarawa	NC	Stream	x	HCl	FAAS(Pb,Zn,Cu,Fe,Mn,Cd,Hg)	(Opaluwa et al., 2012)
2012	Owena	SW	Dam	48	x	FAAS(Pb,Cd,Cu,Cr,Ni,Fe,M n,Zn)	(Irenosen et al., 2012)
2013	Ile Ife	SW	River	18	HNO_3+HClO_4	FAAS(Pb,Mn,Zn,Cd,Cu,Ni,Co)	(Ogunfowokan et al., 2013)
2013	Kano	NW	Irrigation River	4	HNO_3	FAAS(Cr,Cu,Cd,Zn,Co,Fe,P b,Mn)	(Bichi & Bello, 2013)
2014	Ado Ekiti	SW	River	1	HNO_3	FAAS(Zn,Mn,Cu,Fe,Pb,Cd)	(Edward et al., 2014)
2015	Zamfara	NW	Irrigated water	2	HNO_3+HClO_4	FAAS(Pb,Cd,Fe,Cu,Zn)	(Salawu et al., 2015)
2015	Kaduna	NW	River Surface	5	HNO_3	XRF(Pb,Cr,As,Fe,Cu,Zn)	(Aliyu et al., 2015)
2016	Gombe	NE	Borehole	5	x	FAAS(Fe,Mn,Cu,Pb,Co,Ni,Zn)	(Maigari et al., 2016)
2016	Ajaokuta	NC	Well	60	HNO_3 + HCl	FAAS(Mn,Cu,Zn,Fe,Pb,Cd,A g,As,Cr)	(Orosun et al., 2016)
2017	Zaria	NW	Irrigation River	1	$HClO_4+HNO_3+H_2SO_4$	FAAS(Pb,Cd,Zn,Hg)	(Lawal et al., 2017)
2017	Wukari	NE	Well	3	HCl	FAAS(Cd,Pb,As,Fe,Cu,Hg,Mn)	(Aremu et al., 2017)
2018	Ebocha-Obrikom	SS	Groundwater	8	HNO_3	FAAS(Fe,Mn,Zn,Ni,Pb,Cr,Cu)	(Raimi et al., 2018)
2018	Ebocha-Obrikom	SS	Well	8	HNO_3	FAAS(Fe,Mn,Zn,Ni,Pb,Cr,Cu)	(Raimi et al., 2018)
2018	Yenogoa	SS	River	9	HNO_3	FAAS(Fe,Zn,Cd,Cr,Pb,Co,Ni)	(Aghoghovwia et al., 2018)
2019	Dutse	NW	Groundwater	10	HCl	FAAS(Cu,Cr,Pb,Ni,Zn)	(Tahir et al., 2019)
2019	Lagos	SW	Borehole	21	HNO_3	FAAS(Fe,Zn,Pb,Cu,Ni,Cr,M n,Cd)	(Egbueri & Unigwe, 2019)
2019	Abakaliki	SE	Surface	106	HNO_3	FAAS(As,Cr,Zn,Ni,Mo,Al,Pb,C u,Hg,Cr,Ni,Cd,Ag,Mn)	(Obasi & Akudinobi, 2019)
2019	Abakaliki	SE	Groundwater	106	HNO_3	FAAS(As,Cr,Zn,Ni,Mo,Al,Pb,C u,Hg,Cr,Ni,Cd,Ag,Mn)	(Obasi & Akudinobi, 2019)
2019	Gboko	NC	Well	6	HNO_3	FAAS(Cd,Cr,Cu,Fe,Mn,Pb,Zn)	(Sesugh et al., 2019)
2019	Cross river	SS	River	6	HNO_3	FAAS(Fe,Zn,Mn,Cu,Pb,Cr)	(Okogwu et al., 2019)

Table 2 (continued)

Year	City	Region	Type	No of Samples	Digestion	Analysis method and metals	Ref
2019	Gombe	NE	Dam	3	HNO_3 + HCl	FAAS(Cu,Pb,Cr,Co,Ni,Cd,Mn,Mg)	(Ezekiel et al., 2019)
2019	Benin	SS	River	4	x	FAAS(Mn,Zn,Cu,Pd,Cd,Cr)	(Isibor et al., 2019)

x: Not reported *SS* South-South, *SW* South-West, *SE* South-East, *NC* North Central, *NW* North-West, *NE* North-East, A-Industrial Land, B-Agricultural Land, C-Dump sites

Similarly, heavy metal levels have been investigated in water bodies throughout the country. Surface water from rivers and streams, groundwater from wells or boreholes, dams, sachets and water from public vendors, among others have been studied. Human activities such as mining, smelting, quarrying, landfill and waste dumping around the water sources have been the major cause of heavy metals concentration (Maigari et al., 2016; Obasi & Akudinobi, 2019; Orosun et al., 2016). Several of the reports ascertained the degree of pollution in the water used for irrigation and drinking purposes by man and livestock. Usually, the water samples were digested with acids such as HCl, HNO_3, HF and $HClO_4$ according to American Public Health Association (APHA) sample preparation methods (APHA 2005, 1998 and 1992). Some authors utilized the old methods (Alexander, 2008; Aremu et al., 2017) while some used the latest (Akinbile, 2012; Dusa et al., 2017; Egbueri & Unigwe, 2019), one would suggest that authors should avoid using 1992 and 1998 methods but rather use a recent method such as APHA 2005 due to changes in improvements in quality-control procedures (Young et al., 2005) for better accuracy and sensitivity to analytical tools. As, Cr, Zn, Ni, Mo, Al, Pb, Cu, Hg, Cr, Ni, Cd, Ag and Mn concentrations were determined, but studies on As levels were very limited, perhaps due to the same problem of inability of suitable hollow cathode lamps as mentioned in the case of soil samples. Only one case of metal analysis with XRF was found, the rest were analyzed with AAS(Aliyu et al., 2015). Just as discussed for soil samples, measuring metals with ICP-AES or XRF would help overcome the sequential AAS metal analysis to cover wide range of heavy metals.

The digestion (dry or wet) methods of analysis and metals investigated of crop samples were similar to that of the soil samples. Additionally, samples per study varied from 1 to 162. We recommend multiple samples in future analysis to increase the degree of precision and minimize the possibility of errors due to instrument insensitivity.

Few general takeaway from the sampling and analytical methods include; in most cases the number of samples per study was small considering the population and the land space of the country. A similar review in China showed samples per author ranged from 10 to 773 samples for each study (Wei & Yang, 2010) (Wei & Yang, 2010). Adequate funding for research could help to resolve this deficiency. Arsenic (As) and mercury (Hg) have been understudied due to the cost of suitable analytical techniques such as Cold Vapor Atomic Absorption Spectrometry (CVAAS), Inductively Coupled Plasma-Mass Spectrometry (ICP-MS), and Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES). CVAAS is the least expensive of these techniques, but can only be used to analyze Hg as it is the only analyte with an appreciable atomic vapour pressure at room temperature. To gain a comprehensive understanding of the pollution levels, especially at mining sites, the exclusion of these metals would provide insufficient information for policymaking.

3 Heavy Metal Concentrations

The mean concentrations of Cd, Cu, Ni, Pb, Zn, Co, Cr, Fe and As in soils, water, food crops, meat and milk products with their respective international maximum permissible limits are presented in Tables 5, 6, 7 and 8 respectively. This would provide a strong basis for understanding heavy metal pollution levels in Nigeria. In general, by intercomparing these heavy metals, it can be inferred that metal concentrations have good relationship with the type of anthropogenic site involved and the distance away from the polluting sites. All the six geopolitical zones have their individual large share of high metal concentrations, while some are quite at alarming degrees, others are mild.

Table 3 Materials and analytical tools of heavy metals analysis in food crops in Nigeria

Year	City	Region	Type	Item	No of Samples	Digestion	Analysis method and metals	Ref
2003	Osun	SW	B	Plant	10	HCl	FAAS (Pc, Cd, Ni, V, Zn)	(Amusan et al., 2003)
2005	Ile Ife	SW	C	Pawpaw	2	HNO_3+HClO_4+HCl	FAAS(Zn,Fe, Co, Cu,Pb,Cd)	(Amusan et al., 2005)
2005	Rivers	SS	B	Cassava	6	$HNO_3+H_2SO_4+HClO_4$	FAAS(Pb,Fe,Cu,Zn)	(Hart et al., 2005)
2005	Rivers	SS	B	Cocoyam	6	$HNO_3+H_2SO_4+HClO_4$	FAAS(Pb,Fe,Cu,Zn)	(Hart et al., 2005)
2005	Rivers	SS	B	Okra	6	$HNO_3+H_2SO_4+HClO_4$	FAAS(Pb,Fe,Cu,Zn)	(Hart et al., 2005)
2005	Rivers	SS	B	Pumpkin	6	$HNO_3+H_2SO_4+HClO_4$	FAAS(Pb,Fe,Cu,Zn)	(Hart et al., 2005)
2005	Rivers	SS	B	Waterleaf	6	$HNO_3+H_2SO_4+HClO_4$	FAAS(Pb,Fe,Cu,Zn)	(Hart et al., 2005)
2008	Ile Ife	SW	C	Maize	5	$HClO_4+HNO_3+H_2SO_4$	FAAS(As,Cd,Co,Cr,Fe,Mn,Ni,Pb,Zn)	(Oluyemi et al., 2008)
2008	Ile Ife	SW	C	Cassava	5	$HClO_4+HNO_3+H_2SO_4$	FAAS(As,Cd,Co,Cr,Fe,Mn,Ni,Pb,Zn)	(Olajire et al., 2003)
2009	Otukpo	NC	B	Beans	16	$HCl+HNO_3$	FAAS(Cd,Cu,Ni,Pb,Zn,Co,Cr,Fe)	(Abah et al., 2009)
2011	Makurdi	NC	B	Tomato	10	x	FAAS(Cd,Cu,Ni,Mn,Pb,Zn)	(Rapheal & Adebayo, 2011)
2011	Makurdi	NC	B	Pumpkin	10	x	FAAS(Cd,Cu,Ni,Mn,Pb,Zn)	(Rapheal & Adebayo, 2011)
2011	Makurdi	NC	B	Spinach	10	x	FAAS(Cd,Cu,Ni,Mn,Pb,Zn)	(Rapheal & Adebayo, 2011)
2011	Kano	NW	B	Spinach	6	$HClO_4+HNO_3$	FAAS(Co,Cr,Cu,Ni,Pb,Zn)	(Lawal & Audu, 2011)
2011	Kano	NW	B	Okra	6	$HClO_4+HNO_3$	FAAS(Co,Cr,Cu,Ni,Pb,Zn)	(Lawal & Audu, 2011)
2011	Kano	NW	B	Onion	6	$HClO_4+HNO_3$	FAAS(Co,Cr,Cu,Ni,Pb,Zn)	(Lawal & Audu, 2011)
2011	Kano	NW	B	Tomato	6	$HClO_4+HNO_3$	FAAS(Co,Cr,Cu,Ni,Pb,Zn)	(Lawal & Audu, 2011)
2012	Owerri	SE	B	Beans		HNO_3+HClO_4	FAAS(Pb,Cd,Ni)	(Orisakwe et al., 2012)
2012	Owerri	SE	B	Cassava		HNO_3+HClO_4	FAAS(Pb,Cd,Ni)	(Orisakwe et al., 2012)

Table 3 (continued)

Year	City	Region	Type	Item	No of Samples	Digestion	Analysis method and metals	Ref
2013	Borno	NE	B	Onion	12	$HCl+HNO_3$	FAAS(Pb,Fe,Cu,Zn,Cd,Ni, Mn,Cr)	(Akan et al., 2013)
2013	Borno	NE	B	Cabbage	12	$HCl+HNO_3$	FAAS(Pb,Fe,Cu,Zn,Cd,Ni, Mn,Cr)	(Akan et al., 2013)
2013	Borno	NE	B	Lettuce	12	$HCl+HNO_3$	FAAS(Pb,Fe,Cu,Zn,Cd,Ni, Mn,Cr)	(Akan et al., 2013)
2013	Borno	NE	B	Spinach	12	$HCl+HNO_3$	FAAS(Pb,Fe,Cu,Zn,Cd,Ni, Mn,Cr)	(Akan et al., 2013)
2013	Enyigba	SE	A	Yam	x	x	XRF(Pb,As,Cd,Cu,Cr,Zn,Mn,Ni)	(Wilberforce & Nwabue, 2013)
2013	Enyigba	SE	A	Sweet potato	x	x	XRF(Pb,As,Cd,Cu,Cr,Zn,Mn,Ni)	(Wilberforce & Nwabue, 2013)
2014	Zaria	NW	B	Okra	4	x	FAAS(Pb,Fe,Cr,Zn)	(Funtua et al., 2014)
2014	Zaria	NW	B	Beans	4	x	FAAS(Pb,Fe,Cr,Zn)	(Funtua et al., 2014)
2014	Zaria	NW	B	Maize	4	x	FAAS(Pb,Fe,Cr,Zn)	(Funtua et al., 2014)
2014	Rivers	SS	B	Avocado pear	4	HNO_3+HClO_4+HCl	FAAS(Cd,Cu,Ni,Pb,Zn,Co, Fe,Mn)	(Ihesinachi & Eresiya, 2014)
2014	Rivers	SS	B	Orange	4	HNO_3+HClO_4+HCl	FAAS(Cd,Cu,Ni,Pb,Zn,Co, Fe,Mn)	(Ihesinachi & Eresiya, 2014)
2014	Rivers	SS	B	Pawpaw	4	HNO_3+HClO_4+HCl	FAAS(Cd,Cu,Ni,Pb,Zn,Co, Fe,Mn)	(Ihesinachi & Eresiya, 2014)
2014	Rivers	SS	B	Pineapple	4	HNO_3+HClO_4+HCl	FAAS(Cd,Cu,Ni,Pb,Zn,Co, Fe,Mn)	(Ihesinachi & Eresiya, 2014)
2014	Lagos	SW	B	Mango	162	HNO_3+HCl	FAAS(Pb,Cd,Zn,Cu,Co,Ni,As,Hg,Mn,Cr)	(Ogunkunle et al., 2014)
2014	Lagos	SW	B	Pawpaw	162	HNO_3+HCl	FAAS(Pb,Cd,Zn,Cu,Co,Ni,As,Hg,Mn,Cr)	(Ogunkunle et al., 2014)
2014	Lagos	SW	B	Water-melon	162	HNO_3+HCl	FAAS(Pb,Cd,Zn,Cu,Co,Ni,As,Hg,Mn,Cr)	(Ogunkunle et al., 2014)
2014	Lagos	SW	B	Cabbage	162	HNO_3+HCl	FAAS(Pb,Cd,Zn,Cu,Co,Ni,As,Hg,Mn,Cr)	(Ogunkunle et al., 2014)
2014	Lagos	SW	B	Lettuce	162	HNO_3+HCl	FAAS(Pb,Cd,Zn,Cu,Co,Ni,As,Hg,Mn,Cr)	(Ogunkunle et al., 2014)

Table 3 (continued)

Year	City	Region	Type	Item	No of Samples	Digestion	Analysis method and metals	Ref
2015	Zamfara	NW	B	Spinach	2	$HNO_3+H_2O_2$	FAAS(Pb,Cd,Fe,Cu,Zn)	(Salawu et al., 2015)
2016	Ughelli	SS	B	Cassava	6	$HCl+HNO_3$	FAAS(Cd,Zn,Ni,Cu,Cr)	(Nwaichi et al., 2016)
2017	Zaria	NW	B	Spinach	3	$HClO_4+HNO_3+H_2SO_4$	FAAS(Pb,Cd,Zn,Hg)	(Lawal et al., 2017)
2017	Abuja	NC	B	Green peas	3	$H_2SO_4+HClO_4+HNO_3$	FAAS(Cd,Cr,Cu,Pb,Zn)	(Oloruntoba et al., 2017)
2017	Kaduna	NW	B	Tomato	x	$HNO_3+H_2O_2+HCl$	FAAS(Pb,Fe,Cu,Zn,Cd,Ni,Mn,Cr)	(Ugya & Imam, 2017)
2017	Kaduna	NW	B	Okra	x	$HNO_3+H_2O_2+HCl$	FAAS(Pb,Fe,Cu,Zn,Cd,Ni,Mn,Cr)	(Ugya & Imam, 2017)
2017	Kaduna	NW	B	Garden egg	x	$HNO_3+H_2O_2+HCl$	FAAS(Pb,Fe,Cu,Zn,Cd,Ni,Mn,Cr)	(Ugya & Imam, 2017)
2017	Rivers	SS	C	Mango	6	$HClO_4+HCl+H_2SO_4$	FAAS(Pb,Cd,Cu,Mn,Mg,Zn)	(Kpee & Edori, 2017)
2017	Rivers	SS	C	Pawpaw	6	$HClO_4+HCl+H_2SO_4$	FAAS(Pb,Cd,Cu,Mn,Mg,Zn)	(Kpee & Edori, 2017)
2018	Ile Ife	SW	B	Maize	30	$H_2SO_4+HNO_3$	FAAS(As,Cd,Co,Cr,Cu,Ni,Pb,Zn)	(Adekiya et al., 2018)
2018	Ile Ife	SW	B	Tomato	30	$H_2SO_4+HNO_3$	FAAS(As,Cd,Co,Cr,Cu,Ni,Pb,Zn)	(Adekiya et al., 2018)
2018	Enyigba	SE	C	Yam	5	$HNO_3+HClO_4+H_2SO_4$	FAAS(Zn,Pb,Fe,Mn,Cu,As,Cd,Cr,Ni)	(Nworu et al., 2018)
2018	Enyigba	SE	C	Cassava	5	$HNO_3+HClO_4+H_2SO_4$	FAAS(Zn,Pb,Fe,Mn,Cu,As,Cd,Cr,Ni)	(Nworu et al., 2018)

x: Not reported, *SS* South-South, *SW* South-West, *SE* South-East, *NC* North Central, *NW* North-West, *NE* North-East, A-Industrial Land, B-Agricultural Land, C-Dump sites

Records of metals within standard permissible limits are also found in studies scattered across the country posing no health risk.

3.1 Heavy Metal Concentration in Soils

Reported concentrations of heavy metals content in soils are as presented in Table 5. Studies indicate the major sources of these metals as urban and industrial effluents, deterioration of sewage pipe, treatment water works, sewage sludge, fertilizers and pesticide applications in agricultural soils. The concentration ranges of heavy metals in the literature covered as shown in Table 5 are observed to be 0.01–210 for Cd, 0.3–844 for Cu, 0.05–1086 for Ni, 0.03–1620 for Pb, 0.81–6440 for Zn, 0.37–62.36 for Co, 0.14–1096.3 for Cr, 10.82–48947.5 for Fe, and 0.00–96.44 mg/kg for As.

Table 4 Materials and analytical tools of heavy metals analysis in meat and milk products in Nigeria

Year	City	Region	Type	No of Samples	Digestion	Analysis method and metals	Ref
2004	Cross river	SS	River	40	$H_2SO_4+HNO_3$	FAAS(Fe,Cu,Cd,Zn,Mn,Pb)	(Asuquo et al., 2004)
2008	Agbor	SS	Whole	10	$HNO_3+HClO_4+H_2O_2$	GFAAS(Cd,Pb,Mn,Ni,Cr,Fe,Zn)	(Iwegbue et al., 2008)
2008	Agbor	SS	Gizzard	10	$HNO_3+HClO_4+H_2O_2$	GFAAS(Cd,Pb,Mn,Ni,Cr,Fe,Zn)	(Iwegbue et al., 2008)
2008	Agbor	SS	Whole	10	$HNO_3+HClO_4+H_2O_2$	GFAAS(Cd,Pb,Mn,Ni,Cr,Fe,Zn)	(Iwegbue et al., 2008)
2010	Maiduguri	NE	Liver	1	$H_2SO_4+H_2O_2$	FAAS(Cu,Zn,Co,Mn,Mg,Fe,Cr,Cd,As,Ni,Pb)	(Akan et al., 2010)
2010	Maiduguri	NE	Liver	1	$H_2SO_4+H_2O_2$	FAAS(Cu,Zn,Co,Mn,Mg,Fe,Cr,Cd,As,Ni,Pb)	(Akan et al., 2010)
2010	Maiduguri	NE	Liver	1	$H_2SO_4+H_2O_2$	FAAS(Cu,Zn,Co,Mn,Mg,Fe,Cr,Cd,As,Ni,Pb)	(Akan et al., 2010)
2010	Maiduguri	NE	Liver	1	$H_2SO_4+H_2O_2$	FAAS(Cu,Zn,Co,Mn,Mg,Fe,Cr,Cd,As,Ni,Pb)	(Akan et al., 2010)
2010	Maiduguri	NE	Kidney	1	$H_2SO_4+H_2O_2$	FAAS(Cu,Zn,Co,Mn,Mg,Fe,Cr,Cd,As,Ni,Pb)	(Akan et al., 2010)
2010	Maiduguri	NE	Kidney	1	$H_2SO_4+H_2O_2$	FAAS(Cu,Zn,Co,Mn,Mg,Fe,Cr,Cd,As,Ni,Pb)	(Akan et al., 2010)
2010	Maiduguri	NE	Kidney	1	$H_2SO_4+H_2O_2$	FAAS(Cu,Zn,Co,Mn,Mg,Fe,Cr,Cd,As,Ni,Pb)	(Akan et al., 2010)
2010	Maiduguri	NE	Kidney	1	$H_2SO_4+H_2O_2$	FAAS(Cu,Zn,Co,Mn,Mg,Fe,Cr,Cd,As,Ni,Pb)	(Akan et al., 2010)
2010	Delta	SS	River	2	HNO_3+HCl	FAAS(Cd,Cr,Mn,Ni,Pb)	(Ekeanyanwu et al., 2010)
2010	Afikpo	SE	River	18	$HClO_4+HF$	FAAS(Fe,Zn,Cu,Mn,Pb,Cr)	(Nwani et al., 2010)
2011	Enugu	SE	Liver	x	HNO_3+HClO_4	FAAS(Pb,Cd,Cu,Zn)	(Okoye et al., 2011)
2011	Enugu	SE	Muscle	x	HNO_3+HClO_4	FAAS(Pb,Cd,Cu,Zn)	(Okoye et al., 2011)
2011	Enugu	SE	Gizzard	x	HNO_3+HClO_4	FAAS(Pb,Cd,Cu,Zn)	(Okoye et al., 2011)
2013	Ado Ekiti	SW	River	15	$HNO_3+H_2SO_4+H_2O_2$	FAAS(Zn,Mn,Cu,Fe,Pb,Cd)	(Edward et al., 2014)
2014	Sokoto	NW	Skin	x	HNO_3+HClO_3	FAAS(Co,Cr,Mn,Pb,Ni,Hg,Ba,Cd,Cu,Zn,Fe)	(Nnadozie et al., 2014)
2014	Sokoto	NW	Milk	x	HNO_3+HClO_3	FAAS(Co,Cr,Mn,Pb,Ni,Hg,Ba,Cd,Cu,Zn,Fe)	(Nnadozie et al., 2014)
2014	Sokoto	NW	Skin	x	HNO_3+HClO_3	FAAS(Co,Cr,Mn,Pb,Ni,Hg,Ba,Cd,Cu,Zn,Fe)	(Nnadozie et al., 2014)
2014	Sokoto	NW	Milk	x	HNO_3+HClO_3	FAAS(Co,Cr,Mn,Pb,Ni,Hg,Ba,Cd,Cu,Zn,Fe)	(Nnadozie et al., 2014)
2014	Sokoto	NW	Skin	x	HNO_3+HClO_3	FAAS(Co,Cr,Mn,Pb,Ni,Hg,Ba,Cd,Cu,Zn,Fe)	(Nnadozie et al., 2014)
2014	Sokoto	NW	Milk	x	HNO_3+HClO_3	FAAS(Co,Cr,Mn,Pb,Ni,Hg,Ba,Cd,Cu,Zn,Fe)	(Nnadozie et al., 2014)
2014	Sokoto	NW	Skin	x	HNO_3+HClO_3	FAAS(Co,Cr,Mn,Pb,Ni,Hg,Ba,Cd,Cu,Zn,Fe)	(Nnadozie et al., 2014)
2014	Sokoto	NW	Milk	x	HNO_3+HClO_3	FAAS(Co,Cr,Mn,Pb,Ni,Hg,Ba,Cd,Cu,Zn,Fe)	(Nnadozie et al., 2014)
2015	Yola	NE	Heart	24	$HNO_3+H_2SO_4$	FAAS(Zn,Co,Cu,Cd,Pb)	(Milam et al., 2015)
2015	Yola	NE	Intestine	24	$HNO_3+H_2SO_4$	FAAS(Zn,Co,Cu,Cd,Pb)	(Milam et al., 2015)
2015	Yola	NE	Stomach	24	$HNO_3+H_2SO_4$	FAAS(Zn,Co,Cu,Cd,Pb)	(Milam et al., 2015)
2015	Yola	NE	Kidney	24	$HNO_3+H_2SO_4$	FAAS(Zn,Co,Cu,Cd,Pb)	(Milam et al., 2015)
2015	Yola	NE	Liver	24	$HNO_3+H_2SO_4$	FAAS(Zn,Co,Cu,Cd,Pb)	(Milam et al., 2015)
2017	Zamfara	NW	Liver	x	$HClO_4+HNO_3$	FAAS(Pb,Cd,Zn,Cr,Cu,Mg,Ni)	(Orisakwe et al., 2017)
2017	Zamfara	NW	Liver	x	$HClO_4+HNO_3$	FAAS(Pb,Cd,Zn,Cr,Cu,Mg,Ni)	(Orisakwe et al., 2017)
2018	South-West	SW	Whole	25	HNO_3+HClO_4	FAAS(Cu,Cd,Cr,Pb)	(Taiwo et al., 2018)
2018	South-West	SW	Skin	25	HNO_3+HClO_4	FAAS(Cu,Cd,Cr,Pb)	(Taiwo et al., 2018)
2018	South-West	SW	Whole	25	HNO_3+HClO_4	FAAS(Cu,Cd,Cr,Pb)	(Taiwo et al., 2018)
2019	Abuja	NC		2	HNO_3+HClO_4	FAAS(Cd,Fe,Mn,Pb,Zn)	(Oloruntoba & Nathaniel, 2019)
2019	Cross river	SS	River	40	HNO_3+HF	FAAS(Fe,Zn,Mn,Cu,Pb,Cr)	(Okogwu et al., 2019)

Table 4 (continued)

Year	City	Region	Type	No of Samples	Digestion	Analysis method and metals	Ref
2019	Gombe	NE	Dam	30	$HNO_3 + HCl$	FAAS(Cu,Pb,Cr,Co,Ni,Cd,Mn,Mg)	(Ezekiel et al., 2019)
2019	Benin	SS	River	6	$HNO_3 + HClO_4 + H_2SO_4$	FAAS(Mn,Zn,Cu,Pd,Cd,Cr)	(Isibor et al., 2019)

x: Not reported, *SS* South-South, *SW* South-West, *SE* South-East, *NC* North Central, *NW* North-West, *NE* North-East

It is obvious that the mean concentrations of metals in all the geopolitical zones exceeded the background values reported by Akpoveta et al. (2010) and Oluyemi et al. (2008). In addition, they also exceeded the EU and WHO maximum allowable limits. While Fe recorded the highest concentration, Cd concentration was the lowest. The highest concentrations of heavy metals were found in SW cities (landfill in Ile Ife) and SE (sediments from Qua Iboe River). The highest concentrations of Cd, Ni, and Zn were found in SE dumpsites representing 210, 1086, and 6,440 mg/kg respectively. Also, at dumpsites were found the highest concentrations of Cu and Fe respective 844 and 48,947.5 mg/kg but at SW (Ile Ife). In similar vein, the highest concentration of As was found in soils samples from dumpsites in SE representing 96.44 mg/kg while 62.36 and 1096.30 mg/kg were the respective highest concentrations from NW (Katsina dumpsites). The highest concentration for Pb was also found in SW (Oyo) but at industrial sites. Though dumpsites accounted for the highest pollution of heavy metals, elevated concentrations were also found at industrial sites; battery production site, cement factory, minerals mining sites, crude oil spillage, among others. In contrast, recent study by Sulaiman et al. (2019) showed low concentrations of Cd, Cu, Pb Ni and Cr in Zamfara where gold mining is quite rampant compared to non-industrial zones. This could partly be attributed to the remediation measures put in place by international organizations after the 2010 episode of mass lead poisoning (Wurr & Cooney, 2014).

Studies across various African countries have yielded consistent findings. Gebeyehu et al. (2020) observed in Ethiopia that agricultural soils exhibited concentrations of As (24.5 mg/kg), Pb (37.9 mg/kg), Cd (5.3 mg/kg), Zn (98.9 mg/kg), Cu (26.0 mg/kg), Hg (6.3 mg/kg), and Co (15.1 mg/kg) surpassing reference levels. Similarly, Kacholi and Sahu (2017) identified in Tanzania that soil samples exceeded agricultural standards for Pb (22.7 mg/kg), Zn (30.7 mg/kg), Cu (1.8 mg/kg), and iron (Fe, 280.1 mg/kg). A review by Kaonga et al. (2017) highlighted that riverbank soils in industrial regions of Blantyre, Malawi, contained elevated heavy metal concentrations, including Cd (0.18 mg/kg dry weight, dw), Cr (8.19 mg/kg dw), Cu (10.13 mg/kg dw), Fe (82.82 mg/kg dw), Mn (31.43 mg/kg dw), Ni (4.32 mg/kg dw), Pb (3.49 mg/kg dw), and Zn (17.45 mg/kg dw). In South Africa, variations in heavy metal levels between winter and summer were noted, with summer season soils showing higher values, except for Cd; reported concentrations included Cd (0.48 mg/kg), Cr (37.52 mg/kg), Cu (22.68 mg/kg), Mn (134.31 mg/kg), Ni (3.12 mg/kg), Pb (22.21 mg/kg), and Zn (99.20 mg/kg). These levels indicate a widespread issue of heavy metal pollution in agricultural soils across the continent. They also demonstrated that dumpsites and industrial sites were hotspots for heavy metals accumulation in Nigeria and some nations in Africa. Proper regulations, steely enforcement and continuous monitoring would abate and eventually forestall this trend and in turn prevent excessive buildup of these metals that can lead to increasing toxicity and elevating the public health risks.

3.2 Heavy Metal Concentration in Water

The analysis of heavy metal concentrations, presented in Table 6, reveals significant levels across the six geopolitical zones, with concentrations in river and well water surpassing the WHO maximum permissible limits for both drinking water and irrigation purposes. Notably, in the NC (Ajaokuta well), the concentrations of As at 24.44 mg/L and Cr at 14.32 mg/L were the highest recorded. The reason is not far-fetched, Ajaokuta is the major hub for iron and steel mining and smelting in Nigeria, hence, metal leachate from the factories could have been responsible. Furthermore, the high concentration of heavy metals in groundwater may originate from lithogenic sources,

Table 5 Concentrations of heavy metals (mg/kg) in soils across Nigeria six geopolitical regions

Year	City	Cd	Cu	Ni	Pb	Zn	Co	Cr	Fe	As	Ref
2000	Abeokuta	50.50	634.30	x	145.80	226.60	x	x	360.10	x	(Odukoya et al., 2000)
2001	Ibadan	0.55	17.00	10.50	81.00	48.00	7.90	22.10	x	x	(Onianwa, 2001)
2002	Lagos	0.13	2.19	1.96	11.67	x	x	0.31	x		(Adeniyi & Afolabi, 2002)
2003	Oyo	50.80	38.40	21.50	1620.00	134.00					(Olajire et al., 2003)
2003	Osun	0.05	x	1.43	4.67	4.15	x	x	x		(Amusan et al., 2003)
2004	Niger delta	x	0.30	18.00	0.80	x	x	x	x	x	(Osuji and C.M, 2004)
2005	Ile Ife	17.00	36.50	x	63.58	63.20	36.00	x	925.93	x	(Amusan et al., 2005)
2006	Port Harcourt	38.75	397.00	17.38	578.00	435.00	x	13.00	x	x	(Iwegbue et al., 2006)
2006	Port Harcourt	32.07	343.00	16.52	501.00	423.00	x	11.00	x	x	(Iwegbue et al., 2006)
2007	Onitsha	1.05	x	x	0.80	x	x	0.60	x	0.80	(Nwajei et al., 2007)
2008	Zaria	12.90	249.42	x	245.27	202.45	x	x	x	x	(Uba et al., 2008)
2008	Ile Ife	10.35	844.00	117.00	304.50	206.61	23.00	181.25	48,947.50	3.20	(Oluyemi et al., 2008)
2009	Niger delta	1.12	11.21	31.70	25.02	29.30	x	28.75	x	x	(Iwegbue et al., 2009)
2010	Abraka	1.50	14.31	5.10	12.24	74.26	9.73	22.40	1431.00		(Akpoveta et al., 2010)
2010	Jos	5.79	2.19	x	12.10	12.88	x	x	160.00		(Abechi et al., 2010)
2010	Agbabu	0.45	8.75	2.63	0.66	28.56	x	26.71	8144.40	x	(Olubunmi & Olorunsola, 2010)
2011	Kaduna	61.27	20.00	93.33	50.77	191.67	x	15.85	383.33		(Achi et al., 2011)
2011	Niger delta	1.12	11.20	31.70	25.00	29.30	x	28.80	x	x	(Iwegbue, 2011)
2012	Owerri	0.10	x	1.56	3.53	x	x	x	x	x	(Orisakwe et al., 2012)
2012	Akure	x	81.00	x	54.20	x	x	x	x	x	(Akinbile, 2012)
2012	Suleja	29.38	29.92	20.00	49.79	75.69	x	21.82	x	x	(Yisa et al., 2012)
2013	Benue	10.50	254.10	18.00	283.70	295.50	x	x	x	x	(Pam et al., 2013)
2013	Sagamu	39.90	156.60	x	613.40	188.50	x	x	x	x	(Ogunkunle & Fatoba, 2013)
2013	Okundi	29.74	13.27	x	5.74	10.92	x	x	x	x	(Aikpokpodion et al., 2013)
2013	Southeast	210.00	70.00	1086.00	70.00	6440.00	x	60.00	2853.00	x	(Uwah et al., 2013)
2013	Enyigba	126.00	812.20	82.60	1116.80	995.20	x	2.12	x	4.80	(Wilberforce & Nwabue, 2013)
2014	Aba	11.78	5.80	x	32.30	202.10	x	x	x	2.50	(Ogoko, 2014)
2014	Minna	0.02	21.41	0.05	15.50	27.70	x	0.16	x	0.00	(Ahaneku & Sadiq, 2014)
2014	Zaria	x	x	x	0.77	0.81	x	0.20	10.82	x	(Funtua et al., 2014)
2015	Enugu	20.15	25.17	34.19	138.48	43.37	51.65	11.40	x	96.44	(Ajah et al., 2015)
2016	Ughelli	0.20	1.05	2.08	x	0.91	x	3.31	x	x	(Nwaichi et al., 2016)
2016	Katsina	15.02	175.28	85.84	202.10	646.23	62.36	1096.30	x	0.56	(Bello et al., 2016)
2016	Ewekoro	x	0.38	x	0.23	2.57	x	0.46	184.71	x	(Okoro et al., 2017)
2017	UYO	9.05	x	12.56	9.90	137.00		3.60	1813.00		(Ihedioha et al., 2017)

Table 5 (continued)

Year	City	Cd	Cu	Ni	Pb	Zn	Co	Cr	Fe	As	Ref
2017	Port Harcourt	0.01	9.57	4.69	2.12	14.33	0.37	2.97	81.70	1.13	(Simeon & Friday, 2017)
2018	Odo-Oba	0.03	9.14	15.24	28.37	31.17	10.59	81.20	x	2.40	(Adagunodo et al., 2018)
2018	Ile Ife	3.00	10.86	3.96	3.73	9.80	3.83	4.20	x	3.87	(Adekiya et al., 2018)
2019	Zamfara	0.01	1.20	0.08	0.03	x	x	13.00	x		(Sulaiman et al., 2019)
2019	Katsina	0.03	x	ND	0.63	1.10	x	0.14	20.20	x	(Yaradua et al., 2019)
2019	Ogun	x	x	6.81	5.42	33.90	x	x	670.80	x	(Osobamiro et al., 2019)
	Minimum	0.01	0.30	0.05	0.03	0.81	0.37	0.14	10.82	0.00	
	Maximum	210	844	1086	1620.0	6440	62.36	1096.30	48,947.5	96.44	
	EU MTL	1	100	60	60	200	20	100	x	5	(Finland, 2007)

x: Not reported, *ND* Not detected, *MTL* Maximum tolerant limit, *PPM* Parts per million = mg kg^{-1} = μg g^{-1}, *PPB* Parts per billion = 10^{-9} = μg kg^{-1} = ng g^{-1}

due to the region's high metal deposits, or from anthropogenic activities. A study by Gleekia et al. (2016) identified high levels of As^{3+}/As^{5+} in surface water near an iron ore mining site in Liberia, implicating surface runoff and leachates from mining tailings as primary contributors. Similarly, elevated As levels were detected in surface water in NW (Kaduna) and well water in SE (Abakaliki), with no reports on irrigation water tested for As pollution.

Irrigation water (river) in Kano, utilized for agricultural purposes, was found contaminated with heavy metals, showcasing the highest concentrations of Cd at 13.7 mg/L, Cu at 4.9 mg/L, Co at 1.9 mg/L, and Zn at 10.4 mg/L. The WHO maximum permissible limit for Cd in drinking water (0.003 mg/L) was surpassed by the majority of water samples, as was the irrigation water limit of 0.01 mg/L for Cd. Conversely, all water samples had Cu concentrations below the WHO maximum limit for drinking water (2.0 mg/L), except for irrigation water in NW (Kano), which also exceeded the WHO permissible limit for Cu in irrigation water (0.2 mg/L). Although Co concentrations were less frequently reported, the observed levels mostly remained under the WHO permissible limit for irrigation water. High Zn concentrations, exceeding the WHO permissible limit for drinking water, were observed in four cities across three geopolitical zones: Ado Ekiti-SW (4.65 mg/L), Zamfara-NW (4.24 mg/L), Itaogbolu-SW (3.2 mg/L), and Nassarawa-NC (3.19 mg/L).Four cities (Ado Ekiti-SW, Zamfara-NW, Itaogbolu-SW, and Nassarawa-NC) coming from three different geopolitical zones have high Zn concentrations above the WHO permissible limit for drinking water which are 4.65, 4.24, 3.2 and 3.19 mg/L, respectively.

While all water samples complied with the WHO permissible limit for Pb in irrigation water (5.0 mg/L), many exceeded the limit for drinking water (0.01 mg/L). The highest Pb concentration was identified in SE (Abakaliki well) at 2.18 mg/L. This analysis indicates that, with the exception of borehole water, most water sources are unsuitable for drinking or agricultural use across the six geopolitical zones. This situation has not seen significant improvement over the years, as indicated by the consistent detection of elevated metal levels in both 2003 and 2019.

Within the African continent, Malan et al. (2015) observed that Cd concentrations in irrigation waters at specific locales in South Africa slightly exceeded or

Table 6 Concentrations of heavy metals (mg/L) in water across Nigeria six geopolitical regions

Year	City	Type	Cd	Cu	Ni	Pb	Zn	Co	Cr	Fe	As	Ref
2003	Benin	River	0.73	1.30	2.05	0.90	1.20	x	0.40	4.00	x	(Oguzie, 2003)
2003	Ilorin	Irrigation River	2.37	x	6.78	x	0.08	x	x	x	x	(Dosumu et al., 2003)
2006	Enugu	Sachet water	0.01	0.71	0.01	0.00	x	x	x	x	x	(Orisakwe et al., 2006)
2006	Otuocha	River	0.00	0.90	0.01	ND	x	x	x	x	x	(Igwilo et al., 2006)
2008	Adamawa	Well	ND	0.02	ND	ND	ND	x	x	0.02	x	(Alexander, 2008)
2010	Lagos	Surface	x	x	0.60	x	0.42	x	x	7.30	x	(Olowu et al., 2010)
2010	Itaogbolu	Well	x	0.18	0.10	0.10	3.20	x	0.02	0.71	x	(Adefemi & Awokunmi, 2010)
2010	Delta	River	0.03	x	0.27	0.01	x	x	0.09	x	x	(Ekeanyanwu et al., 2010)
2010	Afikpo	River	x	1.35	x	0.05	1.93	x	0.06	2.71	x	(Nwani et al., 2010)
2011	Makurdi	River	ND	0.00	ND	0.00	0.00	x	x	x	x	(Rapheal & Adebayo, 2011)
2011	Warri	Surface	0.01	0.04	0.04	0.00	0.08	x	0.01	1.93	x	(Wogu & Okaka, 2011)
2011	Bayelsa	Surface	0.07	x	x	0.00	x	x	x	1.30	ND	(Meindinyo & Agbalagba, 2011)
2012	Nassarawa	Stream	0.02	0.95	x	0.04	3.19	x	x	7.51	x	(Opaluwa et al., 2012)
2012	Owena	Dam	0.00	0.59	0.62	0.01	0.03	x	0.05	2.14	x	(Irenosen et al., 2012)
2013	Ile Ife	River	0.03	1.83	0.35	0.05	1.98	0.07	x	x	x	(Ogunfowokan et al., 2013)
2013	Kano	Irrigation River	13.70	4.90	x	1.30	10.40	1.90	8.80	1.00	x	(Bichi & Bello, 2013)
2013	Ado Ekiti	River	0.13	0.84	x	0.16	4.65	x	x	5.87	x	(Edward et al., 2014)
2015	Zamfara	Irrigated water	0.04	1.84	x	1.64	4.24	x	x	10.05	x	(Salawu et al., 2015)
2015	Kaduna	Surface	x	1.19	x	1.30	0.95	x	2.41	2.14	1.01	(Aliyu et al., 2015)
2016	Gombe	Borehole	0.04	0.08	0.05	0.02	0.07	0.04	x	0.16	x	(Maigari et al., 2016)
2016	Ajaokuta	Well	0.05	0.05	x	0.25	1.54	x	14.32	0.64	24.44	(Orosun et al., 2016)
2017	Zaria	Irrigation River	0.09	x	x	0.46	0.10	x	x	x	x	(Lawal et al., 2017)
2017	Wukari	Well	0.00	0.00	x	0.02	x	x	x	0.04	0.00	(Aremu et al., 2017)
2018	Ebocha-Obrikom	Groundwater	x	0.01	0.00	0.00	0.30	x	0.00	5.30	x	(Raimi et al., 2018)
2018	Ebocha-Obrikom	Well	x	0.00	0.00	0.00	0.80	x	0.00	2.40	x	(Raimi et al., 2018)
2018	Yenogoa	Surface	0.01	x	0.01	0.01	0.15	0.00	0.00	0.14	x	(Aghoghovwia et al., 2018)
2019	Dutse	Groundwater	x	0.27	0.08	0.18	0.05	x	0.07	x	x	(Tahir et al., 2019)
2019	Lagos	Borehole	0.00	0.55	0.04	0.00	0.72	x	0.03	0.35	x	(Egbueri & Unigwe, 2019)
2019	Abakaliki	Surface	1.07	0.03	0.05	1.80	1.54	0.74	0.35	x	0.99	(Obasi & Akudinobi, 2019)
2019	Abakaliki	Groundwater	0.24	0.13	0.09	2.18	0.14	0.11	0.43		2.10	(Obasi & Akudinobi, 2019)
2019	Gboko	Well	ND	0.05	x	ND	0.13	x	ND	1.16	x	(Sesugh et al., 2019)
2019	Cross river	River	x	1.35	x	0.01	1.93	x	0.06	2.71	x	(Okogwu et al., 2019)
2019	Gombe	Dam	0.11	0.12	0.21	0.03	x	0.18	0.95	x	x	(Ezekiel et al., 2019)
2019	Benin	River	0.40	1.05	x	0.83	0.99	x	0.73	1.38	x	(Isibor et al., 2019)

Table 6 (continued)

Year	City	Type	Cd	Cu	Ni	Pb	Zn	Co	Cr	Fe	As	Ref
		Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	
		Maximum	13.70	4.90	6.78	2.18	10.40	1.90	14.32	10.05	24.44	
		WHO	0.00	2.00	0.02	0.01	3.00	x	0.05	0.30	xx	(Raimi et al., 2018)
		NAFDAC	0.00	1.00	0.07	0.01	5.00	xx	0.05	0.3	xx	(Raimi et al., 2018)
		FAO Irrigated water	0.01	0.20	x	5.00	2.00	0.05	0.10	5.00	0.1	(Ayers & Westcott, 1985)

xx: Not available, x: Not reported

reached the upper limit of 0.05 mg Cd/L, a threshold established for irrigation purposes, during both winter and summer agricultural seasons. In Malawi, Kaonga et al. (2017) documented notable concentrations of metals in surface waters, with Cd (0—0.05 ppm), Cr (0.010—0.046 ppm), Cu (0.08—1.98 ppm), Fe (0.045—0.747 ppm), Mn (0.123—0.338 ppm), Ni (0.101—0.578 ppm), Pb (0.21—0.93 ppm), and Zn (0.102—2.614 ppm). Moreover, irrigation waters in Tanzania were reported by Kacholi and Sahu (2018) to contain Pb (0.5 mg/L), Zn (0.8 mg/L), Cu (0.1 mg/L), and Fe (1.1 mg/L), with Pb and Fe levels exceeding permissible standards, attributed to road runoff and atmospheric deposition. Similarly, in Asia, Islam et al. (2018) found elevated levels of heavy metals in Bangladesh rivers, including, As ranging from 0.005 to 0.22 mg/L, Pb from 0.1 to 0.21 mg/L, Cd from 0.03 to 0.09 mg/L, and Cr from 0.012 to 0.18 mg/L, linked to mining activities, industrialization, and urbanization, thereby exceeding standard values. These findings underscore the pervasive nature of metal pollution in aquatic environments worldwide, highlighting the urgent need for stringent regulation and control of industrial discharges to mitigate this global environmental challenge.

3.3 Heavy Metal Concentration in Food Crops

Table 7 shows the reported values for heavy metals concentration in foods across the six geopolitical zones in Nigeria. The concentrations for all the reported food type ranged from 0.00 to 14.00 for Cd, 0.00 to 20.37 for Cu, 0.03 to 38.75 for Ni, 0.07 to 87.50 for Pb, 0.03 to 240.00 for Zn, 0.02 to 3.56 for Co, 0.03 to 17.38 for Cr, 1.18 to 300.00 for Fe, and 0.40 to 4.18 mg/kg in the case of As. The maximum concentrations (mg/kg) of the metals in order of decreasing magnitude were Fe > Zn > Pb > Ni > Cu > Cr > Cd > Co. These maximum concentration values were much higher than WHO/FAO permissible limits in vegetables and food crops except in Co. Rivers state (SS) had the highest concentrations of metals in vegetables and food crops (Okra, pumpkin, cassava, and cocoyam) which was attributed to the prevailing crude oil spillage in the area.

The highest concentration (14 mg/kg) of Cd was found in cassava grown in Ile Ife (SW) landfill site. With the exception of watermelon (approx. 0.00 mg/kg) from Lagos and pawpaw (not detected)

Table 7 Concentrations of heavy metals (mg/kg) in food crops across Nigeria six geopolitical regions

Year	Item	Cd	Cu	Ni	Pb	Zn	Co	Cr	Fe	As	Ref
2003	Plant	0.02	x	0.52	1.35	1.14	x	x	x	x	(Amusan et al., 2003)
2005	Pawpaw	0.36	5.55	x	9.70	4.95	0.63	x	169.19	x	(Amusan et al., 2005)
2005	Cassava	x	7.00	x	4.40	130.00	x	x	60.00	x	(Hart et al., 2005)
2005	Cocoyam	x	7.00	x	1.40	70.00	x	x	60.00	x	(Hart et al., 2005)
2005	Okra	x	14.00	x	5.50	216.00	x	x	150.00	x	(Hart et al., 2005)
2005	Pumpkin	x	17.00	x	5.50	240.00	x	x	300.00	x	(Hart et al., 2005)
2005	Waterleaf	x	8.00	x	4.80	180.00	x	x	160.00	x	(Hart et al., 2005)
2008	Maize	1.75	13.01	ND	65.00	19.23	ND	ND	24.00	4.15	(Oluyemi et al., 2008)
2008	Cassava	14.00	16.00	ND	87.50	36.14	2.50	ND	168.71	4.18	(Oluyemi et al., 2008)
2009	Beans	0.43	0.06	0.03	0.61	0.63	0.03	0.03	1.18	x	(Abah et al., 2009)
2011	Tomato	0.09	1.91	0.76	0.22	5.21	x	x	x	x	(Rapheal & Adebayo, 2011)
2011	Pumpkin	0.13	4.47	0.78	0.22	7.65	x	x	x	x	(Rapheal & Adebayo, 2011)
2011	Spinach	0.12	4.63	0.77	0.22	7.35	x	x	x	x	(Rapheal & Adebayo, 2011)
2011	Spinach	x	0.69	2.02	1.60	6.63	0.68	0.60	x	x	(Lawal & Audu, 2011)
2011	Okra	x	4.24	1.13	1.10	3.26	0.94	0.64	x	x	(Lawal & Audu, 2011)
2011	Onion	x	4.77	0.99	0.95	11.78	0.77	0.64	x	x	(Lawal & Audu, 2011)
2011	Tomato	x	0.74	1.20	1.56	1.55	0.55	0.49	x	x	(Lawal & Audu, 2011)
2012	Beans	0.22	x	2.65	0.22	x	x	x	x	x	(Orisakwe et al., 2012)
2012	Cassava	0.33	x	0.30	0.33	x	x	x	x	x	(Orisakwe et al., 2012)
2013	Onion	1.05	1.05	3.00	2.40	3.48	x	0.23	3.40	x	(Akan et al., 2013)
2013	Cabbage	2.30	3.22	0.80	2.20	2.20	x	2.20	2.50	x	(Akan et al., 2013)
2013	Lettuce	1.01	1.80	5.44	2.40	3.50	x	3.22	1.30	x	(Akan et al., 2013)
2013	Spinach	0.80	1.83	3.70	4.56	8.34	x	3.00	6.70	x	(Akan et al., 2013)
2013	Yam	0.20	0.55	0.22	1.37	0.62	x	0.20	x	1.20	(Wilberforce & Nwabue, 2013)
2013	Sweet potato	0.20	0.58	0.15	0.40	0.75	x	3.60	x	1.40	(Wilberforce & Nwabue, 2013)
2014	Okra	x	x	x	0.87	0.04	x	0.74	4.43	x	(Funtua et al., 2014)
2014	Beans	x	x	x	0.48	0.06	x	0.34	3.13	x	(Funtua et al., 2014)
2014	Maize	x	x	x	0.69	0.05	x	0.26	2.12	x	(Funtua et al., 2014)
2014	Avocado pear	0.15	3.10	3.34	1.69	8.87	1.62	x	28.60	x	(Ihesinachi & Eresiya, 2014)
2014	Orange	0.10	0.23	2.99	5.80	7.22	1.67	x	19.00	x	(Ihesinachi & Eresiya, 2014)
2014	Pawpaw	0.22	5.29	5.87	5.57	7.31	3.56	x	29.60	x	(Ihesinachi & Eresiya, 2014)
2014	Pineapple	0.08	0.64	1.16	5.01	6.78	1.43	x	25.70	x	(Ihesinachi & Eresiya, 2014)
2014	Mango	0.09	0.01	0.05	1.62	0.03	0.03	ND	x	ND	(Ogunkunle et al., 2014)
2014	Pawpaw	0.08	0.00	0.11	0.07	0.06	0.02	ND	x	ND	(Ogunkunle et al., 2014)
2014	Watermelon	0.00	0.01	0.14	1.76	0.05	0.02	ND	x	ND	(Ogunkunle et al., 2014)
2014	Cabbage	0.06	0.07	0.14	1.84	0.06	0.05	ND	x	ND	(Ogunkunle et al., 2014)
2014	Lettuce	0.09	0.00	0.29	1.93	0.13	0.05	ND	x	ND	(Ogunkunle et al., 2014)
2015	Spinach	0.02	1.93	x	0.61	1.84	x	x	25.67	x	(Salawu et al., 2015)
2016	Cassava	0.24	3.01	2.67	x	6.43	x	1.33	x		(Nwaichi et al., 2016)
2017	Spinach	0.22	x	x	7.19	12.92	x	x	x	x	(Lawal et al., 2017)
2017	Green peas	0.75	0.13	x	ND	34.50	x	17.38	x	x	(Oloruntoba et al., 2017)
2017	Tomato	1.50	1.21	1.44	1.20	1.22	x	1.20	x	x	(Ugya & Imam, 2017)
2017	Okra	0.70	0.38	1.53	0.70	1.18	x	1.54	x	x	(Ugya & Imam, 2017)
2017	Garden egg	0.50	0.81	0.70	0.80	0.54	x	0.86	x	x	(Ugya & Imam, 2017)
2017	Mango	0.20	4.03	x	2.74	1.98	x	x	x	x	(Kpee & Edori, 2017)
2017	Pawpaw	ND	4.01	x	1.41	4.92	x	x	x	x	(Kpee & Edori, 2017)

Table 7 (continued)

Year	Item	Cd	Cu	Ni	Pb	Zn	Co	Cr	Fe	As	Ref
2018	Maize	3.03	18.12	3.80	1.63	5.67	1.46	1.00	x	1.20	(Adekiya et al., 2018)
2018	Tomato	2.53	20.37	3.43	1.85	5.37	3.20	1.23	x	1.21	(Adekiya et al., 2018)
2018	Yam	0.50	12.75	28.00	0.55	58.75	x	0.04	12.00	0.45	(Nworu et al., 2018)
2018	Cassava	0.65	16.50	38.75	0.85	77.75	x	0.06	15.00	0.40	(Nworu et al., 2018)
	Minimum	0.00	0.00	0.03	0.07	0.03	0.02	0.03	1.18	0.40	
	Maximum	14.00	20.37	38.75	87.50	240.00	3.56	17.38	300.00	4.18	
	WHO/FAO	0.01	0.20	67.00	5.00	2.00	50.00	1.30	5.00	0.43	(Akan et al., 2013)

x: Not reported, *ND* Not detected, *PPM* Parts per million = mg kg^{-1} = μg g^{-1} = mg/L, *PPB* Parts per billion = 10^{-9} = μg kg^{-1} = ng g^{-1}

from Rivers state, all other food crops exceeded WHO/FAO tolerant limit for Cd.

On the other hand, the highest concentration of Cu was found in Tomato grown around gold mining site in Ile Ife (SW) region representing 20.37 mg/kg. While lower concentrations of Cu were found in vegetables obtained in Lagos (SW), Kano (NW), Abuja (NC), Kaduna (NC), and Otukpo (NC), higher concentrations of Cu above standard limit were found in Rivers (SS), Enyigba (SE), Ile Ife (SW) and Markurdi (NC). The low concentrations were obtained from food crops grown in farms and gardens with no history of industrial activities close to the area. As expected, higher concentrations were found in food crops grown on or around dump sites, mining sites and with irrigation water.

For Ni, highest concentration (38.75 mg/kg) was found in cassava grown within the vicinity of lead–zinc mining site in Enyigba (SE). Contrary to the result of Ile Ife (SW) for Cd, Ni was not detected in the maize and cassava grown on the landfill and only low concentrations of Ni were observed in vegetables.

The concentrations of Pb observed in food crops grown on Ile Ife landfill (SW) were highest (87.5 mg/kg) in cassava than any other region, next is 65 mg/kg observed in maize and 9.7 mg/kg in pawpaw. Although lower concentrations of Pb than WHO/FAO permissible limits are observed across many of the food crops, however, higher concentrations were found in vegetables (spinach, okra, pumpkin) grown with irrigation water in Zaria (NC), and fruits (orange, pawpaw, pineapple) harvested in Rivers (SS). No Pb concentration was detected in green peas obtained in Abuja market (NC).

While the highest concentration (240 mg/kg) of Zn was found in pumpkin grown around areas of high industrial activities in River state (SS), elevated levels of Zn above WHO/FAO permissible limit of 2 mg/kg in food crops were also found across all the geopolitical zones. Few exceptions of lower Zn concentrations were found in Kano (NW), Kaduna (NW), Zaria (NW), Enyigba (SE), and Lagos (SW).

Although only few studies investigated Co concentrations in food crops, most of the regions reported lower concentrations of Co below the permissible limit of WHO/FAO in vegetables and food crops. However, 3.56 mg/kg representing the highest concentration of Co was found in Pawpaw harvested in Rivers state around heavy industrial sites.

Similarly, lower levels of Cr were found in the few available studies. The highest Cr concentration (17.38 mg/kg) was found in green peas bought from Abuja market (NC) which is higher than the permissible limit of WHO/FAO for Cr in vegetables. Higher concentrations of Cr in vegetables were also observed in Kaduna (NW) and Rivers (SS); with cabbage having 2.2 mg/kg, lettuce (3.22 mg/kg), spinach (3.0 mg/kg), tomato (1.2 mg/kg), and okra (1.54 mg/kg).

Elevated levels of Fe were found across all the zones with the highest concentrations in pumpkin grown around areas of high industrial activities in Rivers state (SS) representing 300 mg/kg. The concentration of Fe in most of the food crops are higher than WHO/FAO maximum limit in food crops of 5 mg/kg. Areas of heavy anthropogenic activities except Lagos (SW) had the largest share of these high concentrations.

Similar to Co, there were limited available studies on As concentration in food crops. Vegetables in Lagos (SW) were reported to be free from As and the

Table 8 Concentrations of heavy metals (mg/kg) in meat and milk products across Nigeria six geopolitical regions

Year	City	TYPE	Meat/Milk	Cd	Cu	Ni	Pb	Zn	Co	Cr	Fe	Ref
2004	Cross river	River	Fish	0.80	1.80	x	3.00	30.80	x	x	131.00	(Asuquo et al., 2004)
2008	Agbor	Whole	Chicken	0.01	0.01	6.62	0.01	16.25	x	0.01	14.32	(Iwegbue et al., 2008)
2008	Agbor	Gizzard	Chicken	0.23	0.33	7.30	0.98	6.12	x	0.33	92.72	(Iwegbue et al., 2008)
2008	Agbor	Whole	Turkey	0.01	0.46	6.03	3.22	10.19	x	1.05	32.88	(Iwegbue et al., 2008)
2010	Maiduguri	Liver	Cow	0.43	0.87	0.29	0.25	4.24	0.43	0.43	2.13	(Akan et al., 2010)
2010	Maiduguri	Liver	Mutton	0.76	0.54	0.09	0.16	2.34	0.77	0.76	3.76	(Akan et al., 2010)
2010	Maiduguri	Liver	Caprine	1.22	1.02	0.19	1.34	6.23	0.22	1.22	3.98	(Akan et al., 2010)
2010	Maiduguri	Liver	Chicken	0.65	1.44	1.09	0.22	3.11	0.33	0.65	4.65	(Akan et al., 2010)
2010	Maiduguri	Kidney	Cow	0.17	0.54	0.16	0.15	3.87	0.23	0.32	1.87	(Akan et al., 2010)
2010	Maiduguri	Kidney	Mutton	0.34	0.34	0.04	0.08	1.76	0.56	0.65	3.07	(Akan et al., 2010)
2010	Maiduguri	Kidney	Caprine	0.39	0.62	0.13	1.20	4.76	0.14	0.85	2.51	(Akan et al., 2010)
2010	Maiduguri	Kidney	Chicken	0.16	0.44	0.24	0.16	2.23	0.17	0.27	3.54	(Akan et al., 2010)
2010	Delta	River	Catfish	0.27	x	0.28	0.01	x	x	0.08	x	(Ekeanyanwu et al., 2010)
2010	Afikpo	River	Fish	x	2.10	x	0.50	34.40	x	1.12	702.20	(Nwani et al., 2010)
2011	Enugu	Liver	Chicken	21.00	35.00	x	73.46	5.23	x	x	x	(Okoye et al., 2011)
2011	Enugu	Muscle	Chicken	18.04	54.49	x	100.50	ND	x	x	x	(Okoye et al., 2011)
2011	Enugu	Gizzard	Chicken	13.82	3.71	x	62.00	3.71	x	x	x	(Okoye et al., 2011)
2013	Ado Ekiti	River	Fish	0.04	0.66	x	0.09	0.95	x	x	1.09	(Edward et al., 2014)
2014	Sokoto	Skin	Camel	0.35	0.45	ND	ND	0.21	ND	ND	0.87	(Nnadozie et al., 2014)
2014	Sokoto	Milk	Camel	0.11	0.16	ND	ND	0.42	ND	0.19	0.15	(Nnadozie et al., 2014)
2014	Sokoto	Skin	Goat	0.08	0.36	ND	ND	0.16	ND	ND	0.42	(Nnadozie et al., 2014)
2014	Sokoto	Milk	Goat	0.42	0.13	ND	ND	0.32	ND	ND	0.22	(Nnadozie et al., 2014)
2014	Sokoto	Skin	Mutton	0.22	0.34	ND	ND	0.15	ND	ND	0.33	(Nnadozie et al., 2014)
2014	Sokoto	Milk	Mutton	0.10	0.72	ND	ND	0.57	ND	ND	0.11	(Nnadozie et al., 2014)
2014	Sokoto	Skin	Cow	0.20	0.22	ND	ND	0.16	ND	ND	0.12	(Nnadozie et al., 2014)
2014	Sokoto	Milk	Cow	0.00	0.14	ND	ND	0.43	ND	ND	0.21	(Nnadozie et al., 2014)
2015	Yola	Heart	Cow	0.04	2.05	x	0.17	2.05	0.00	x	x	(Milam et al., 2015)
2015	Yola	Intestine	Cow	0.03	2.35	x	0.15	2.35	0.00	x	x	(Milam et al., 2015)
2015	Yola	Stomach	Cow	0.04	2.58	x	0.15	2.58	0.00	x	x	(Milam et al., 2015)
2015	Yola	Kidney	Cow	0.30	1.91	x	0.17	1.91	0.00	x	x	(Milam et al., 2015)
2015	Yola	Liver	Cow	0.03	3.96	x	0.15	3.96	0.00	x	x	(Milam et al., 2015)
2017	Zamfara	Liver	Chicken	0.23	1.01	1.01	4.72	4.18	x	2.55	x	(Orisakwe et al., 2017)
2017	Zamfara	Liver	Cow	0.25	3.45	3.06	2.84	4.18	x	2.55	x	(Orisakwe et al., 2017)
2018	SouthWest	Whole	Fish	0.85	2.79	x	1.46	x	x	2.29	x	(Taiwo et al., 2018)

Table 8 (continued)

Year	City	TYPE	Meat/Milk	Cd	Cu	Ni	Pb	Zn	Co	Cr	Fe	Ref
2018	SouthWest	Skin	Cow	0.94	1.21	x	2.34	x	x	2.41	x	(Taiwo et al., 2018)
2018	SouthWest	Whole	Crayfish	1.20	19.92	x	1.86	x	x	2.71	x	(Taiwo et al., 2018)
2019	Abuja	Liver	Cow	0.50	x	x	ND	57.00	x	x	119.50	(Oloruntoba & Nathaniel, 2019)
2019	Cross river	River	Fish	x	0.60	x	0.20	7.00	x	0.30	2.71	(Okogwu et al., 2019)
2019	Gombe	Dam	Fish	0.01	0.03	0.25	ND	x	0.42	0.06	x	(Ezekiel et al., 2019)
2019	Benin	River	Fish	0.10	14.90	x	1.10	57.80	x	6.40	281.80	(Isibor et al., 2019)
			Minimum	0.00	0.01	0.04	0.01	0.15	0.00	0.01	0.11	
			Maximum	21.00	54.49	7.30	100.50	57.80	0.77	6.40	702.20	
			WHO	1.00	0.02	x	0.50	50.00	x	x	300.00	(Asuquo et al., 2004)

x: Not reported, *ND* Not detected, *PPM* Parts per million = mg kg^{-1} = μg g^{-1}, *PPB* Parts per billion = 10^{-9} = μg kg^{-1} = ng g^{-1}

cassava analyzed in Enyigba (SE) was in low concentration, 0.40 mg/kg. The rest of the food crops had As concentrations higher than the maximum permissible limit of WHO/FAO of 0.43 mg/kg.

In Ethiopia, elevated levels of metals in tomatoes and cabbages on a dry weight basis (mg/kg) included arsenic (As, 1.93 and 5.73), Pb (3.63 and 7.56), Cd (0.56 and 1.56), Zn (24.50 and 23.53), Cu (16.27 and 9.42), Fe (85.10 and 490.46), Mn (27.20 and 302.23), Cr (1.49 and 4.63), mercury (Hg, 3.43 and 4.23), Ni (1.86 and 4.13), and cobalt (Co, 0.63 and 1.86) (Gebeyehu & Bayissa, 2020). In South Africa, concentrations of heavy metals in vegetables (cabbage, cauliflower, carrots, and lettuce) during the winter season were reported as follows: Cd (0.01–0.51 mg/kg), Cr (1.41–4.48 mg/kg), Cu (2.91–16.14 mg/kg), Mn (6.12–79.85 mg/kg), Ni (0.02–2.01 mg/kg), Pb (0.03–9.96 mg/kg), and Zn (24.90–89.10 mg/kg) (Malan et al., 2015). In Tanzania, concentrations of heavy metals in vegetables (eggplant, sweet potato, green amaranth, and okra) exceeded the FAO/WHO maximum permissible limits for Pb (0.32–2.46 mg/100 g), Zn (2.64–10.29 mg/100 g), and Cu (0.55–1.04 mg/100 g), but not for iron (Fe, 4.84–13.64 mg/100 g) when compared to their respective limits, except for Fe (0.03, 6.0, 4.0, 42.5 mg/100 g) (Kacholi & Sahu, 2018).

3.4 Heavy Metal Concentration in Meat and Milk Products

Reported heavy metals concentration in meat and milk products across the six geopolitical zones are presented in Table 8. The concentrations (mg/kg) ranged from 0 to 21.00 for Cd, 0.01 to 54.49 for Cu, 0.04 to 7.30 for Ni, 0.01 to 100.5 for Pb, 0.15 to 57.80 for Zn, 0 to 0.77 for Co, 0.01 to 6.40 for Cr, 0.11 to 702.20 for Fe. The maximum concentrations found for all the metals were higher than WHO/FAO permissible limits in meat and milk products.

Lower concentrations of Cd were observed in all the meat and milk products except in two cities; Enugu (SE) and Maiduguri (NE) where elevated concentrations of Cd were found in caprine liver (1.22 mg/kg), chicken gizzard (13.82 mg/kg), and chicken muscle (18.04 mg/kg) which was the highest of all the meat samples. It is noteworthy that although none of the meat and milk samples lack the presence of Cd, most are below WHO maximum permissible limit.

On the contrary, elevated concentrations of Cu above standard limit were found in most of the meat and milk products across all the regions. The highest Cu concentration was found in Enugu (SE) chicken muscle representing 54.49 mg/kg which was higher than the standard permissible limit. However, Agbor (SE) whole chicken has the lowest concentration (0.01 mg/kg). For the milk products, though the concentration of Cu in milk obtained from camel, goat and cow in Sokoto (NW) representing 0.16, 0.13 and 0.14 mg/kg respectively are low, that of sheep in the same region was relatively high (0.72 mg/kg).

Ni concentrations in all the meat and milk products on the average was low but high concentrations were found in Agbor (SE) for whole chicken and turkey in the range of 6.03 to 7.3 mg/kg. Elevated concentrations were also found in the liver of cow and chicken in Zamfara (NW) representing 1.01 and 3.06 mg/kg respectively. Notably, most of the studies on fish excluded Ni analysis and few reported very low concentrations.

Although the average concentration of Pb in the fish and milk products was high. The concentrations across many of the studies were lower than WHO maximum limit of 0.5 mg/kg. The highest concentration of Pb was found in chicken muscle in Enugu (SE) representing 100.5 mg/kg. Similarly, elevated Pb concentrations were observed in Enugu (SE) chicken muscle, Zamfara (NW) chicken liver, Zamfara (NW) cow liver representing 73.46, 4.72, 2.84 mg/kg respectively. Additionally, the levels of Pb in fish were also relatively high as can be seen in fish from Benin river (SS), fish and crayfish in southwest (SW) representing 1.1, 1.46 and 1.86 mg/kg respectively. Fish obtained from dam was free of Pb likewise the raw milk samples.

Apart from the cow liver in Abuja (NC) which had the highest Zn concentrations of 57 mg/kg, all other meat and milk products had low Zn concentrations below WHO/FAO permissible limits. Co and Cr were not detected in most of the few available metal investigated in meat and milk products.

The distribution of Fe concentration in the meat and milk products was quite low relative to the permissible limit (300 mg/kg) set by WHO. The only elevated Fe concentration was observed in whole fish from Afikpo river (SE) representing 702.2 mg/kg which was much higher than the standard permissible limit. Data for As concentration in meat and milk products was not provided because most of the studies excluded it in their investigations.

In studies conducted within Egypt, Tanzania, and Zambia, concentrations of lead (Pb) in fish were reported as 4.7, 4.9, and 3.8 mg/kg, respectively. Associated levels of cadmium (Cd), copper (Cu), zinc (Zn), and chromium (Cr) were identified as Cd (2.8, 0.39, 4.4 mg/kg), Cu (8.3, 5.90, 9700 mg/kg), Zn (43.9, 64, 300 mg/kg), and Cr (20.1, not reported, 0.7 mg/kg), respectively (Yabe et al., 2010). The sources of these metals were attributed to municipal, industrial, and agricultural wastes in Egypt; gold mining activities in Tanzania; and operations in the Copperbelt mines of Zambia (Yabe et al., 2010). In addition, in Marrakech City, Morocco, Cd contamination in cattle grazed on fields irrigated with municipal wastewater reached 10.3—2.5 mg/kg in kidney tissues and 0.6—0.2 mg/kg in muscle tissues. Further, elevated concentrations in Egypt of Pb (0.72 mg/kg) in cattle kidneys and Cd (0.91 mg/kg) in goat livers were detected, which was also linked to industrial emissions from urban areas. The parallels drawn with Nigerian data underscore the imperative for timely and precise regulation of industrial outputs to mitigate the widespread issue of heavy metal contamination in Africa (Yabe et al., 2010).

3.5 Contamination Levels of Heavy Metals in Soils

Muller (1969) introduced geo-accumulation index (I_{geo}) as a tool for assessing the ecological risks of heavy metals in different soils even in sediments by comparing the present concentrations with the background or pre-industrial concentrations. After using the calculation of I_{geo} as presented below, Muller devolved pollution levels into 6 classes as shown in Table 9; the classes increase with contamination levels.

$$I_{geo} = log_2\left[\frac{C_n}{1.5B_n}\right]$$

where, C_n represents the present measured concentration of metal *n* in the soil samples, B_n represents the background or pre-industrial value for the metal *n*, while 1.5 correction factor is the possible lithological or anthropogenic variations in the background

Table 9 Levels of heavy metals contamination based on geo-accumulation Index classes

Level of Contamination	Geo accumulation index	Class
Non contamination	$I_{geo} \leq 0$	0
Light to moderate	$0 < I_{geo} < 1$	1
Moderate	$1 < I_{geo} < 2$	2
Moderate to strong	$2 < I_{geo} < 3$	3
Strong	$3 < I_{geo} < 4$	4
Strong to extremely serious	$4 < I_{geo} < 5$	5
Extremely serious	$5 < I_{geo} < 10$	6

concentration. In Nigeria, best to the knowledge of the authors, since there is no available standard background value for all the metals for each region or for the whole country, most authors utilized the values of control samples to extract the background concentrations (Funtua et al., 2014; Isibor et al., 2019; Iwegbue et al., 2009; Izah et al., 2017; Ogoko, 2014; Ogunfowokan et al., 2013; Olubunmi & Olorunsola, 2010; Onianwa, 2001) while few utilized reported world mean elemental concentrations which limits the number of metals that could be evaluated (Akpoveta et al., 2010; Bello et al., 2016; Ihedioha et al., 2017).

The I_{geo} values for the heavy metals in soils across all the geopolitical zones are presented in Table 10. For all the metals in all the zones, I_{geo} levels ranged very widely suggesting that there were variations in the soils properties as well as the sources of heavy metals contamination.

The least I_{geo} values for Ni, Fe, Cu, and Pb were found in Zamfara (NW) depicting that it was the least contaminated zone, while Ewekoro, the cement factory sites in Ogun state (SW) and Benue (NC) indicate the highest I_{geo}. The average I_{geo} value for Cd, Cu, Ni, Pb, Zn, Co, Cr, Fe and As are 1.20, 0.22, -0.60, -0.12, 0.27, 0.34, -1.20, 25.00, and -1.09 respectively. The obtained mean data suggests that Cr, Ni, As, Cu, Pb, Co, and Zn falls into the class of "uncontaminated soil". A similar finding reported

Table 10 Geoaccumulation index of soils in Nigeria

Year	City	Region	Cd	Cu	Ni	Pb	Zn	Co	Cr	Fe	As	Ref
2010	Abraka	SS	3.00	0.48	0.13	1.22	0.83	1.22	0.22	0.04	x	(Akpoveta et al., 2010)
2010[a]	Agbabu	SW	-2.35	0.51	0.67	0.21	0.10	x	0.15	0.00	x	(Olubunmi & Olorunsola, 2010)
2010[b]	Agbabu	SW	-1.49	0.51	0.47	0.53	0.12	x	0.18	0.00	x	Olubunmi & Olorunsola, 2010)
2012	Suleja	NC	0.15	0.29	0.55	-0.17	0.45	x	-0.46	x	x	(Yisa et al., 2012)
2013	Benue	NC	0.33	4.69	1.05	3.88	0.68	x	x	x	x	(Pam et al., 2013)
2013	Southeast	SE	3.40	0.20	6.30	0.40	1.80	x	0.60	-0.90	x	(Uwah et al., 2013)
2013	Ile Ife	SW	7.30	4.46	5.89	0.08	3.00	5.65	x	x	x	(Ogunfowokan et al., 2013)
2014	Zaria	NW	x	x	x	0.10	0.88	x	-3.78	-0.26	x	(Funtua et al., 2014)
2014	Aba	SE	5.86	-2.90	x	0.30	-4.86	x	x	x	-2.71	(Ogoko, 2014)
2015	Enugu	SE	-1.20	-1.20	0.10	0.20	-1.10	-1.90	-1.30	1.90	x	(Ajah et al., 2015)
2016	Katsina	NW	-0.60	2.00	0.53	x	2.06	-1.07	x	x	-0.58	(Bello et al., 2016)
2016	Ewekoro	SW	x	0.49	x	0.30	4.47	x	0.56	323.49	x	(Okoro et al., 2017)
2017	Niger Delta	SS	-0.62	-0.56	-0.03	0.45	-2.32	-1.89	0.68	-1.74	x	(Izah et al., 2017)
2017	Port Harcourt	SS	0.00	0.04	0.01	0.02	0.03	0.00	0.01	0.00	0.02	(Simeon & Friday, 2017)
2017	UYO	SS	4.20	x	-3.40	-1.90	0.40	x	-5.60	-5.20	x	(Ihedioha et al., 2017)
2019	Zamfara	NW	1.00	-6.00	-20.00	-6.00	x	x	-4.00	-18.00	x	(Sulaiman et al., 2019)
2019	Katsina	NW	-0.95	x	x	-1.58	-2.24	x	-2.89	0.11	x	(Yaradua et al., 2019)
		Min	-2.35	-6	-20	-6	-4.86	-1.9	-5.6	-18	-2.71	
		Max	7.30	4.69	6.3	3.88	4.47	1.22	0.68	323.49	0.02	
		Mean	**1.20**	**0.22**	**-0.60**	**-0.12**	**0.27**	**0.34**	**-1.20**	**25.00**	**-1.09**	

x: Not reported

[a]dry season

[b]rainy season

by Wei and Yang (Wei & Yang, 2010) showed that Cr, Ni, Cu, Pb, Zn and Cd were in the uncontaminated category for urban road side and agricultural soils in China. However, the mean I_{geo} values of Fe and Cd indicated that they were at contamination levels. In fact, Fe (323.49 I_{geo}) was extremely abundant. This pollution principally stemmed from the soils around Ewekoro (SW) which is one of the cities known for cement manufacturing. Adding to this, Ewekoro (SW) as shown in Fig. 6 also had the highest I_{geo} value for Zn (4.47) in the category of strong to extremely serious contamination level. For Cd, the highest I_{geo} value (5.86) was found in Aba (SE), where the soils were obtained from oil depot vicinity. Strong level of Cu and Pb contamination of 4.69 and 3.88 I_{geo} value respectively were observed in Benue (NC) where the soils were obtained from auto mechanic workshops. The lowest and the highest Co I_{geo} values of -1.89 and 5.65 were obtained from Niger delta region (SS) and a dumpsite in Ile Ife (SW) respectively. The latter fell into the category of extremely serious contamination level. As was understudied, and the few available data show that it was uncontaminated contrary to the report of extremely high concentration of 96.44 mg/kg in Enugu dumpsite (SE). Future studies should consider analyzing As metal in pollution investigations especially in agricultural soils and sediments.

Predominantly, landfills and industrial endeavors contribute significantly to soil pollution within Nigeria, a conclusion that aligns with observations recorded in the United States. An analysis of literature data spanning from 1996 to 2016 in the United States reveals that areas with extensive urban development history and rural areas engaged in lead (Pb)-related industrial activities demonstrate higher soil Pb concentrations in comparison to those found in less urbanized and untouched regions. A meticulous synthesis of information from residential Superfund sites indicates that while remediation efforts have effectively lowered soil Pb levels, these levels persistently exceed those typical of non-urbanized areas. Furthermore, despite soil Pb remediation, dust analyses from these sites consistently report elevated Pb concentrations, highlighting the imperative need for additional research to comprehensively understand the

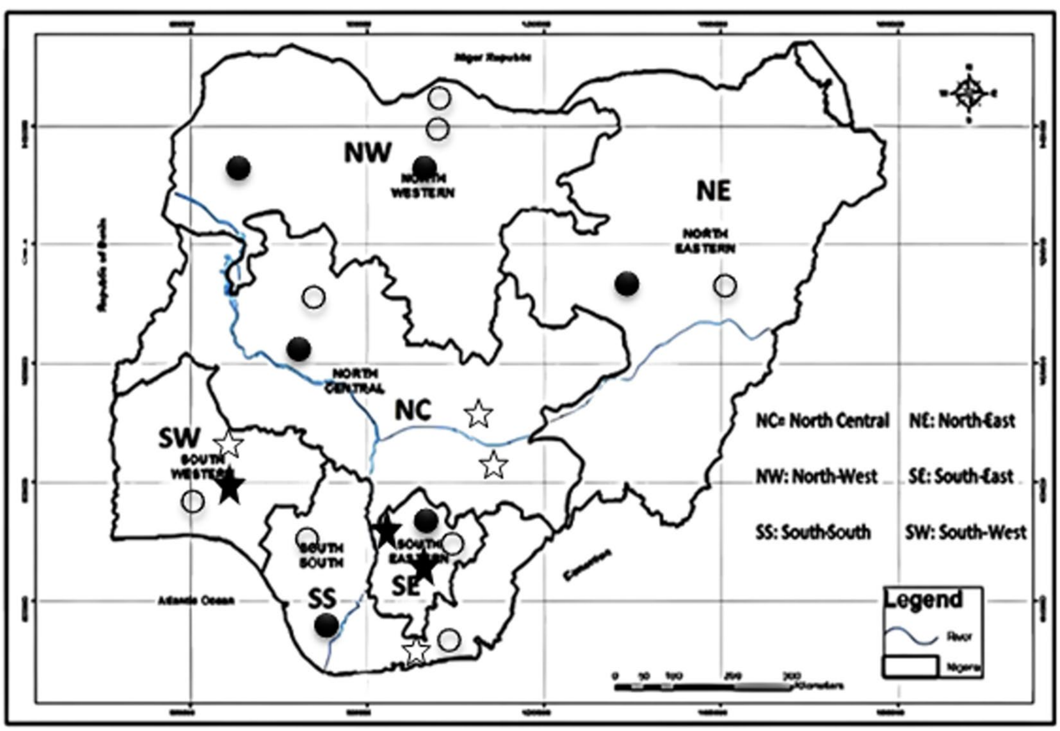

Fig. 6 Spatial distribution of the geoaccumulation index in soils from different geopolitical zones in Nigeria

persistence of Pb contamination in dust at residential Superfund locations (Frank et al., 2019).

4 National Regulations on Heavy Metals Remediation and Recommendations

Good policy is the vehicle for achieving clean and full value of natural resources. It is also upon its wings that heavy metal pollution can be addressed. Not until 2010 when heavy metals poisoning accounted for high mortality, heavy metal assessment in Nigeria was not given serious attention because its build up in the environment is always invisible and unnoticed, in addition to the fact that its effects are mostly chronic and not acute (Bartrem et al., 2014; Lar et al., 2013; Saxena et al., 2019).

The constitution of the Federal Republic of Nigerian (CFN) of 1999 gives the general driving force of the nation's environmental policy through S.20 which states that "The state shall protect and improve the environment and safeguard the water, air and land, forest and wild life of Nigeria". The interpretation of "improve and safeguard" envelops a non-discontinuous check on anthropogenic pollutions. Therefore, any activities promoting heavy metal pollution breaches the law. Additionally, supplementary laws and regulations have been made to directly mitigate heavy metal problems and international conventions relating to environmental issues have been signed.

Furthermore, the Nigeria Land Use Act of 1978 requires the use of land "in sufficient quality"(Agbosu, 1988). This suggests that activities leading to pollution of the land contravenes the decree. The act assigns the control and management of urban land to the state governors and that of rural land to the local government authorities. Since 1999, the Nigeria government has passed more than a score laws, guidelines and regulations that cover heavy metal pollutions mitigations, few among them are listed below. The main pain points of these policies are the absence of steely determination to implement to enforce them on the part of the regulatory bodies and policymakers. Therefore, no new policy formulation is encouraged, instead the compliance and effectiveness of the existing policies be sought through government concerted efforts to address the inherent problems. For example, the National Agency for Food and Drug administration and Control (NAFDAC) sets permissible limits of toxic metals in water, food and drugs sold in Nigeria but these standards are not easily accessible to researchers or public and the compliance among local manufacturers is zero. This needs to be overhauled.

Related heavy metals pollution regulations in Nigeria are (Orji, 2012):

- The National Policy on the Environment (FAO/FAOLEX, 2016),
- The National Effluents Limitations Regulation (FAOLEX, 1991),
- The NEP (Pollution Abatement in Industries and facilities generating waste) regulations (FAO/FAOLEX, 1991b),
- The Management of Solid and Hazardous Wastes Regulations (FAO/FAOLEX, 1991a),
- National Guidelines on Environmental Management Systems (Office of Environmental Assessment Department, 1988),
- National Guidelines for Environmental Audit (Office of Environmental Assessment Department, 1988),
- National Air Quality Standard Decree No.59 of 1991(Office of Environmental Assessment Department, 1988),
- The National Environmental Standards and Regulations Enforcement Agency Act 2007 (NESREA Act)(PLAC, 2007), and
- The National Oil Spill Detection and Response Agency Act 2005 (NOSDRA Act)(FAO, 2006).

Essentially, private companies and public institutions should implement technical strategies to prevent heavy metal pollution in their workplace. Table 11 summarizes some of the technical and policy solutions which could be employed. Additionally, other recommendations to reduce heavy metal pollution include:

i. Intelligent discussions on heavy metals pollution between academics, research institutes, industries and policy makers are invaluable; an annual national multi-stakeholders conference on metal pollution jointly funded by government and private companies could be launched to achieve this.
ii. Most academic labs do not have adequate analytical tools for research, it is therefore sug-

Table 11 Summary of Heavy Metal Pollutant Sources, Technological Interventions, and Policy Strategies in Nigeria

Key Pollution source	Metals released	Technical measures	Policy measures	Reference
Waste Dumpsites	Pb, Hg, Cd, Cr, As, Cu, Fe	• Installing a proper communal waste management system to reduce the amount of waste entering the dumpsite • Covering the dumpsite with an impermeable membrane to reduce leaching of heavy metals into the soil • Constructing a leachate collection system to capture and treat hazardous liquids that escape from the dumpsite • Installing a ventilation system to reduce air pollution from burning garbage • Regularly monitoring the site for heavy metal contamination	• Setting up a system to identify and monitor dumpsites that are sources of pollution • Enforcing guidelines and regulations to ensure proper management of dumpsites • Creating public awareness and education campaigns about the health and environmental risks associated with dumpsite pollution • Implementing strict enforcement of regulations and penalties for violators	(Amusan et al., 2005; Ihedioha et al., 2017; Iwegbue et al., 2006; Nwajei et al., 2007)
Mining and quarry activities	Pb, Hg, Cd, Cr, Ar, Zn, Cu	• Implementing preventive measures to reduce the amount of dust and other pollutants released from mining and quarrying operations • Installing pollution control equipment to reduce the amount of heavy metals released into the air • Establishing a system for monitoring and controlling the release of pollutants from mines and quarries • Establishing a system for reclaiming and restoring mined and quarried areas • Implementing a system for collecting and treating wastewater and leachate from mines and quarries	• Enforcing guidelines and regulations to ensure proper management of mining and quarrying operations • Setting up a system to identify and monitor mines and quarries that are sources of pollution • Establishing a system of penalties and enforcement for violations of regulations • Requiring mining and quarrying companies to develop and implement pollution prevention plans • Ensuring that mine and quarry operators are properly trained and equipped to handle the hazardous materials they are dealing with	(Bartrem et al., 2014; Nworu et al., 2018; Sulaiman et al., 2019)

Table 11 (continued)

Key Pollution source	Metals released	Technical measures	Policy measures	Reference
Automechanic workshop	Pb, Hg, Cd, Cr, Ar	• Installing pollution control equipment such as exhaust scrubbers and catalytic converters to reduce the amount of pollutants released into the air • Establishing a system for monitoring and controlling the release of pollutants from auto mechanic workshops • Implementing a system for collecting and treating wastes and leachates from auto mechanic workshops • Implementing proper waste management systems to reduce the amount of hazardous materials entering the workshop • Requiring auto mechanic workshops to use approved cleaning solvents and other materials	• Establishing guidelines and regulations to ensure proper management of auto mechanic workshops • Setting up a system to identify and monitor auto mechanic workshops that are sources of pollution • Requiring auto mechanic workshops to develop and implement pollution prevention plans • Implementing strict enforcement of regulations and penalties for violators • Creating public awareness and education campaigns about the health and environmental risks associated with auto mechanic workshop pollution	
Heavy industrial plant	Pb, Hg, Cd, Cr, Ar, Ni, Zn, Cu	• Installing pollution control equipment such as scrubbers and filters to reduce the amount of pollutants released into the air • Establishing a system for monitoring and controlling the release of pollutants from heavy industrial plants • Implementing a system for collecting and treating wastewater and leachate from heavy industrial plants • Requiring heavy industrial plants to use approved cleaning solvents and other materials	• Establishing guidelines and regulations to ensure proper management of heavy industrial plants • Setting up a system to identify and monitor heavy industrial plants that are sources of pollution • Requiring heavy industrial plants to develop and implement pollution prevention plans • Implementing strict enforcement of regulations and penalties for violators	(Olajire et al., 2003)

Table 11 (continued)

Key Pollution source	Metals released	Technical measures	Policy measures	Reference
Oil spillage	Pb, Cd, Ni, Cr, V	• Install oil containment booms to absorb and prevent oil from entering water sources • Use absorbent materials to absorb and clean up oil from water sources • Utilize low-pressure water jetting to break up oil slicks • Construct sedimentation ponds to allow oil to settle out of water • Utilize chemical dispersants to break oil slicks into small droplets	• Implement strict regulations on oilfield operations and storage to prevent spills • Establish emergency response plans and teams to respond quickly to spills • Increase penalties for companies that cause spills and increase fines • Require companies to use best management practices to store, transport, and monitor oil • Require companies to create plans for spill clean-up and remediation	(Hart et al., 2005; Iwegbue, 2011; Nwaichi et al., 2016; Osuji and C.M, 2004)
Abattoirs	Pb, Hg, Cd, Cr, Ar	• Installing a proper waste management system to stop blood waste coming out of the abattoir • Installing pollution control equipment to reduce the amount of pollutants released into the air • Establishing a system for monitoring and controlling the release of pollutants from abattoirs • Implementing a system for collecting and treating wastewater and leachate from abattoirs • Requiring abattoirs to use approved cleaning solvents and other materials	• Establishing guidelines and regulations to ensure proper management of abattoirs • Setting up a system to identify and monitor abattoirs that are sources of pollution • Requiring abattoirs to develop and implement pollution prevention plans • Implementing strict enforcement of regulations and penalties for violators • Creating public awareness and education campaigns about the health and environmental risks associated with abattoir pollution	(Milam et al., 2015; Simeon & Friday, 2017)

gested that as a starting point, well-equipped regional and national laboratories can be set up instead of individual institutions which are poorly funded and managed. In the future, universities can therefore upon learning from the operation of regional labs coupled with general improvement in funding set up their own labs to enable them to more efficiently and effectively conduct their technical investigations.

iii. The current waste management system in the Nigeria is inadequate. The provision of subsidized or free trash collection and domestic waste management in all states and cities could drastically reduce the prevalence of open waste dumps. Moreover, landfill facilities should be engineered to meet the standards and practices of more advanced countries, such as those prescribed by the European Union directives. Furthermore, government regulators should ensure industrial compliance with environmental regulations and monitor and document waste disposal practices. As an example, in Nigeria, many auto mechanic workshops release battery waste, engine oils, and metal filings onto open lands and in drainages, where they are washed into water sources. Although there is a law prohibiting toxic waste disposal, enforcement of this law is weak. This loophole requires attention from the regulators.

iv. Phytoremediation is recommended as the most cost-effective and technically-feasible remediation technique for heavy metal pollution in soils in Nigeria. To further promote its adoption and to ensure successful implementation, the government should collaborate with academic institutions to provide educational resources for farmers.

5 Conclusions

This review provides a systematic review of the decade-long trend of heavy metal pollution levels in soil, water, food crops, meat and milk products in Nigeria. The sampling and analytical techniques adopted by researchers adhered to accepted standards. Analysis of the I_{geo} data revealed that the levels of Fe and Cd contamination exceeded those of other investigated metals, likely due to anthropogenic sources. Meanwhile, the concentrations of Cr, Ni, Co, As, Cu and Pb were relatively low, suggesting they were not significantly contaminated.

Borehole groundwater was found to have the lowest levels of all the determined metals, with the exception of Cu and Zn, making it the only relatively safe water source for drinking and grazing. Elevated levels of heavy metals were also observed in food crops such as vegetables, fruits, tubers and cereals across the nation. Evidently, the primary sources of heavy metal pollution in Nigeria are dumpsites, landfills, industrial point sources, mines and smelters, and oil spillage.

In the pursuit of advancing a collective understanding of heavy metal contamination and its ecological and health implications, it is imperative to adopt a meticulous approach in the reporting of metal analysis in environmental studies. A critical aspect that warrants particular attention is the lack of specification of ionic species, including the valency of metals, in the reported analyses. The distinct chemical forms of heavy metals, delineated by their ionic states, play pivotal roles in influencing their bioavailability, mobility, and toxicity in environmental matrices. Thus, we strongly recommend that researchers in heavy metals analysis endeavor to report not only the total concentrations of heavy metals in their samples but also the specific ionic species present. This practice will significantly enhance the interpretative value of the data, facilitating a more accurate assessment of environmental risk and the formulation of remediation strategies. Moreover, the specification of ionic species will allow for a more nuanced comparison across studies, contributing to a more comprehensive and coherent understanding of heavy metal pollution dynamics.

It is also recommended that a national guideline containing background values for heavy metals in soils and permissible limits of these in different environmental media be gazetted and made easily accessible to researchers and industrial experts for quality research and quality control. Furthermore, waste management systems in the country should be urgently overhauled, particularly with regard to eliminating open waste dumping systems from cities and villages and embracing the engineering of landfill facilities.

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