

HEALTH RISK ASSESSMENT OF HEAVY METALS FROM WATER SOURCES AROUND SELECTED DUMPSITES IN ONDO CITY, NIGERIA

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ABSTRACT

This study assessed the health risk of heavy metals in different water sources around dumpsites in selected areas of Ondo City, Ondo State. Water samples were collected for a period of six months spanning the dry and wet seasons. The samples were digested following standard procedures, and heavy metals were analysed using an Atomic Absorption Spectrophotometer. Health risks from ingestion were determined by calculating the hazard quotient (HQ), hazard index (HI), and incremental lifetime cancer risk (ILCR). Arsenic, Cadmium, Mercury, Lead and Chromium had values higher than the WHO recommendation for drinking and irrigation purposes. Cadmium and Mercury had $HQ \geq 1$, while ILCR for Chromium was not within the range stipulated by the United States Environmental Protection Agency (USEPA). This shows that water from these locations is not safe for any domestic or irrigation purposes; hence, regulations against indiscriminate dumping of waste should be strictly enforced to avoid water contamination.

Keywords: Heavy metals, Water Quality, Health risk assessment, Waste management, Ondo State.

INTRODUCTION

Water is a fundamental resource for life, playing a crucial role in domestic use, agriculture, industry, and ecosystem balance (Kilic, 2020). Surface water bodies (rivers, streams, and lakes), groundwater (wells and boreholes) and public taps/stand pipes are the most accessible sources of water for many communities in Nigeria (Abugu *et al.*, 2024). However, these water sources are increasingly threatened by pollution due to rapid urbanization, population growth, and poor waste management practices (Tariq & Mushtaq, 2023). One of the most common forms of water pollution is improper waste disposal practices, which can introduce heavy metals to water sources.

Heavy metals are non-biodegradable elements that can persist in the environment and accumulate in living organisms over time (Whitcombe, 2026). Heavy metals such as lead (Pb), Cadmium (Cd), Arsenic (As), chromium (Cr), and mercury (Hg) are toxic even at low concentrations and can pose severe risks to both human health and the environment (Rahman & Singh, 2019). These metals can enter surface water systems through various pathways, including atmospheric deposition, industrial discharge, agricultural runoff, and leakage of leachates from dumpsites (Njoku *et al.*, 2021; Xu *et al.*, 2024). Improper waste disposal and lack of engineered landfill systems have resulted in open dumpsites

becoming prominent sources of heavy metal pollution, especially in urban and semi-urban communities (Adejumo *et al.*, 2019). Surface water is a vital source of water for domestic, agricultural, and industrial uses in many communities. However, its contamination by heavy metals poses a serious threat to public health and environmental sustainability (Rahman & Singh, 2019). Prolonged exposure to contaminated water can lead to bioaccumulation of metals in the human body, causing adverse health effects such as organ damage, neurological disorders, and cancer (Bukhari *et al.*, 2024; Sharma *et al.*, 2023).

The rapid increase in urbanization and poor waste management practices in Ondo city, Ondo State, have led to the proliferation of open dumpsites, particularly near residential settlements. These dumpsites often receive various types of waste, including agricultural, organic, household, and electronic waste, which are capable of introducing heavy metals such as lead (Pb), cadmium (Cd), arsenic (As), nickel (Ni), zinc (Zn), mercury (Hg), and chromium (Cr) (Adejumo *et al.*, 2019; Ogunyemi *et al.*, 2020). When improperly managed, these heavy metals can leach into surrounding water sources through runoff and infiltration, especially during rainfall (Wang *et al.*, 2024). Given the widespread indiscriminate dumping of waste, the study thereby aims to determine the physico-chemical parameters and heavy metal concentrations (As, Cd, Pb, Hg, Zn, Cr, Cu, Ni, Fe) of water samples collected from water sources closest to two dumpsites in Ondo City, Nigeria.

MATERIALS AND METHODS

Description of study area

This study was carried out in Ondo City, Ondo State, Nigeria. The town lies between latitudes 7°05'N and 7°45'N and longitudes 4°45'E and 5°05'E. It is bordered by Idanre LGA to the west, Akure South to the north, and Ile-Oluji/Okeigbo to the east. The climate of Ondo is characterized by a tropical wet and dry climate, with distinct rainy and dry seasons. The rainy season typically spans from May to October, while the dry season lasts from November to April. Average annual rainfall ranges between 1,200 mm and 1,800 mm, with temperatures generally ranging between 22 and 40°C (Ekwezuo, 2025). The economy is predominantly agrarian, with residents engaging in the cultivation of crops such as cocoa, cassava, yam, maize, and plantain (Adegbite & Adegbite, 2021). Ondo is also home to several small and medium-scale industries, including sawmills, cassava processing plants, and local craftworks. Water supply in the area is sourced from a combination

of boreholes, wells, streams, and public water systems. However, due to rapid urbanization and population growth, water quality and accessibility remain critical challenges in some parts of the community.

Sample Collection

Water samples were collected from a river in Sabo and a public water system in the Government Residential Area (GRA) of Ondo City, as shown in Figure1. Although there are five dumpsites in Ondo, Sabo and GRA dumpsites were selected because of their proximity to residential areas. To ensure a representative and unbiased sample, three sampling points were selected along the Sabo River, accounting for its various sources and flow paths, while

samples were collected from only one sampling point due to its single source in GRA. Samples were collected for a period of six months spanning the dry and wet periods.

Sampling was performed early in the morning when the water was less disturbed, allowing for more stable readings (Schroeter *et al.*, 2025). At each sampling site, water samples were cleared of visible debris and collected in pre-cleaned, acid-washed polyethylene bottles to avoid contamination. Acidification of samples was then done with 1.0 mL of conc. HNO₃ using new syringes; this was done to keep metals dissolved and stable and also prevent microbial growth. After acidification, the samples were stored in ice packs and transported to the laboratory for further analysis.

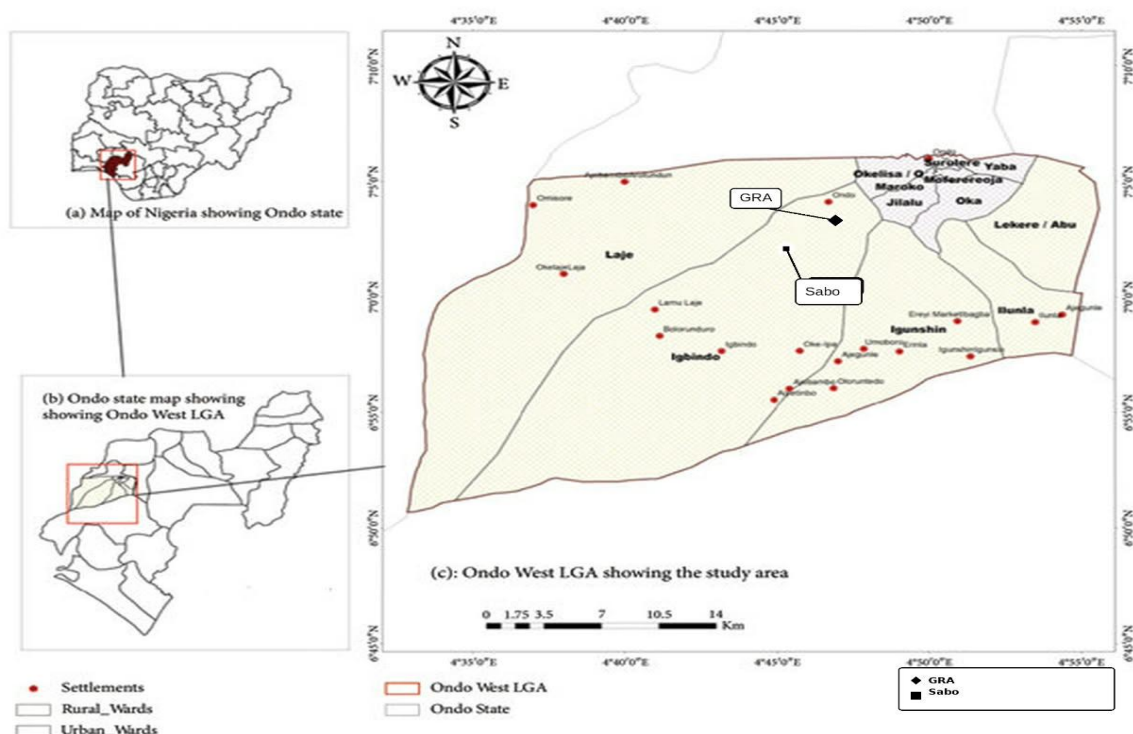


Figure1: Map of Ondo state showing the sampling points

Determination of physicochemical parameters

On-site measurements of physicochemical parameters such as temperature, pH, electrical conductivity (EC), and total dissolved solids (TDS) were performed immediately after sample collection using HANNA Combo Meter HI 98136, made in Romania. Measurements were taken in triplicate to ensure accuracy and reliability. Measuring the parameters in situ was crucial to obtain an accurate representation of the natural water conditions and to prevent alterations that could occur during sample transportation.

BOD (Biochemical Oxygen Demand) of water

Fifty (50ml) of each water sample was measured into a BOD bottle, while the dilution water was measured into another BOD bottle, which served as a blank. The DO (dissolved oxygen) of each bottle was measured using a DO meter and recorded as the initial reading. The BOD bottles were tightly closed so as to prevent any

air bubbles in the bottle and incubated for 5 days at 20°C. After 5 days, the samples were taken out, and the DO was measured again (Dak, 2021). BOD was then calculated using the formula;

$$\text{BOD (mg/L)} = \frac{D_1 - D_2}{V} \quad (1)$$

Where D₁ = Initial DO reading, D₂ = Final DO reading, V = volume of sample

Dissolved oxygen

MnSO₄ (1.0 mL) and alkaline iodide solutions (1.0 mL) were added to each sample in a 300 mL glass-stoppered container, and the vial was tightly closed to avoid air bubbles. The container was then tilted several times to mix the contents. The precipitates were allowed to settle, and 1.5 mL of H₂SO₄ was added and mixed thoroughly. An aliquot (25 mL) of Na₂S₂O₃·5H₂O solution was titrated to a colorless end point using starch indicator (Moses *et al.*, 2019). DO was calculated using the following formula:

$$DO \text{ (mg/L)} = \frac{T \text{ (cm}^3\text{)} \times 100}{\text{Volume (ml) of aliquot}} \quad (2)$$

Where T =volume of titrant used.

Chemical oxygen demand (COD)

Ten (10) mL of water sample was added into a round-bottom reflux flask with a few glass beads; 1 mL of mercury sulfate was added with 5 mL of potassium dichromate solution to digest the sample, while 2-3 drops of ferroin indicator were used to titrate the solution to the end point. The COD was calculated using the formula:

$$COD = \frac{8 \times 1000 \times D \times M \times (V1 - V2)}{\text{Volume of sample}} \quad (3)$$

Where, D – Dilution Factor; M – Molarity of standardized Ferrous Ammonium Sulfate solution; V1 – Volume consumed in titration using blank; V2 – Volume consumed in titration using sample.

Sample preparation and digestion

Sample digestion was carried out to break down organic matter and release the heavy metals into solution for accurate analysis. The samples were first filtered using a Whatman filter paper to remove any debris, after which a 100 mL aliquot of each filtered and acidified water sample was transferred into a digestion flask. To this, 5 mL of concentrated nitric acid (HNO₃) was added. The mixture was heated on a hot plate at 95°C to 105°C in a fume hood until a clear solution was obtained, indicating complete digestion (Okorie *et al.*, 2024; APHA, 2012). After digestion, the samples were allowed to cool to room temperature. The digested solutions were then filtered using Whatman filter paper to remove the remaining particulates. The filtrates were then transferred into 50 mL volumetric flasks and made up to the mark with distilled water. The prepared digests were stored in labelled polyethylene bottles and kept in a refrigerator at 4°C prior to heavy metal analysis. HNO₃ used for the analysis was of analytical grade.

2.5 Determination of Heavy Metal Contents

The digested samples were analyzed for concentrations of Arsenic (As), Cadmium (Cd), Mercury (Hg), Lead (Pb), Chromium (Cr), Copper (Cu), Iron (Fe), Nickel (Ni), and Zinc (Zn) using an Atomic Absorption Spectrophotometer (AAS; Buck Scientific Model 211 VGP made in China) at Afe Babalola University, Ado Ekiti.

2.6 Statistical Analysis

The collected data were subjected to both descriptive and inferential statistical analyses using SPSS software (Version 25). Descriptive statistics, including mean and standard deviation, were calculated for each parameter, while analysis of variance (ANOVA) was used to determine the level of significance.

Health risk assessment

Exposure assessment

To assess both non-cancer and cancer risks for children and adults, the chronic daily intake (CDI) of HMs, which represents the lifetime average daily dose (ADD) of exposure to each metal, was used (Joseph *et al.*, 2024). The CDI of the HMs via oral ingestion was calculated using Equation 4:

$$CDI = \frac{C \times IR \times EF \times ED}{BW \times AT} \quad (4)$$

Where: CDI is the chronic daily intake (mg/kg/day); C is the concentration of each metal in the water sample (mg/L); IR is the ingestion rate per unit time (1L/day for a child and 2.2L/day for an adult); ED is the exposure duration (6 years for a child and 30 years for an adult); EF is the exposure frequency (365 days/year); BW is body weight (15kg for a child and 70kg for an adult); AT is the average exposure time (for carcinogens, AT=70×365=2550 days for both children and adults; for non-carcinogens, AT=ED×365=2190 days and 10950 days for children and adults, respectively) (Emmanuel *et al.*, 2022).

Non-Cancer risks

Health hazards from ingestion of surface water were assessed for non-cancer risk using Equation 5.

$$\text{Hazard quotient (HQ)} = \frac{CDI}{RfD} \quad (5)$$

The Chronic Daily Intake (CDI) and Reference Dose (RfD) are in mg/kg/day. The value of RfD from Integrated Risk Information was utilized for the present study. The possible risk to human health through the combination of all elements was evaluated using the chronic hazard index (HI), which is the sum of all HQ calculated for each heavy metal (Emmanuel *et al.*, 2022). An HQ/HI value higher than 1 indicates a probability of non-cancer-causing impacts on human health, while values under 1 show that the ingestion of such water would not have any effect on humans (Ayantobo *et al.*, 2014; Joseph *et al.*, 2024).

Cancer Risks

Cancer risk of heavy metals is the hazard from a lifetime exposure to an average dose of 1mg/kg body weight/day of heavy metals. Cancer risk was expressed in terms of incremental lifetime cancer risk (ILCR), which is the probability that one may develop cancer over a 70-year lifetime due to a 24-hour exposure to a potential carcinogen (Emmanuel *et al.*, 2022). Cancer risk was calculated as the product of CDI (mg/kg/day) and cancer slope factor (CSF) measured in (mg/kg/day).

$$ILCR = CDI \times CSF \quad (6)$$

Where: ILCR=incremental life cancer risk; CDI=chronic intake (mg/kg/BW/day); CSF=cancer slope factor.

The total cancer risk as a result of exposure to multiple contaminants due to consumption of a particular type of water was assumed to be the sum of each metal incremental risk (Σ ILCR). The United States Environmental Protection Agency (USEPA) considers the minimum or acceptable cancer risk for regulatory purposes within the range of 1×10^{-6} to 1×10^{-4} (Emmanuel *et al.*, 2022).

RESULTS AND DISCUSSION

Physicochemical parameters of water samples

The physicochemical parameters (pH, EC, TDS, Temperature, BOD, COD, DO) of water samples from the two study areas are presented in Table 1. The mean pH of the water samples ranged from 6.62 to 8.08 (Table 1). The mean EC of the water samples varied from 16.50 to 64.23 µS/cm, while TDS ranged from 126.70 to 458.47 ppm.

Table 1: Physicochemical parameters of surface water samples collected from study areas in Ondo

Parameter	Location	Season	N	Mean±SD	WHO Limit
pH	Sabo	Dry	9	8.08 ^b ±0.14	6.5 – 8.5
	Sabo	Wet	9	6.68 ^a ±0.23	6.5 – 8.5
	GRA	Dry	3	7.43 ^a ±0.15	6.5 – 8.5
	GRA	Wet	3	6.62 ^a ±0.57	6.5 – 8.5
EC (µS/cm)	Sabo	Dry	9	16.56 ^a ±0.04	≤ 1000
	Sabo	Wet	9	64.23 ^b ±0.01	≤ 1000
	GRA	Dry	3	23.12 ^a ±0.01	≤ 1000
	GRA	Wet	3	217.86 ^a ±0.00	≤ 1000
TDS (ppm)	Sabo	Dry	9	141.90 ^a ±3.77	≤ 500
	Sabo	Wet	9	458.47 ^b ±6.50	≤ 500
	GRA	Dry	3	126.70 ^a ±0.60	≤ 500
	GRA	Wet	3	158.70 ^a ±1.50	≤ 500
Temperature (°C)	Sabo	Dry	9	34.30 ^b ±1.47	Ambient
	Sabo	Wet	9	24.93 ^a ±0.60	Ambient
	GRA	Dry	3	24.20 ^a ±0.20	Ambient
	GRA	Wet	3	26.60 ^a ±0.10	Ambient
BOD (mg/L)	Sabo	Dry	9	3.44 ^a ±0.15	-
	Sabo	Wet	3	1.12 ^b ±0.02	-
	GRA	Dry	9	1.42 ^b ±0.04	-
	GRA	Wet	3	1.17 ^b ±0.02	-
COD (mg/L)	Sabo	Dry	9	39.32 ^a ±3.11	-
	Sabo	Wet	3	12.12 ^b ±0.91	-
	GRA	Dry	9	18.16 ^b ±0.03	-
	GRA	Wet	3	10.34 ^b ±0.02	-
DO (mg/L)	Sabo	Dry	9	4.30 ^a ±0.29	-
	Sabo	Wet	3	6.42 ^a ±0.63	-
	GRA	Dry	9	5.83 ^a ±0.06	-
	GRA	Wet	3	7.30 ^a ±0.10	-

*N= Number of samples, SD= Standard deviation, WHO= World Health Organization, EC= Electrical Conductivity, TDS= Total Dissolved Solids, BOD= Biochemical Oxygen Demand, COD= Chemical Oxygen Demand, DO= Dissolved Oxygen.

*Means with different superscript within the same parameter are significantly (p<0.05) different.

Heavy metals concentration in water samples

Concentrations of essential and non-essential heavy metals determined in this study are summarized in Table II. The essential heavy metals determined in this study include Cu, Fe, Ni, and Zn while the non-essentials were Pb, Cd, Hg, As and Co.

Table 2: Heavy metal concentrations (mg/L) of water samples collected from study areas

Metals	Location	Season	N	Mean±SD	WHO Limit (mg/L)	NSDWQ Limit (mg/L)
Arsenic (As)	Sabo	Dry	9	0.059 ^a ±0.001	0.010	0.010
Arsenic (As)	Sabo	Wet	9	0.035 ^a ±0.002	0.010	0.010
Arsenic (As)	GRA	Dry	3	0.019 ^b ±0.001	0.010	0.010
Arsenic (As)	GRA	Wet	3	0.018 ^b ±0.001	0.010	0.010
Cadmium (Cd)	Sabo	Dry	9	0.008 ^a ±0.001	0.003	0.003
Cadmium (Cd)	Sabo	Wet	9	0.006 ^a ±0.001	0.003	0.003
Cadmium (Cd)	GRA	Dry	3	0.014 ^a ±0.001	0.003	0.003
Cadmium (Cd)	GRA	Wet	3	0.009 ^a ±0.001	0.003	0.003
Mercury (Hg)	Sabo	Dry	9	0.055 ^a ±0.002	0.006	0.001
Mercury (Hg)	Sabo	Wet	9	0.021 ^b ±0.001	0.006	0.001
Mercury (Hg)	GRA	Dry	3	0.094 ^a ±0.003	0.006	0.001
Mercury (Hg)	GRA	Wet	3	0.017 ^b ±0.002	0.006	0.001
Lead (Pb)	Sabo	Dry	9	0.221 ^a ±0.001	0.010	0.010
Lead (Pb)	Sabo	Wet	9	0.164 ^a ±0.003	0.010	0.010
Lead (Pb)	GRA	Dry	3	0.059 ^b ±0.001	0.010	0.010
Lead (Pb)	GRA	Wet	3	0.111 ^a ±0.005	0.010	0.010
Chromium (Cr)	Sabo	Dry	9	0.094 ^a ±0.002	0.050	0.050
Chromium (Cr)	Sabo	Wet	9	0.056 ^a ±0.001	0.050	0.050
Chromium (Cr)	GRA	Dry	3	0.004 ^b ±0.001	0.050	0.050
Chromium (Cr)	GRA	Wet	3	0.044 ^a ±0.004	0.050	0.050

Copper (Cu)	Sabo	Dry	9	0.035 ^a ±0.001	2.000	1.000
Copper (Cu)	Sabo	Wet	9	0.058 ^a ±0.002	2.000	1.000
Copper (Cu)	GRA	Dry	3	0.060 ^a ±0.001	2.000	1.000
Copper (Cu)	GRA	Wet	3	0.017 ^b ±0.000	2.000	1.000
Iron (Fe)	Sabo	Dry	9	0.094 ^a ±0.002	0.300	0.300
Iron (Fe)	Sabo	Wet	9	0.055 ^b ±0.002	0.300	0.300
Iron (Fe)	GRA	Dry	3	0.061 ^b ±0.001	0.300	0.300
Iron (Fe)	GRA	Wet	3	0.108 ^a ±0.009	0.300	0.300
Nickel (Ni)	Sabo	Dry	9	0.025 ^a ±0.003	0.070	0.020
Nickel (Ni)	Sabo	Wet	9	0.014 ^a ±0.002	0.070	0.020
Nickel (Ni)	GRA	Dry	3	0.028 ^a ±0.007	0.070	0.020
Nickel (Ni)	GRA	Wet	3	0.016 ^a ±0.005	0.070	0.020
Zinc (Zn)	Sabo	Dry	9	0.172 ^a ±0.006	3.000	3.000
Zinc (Zn)	Sabo	Wet	9	0.113 ^b ±0.005	3.000	3.000
Zinc (Zn)	GRA	Dry	3	0.100 ^b ±0.003	3.000	3.000
Zinc (Zn)	GRA	Wet	3	0.099 ^b ±0.000	3.000	3.000

*N= Number of samples, SD= Standard deviation, WHO= World Health Organization, NSDWQ= Nigerian Standard for Drinking Water Quality,

*Means with different superscripts within the same parameter are significantly (p<0.05) different.

Health Risk Assessment of Heavy Metals in Water Samples

Tables 3 and 4 present the Chronic Daily Intake (CDI) values of heavy metals and compare them with their respective Average Daily Dose (ADD) values for adults and children during the dry and wet seasons.

Table 3: Chronic Daily Intake (CDI) dose and Acceptable Daily Dose (ADD) of heavy metals in water samples collected from Sabo, Ondo State (mg/kg/day).

Heavy metals	Season	Age group	CDI	ADD
Arsenic	Dry	Adults	0.002	-
Arsenic	Dry	Children	0.004	-
Arsenic	Wet	Adults	0.001	-
Arsenic	Wet	Children	0.002	-
Cadmium	Dry	Adults	0.000	0.001
Cadmium	Dry	Children	0.001	0.001
Cadmium	Wet	Adults	0.000	0.001
Cadmium	Wet	Children	0.000	0.001
Mercury	Dry	Adults	0.002	0.001
Mercury	Dry	Children	0.004	0.001
Mercury	Wet	Adults	0.001	0.001
Mercury	Wet	Children	0.001	0.001
Lead	Dry	Adults	0.007	-
Lead	Dry	Children	0.015	-
Lead	Wet	Adults	0.005	-
Lead	Wet	Children	0.011	-
Chromium	Dry	Adults	0.003	0.003
Chromium	Dry	Children	0.006	0.003
Chromium	Wet	Adults	0.002	0.003
Chromium	Wet	Children	0.004	0.003
Copper	Dry	Adults	0.001	0.04
Copper	Dry	Children	0.002	0.04
Copper	Wet	Adults	0.002	0.04
Copper	Wet	Children	0.004	0.04
Iron	Dry	Adults	0.003	0.3
Iron	Dry	Children	0.006	0.3
Iron	Wet	Adults	0.002	0.3
Iron	Wet	Children	0.004	0.3
Nickel	Dry	Adults	0.001	0.02
Nickel	Dry	Children	0.002	0.02
Nickel	Wet	Adults	0.001	0.02
Nickel	Dry	Children	0.001	0.02
Zinc	Dry	Adults	0.005	0.3
Zinc	Dry	Children	0.011	0.3

Zinc	Wet	Adults	0.004	0.3
Zinc	Wet	Children	0.008	0.3

Table 4: Chronic daily intake (CDI) dose and Acceptable Daily Dose (ADD) of heavy metals in water samples collected from GRA, Ondo State (mg/kg/day).

Heavy metals	Season	Age group	CDI	ADD
Arsenic	Dry	Adults	0.001	-
Arsenic	Dry	Children	0.002	-
Arsenic	Wet	Adults	0.001	-
Arsenic	Wet	Children	0.002	-
Cadmium	Dry	Adults	0.000	0.001
Cadmium	Dry	Children	0.001	0.001
Cadmium	Wet	Adults	0.000	0.001
Cadmium	Wet	Children	0.001	0.001
Mercury	Dry	Adults	0.003	0.001
Mercury	Dry	Children	0.006	0.001
Mercury	Wet	Adults	0.001	0.001
Mercury	Wet	Children	0.001	0.001
Lead	Dry	Adults	0.002	-
Lead	Dry	Children	0.004	-
Lead	Wet	Adults	0.003	-
Lead	Wet	Children	0.007	-
Chromium	Dry	Adults	0.000	0.003
Chromium	Dry	Children	0.000	0.003
Chromium	Wet	Adults	0.001	0.003
Chromium	Wet	Children	0.003	0.003
Copper	Dry	Adults	0.002	0.04
Copper	Dry	Children	0.004	0.04
Copper	Wet	Adults	0.001	0.04
Copper	Wet	Children	0.001	0.04
Iron	Dry	Adults	0.002	0.3
Iron	Dry	Children	0.004	0.3
Iron	Wet	Adults	0.003	0.3
Iron	Wet	Children	0.007	0.3
Nickel	Dry	Adults	0.001	0.02
Nickel	Dry	Children	0.002	0.02
Nickel	Wet	Adults	0.001	0.02
Nickel	Dry	Children	0.001	0.02
Zinc	Dry	Adults	0.003	0.3
Zinc	Dry	Children	0.007	0.3
Zinc	Wet	Adults	0.003	0.3
Zinc	Wet	Children	0.007	0.3

Tables 5 and 6 show the seasonal Hazard Quotient (HQ) and cumulative Hazard Index (HI) of heavy metals in water samples collected from Sabo and GRA, Ondo, for adults and children during both seasons.

Table 5: Seasonal Hazard Quotient (HQ) and Hazard Index (HI) of heavy metals in water samples from Sabo, Ondo

Heavy metals	Dry season		Wet season	
	Adults	Children	Adults	Children
As	-	-	-	-
Cd	0	1.000	0	0
Hg	2.000	4.000	1.000	1.000
Pb	-	-	-	-
Cr	1.000	2.000	0.667	1.333
Cu	0.025	0.050	0.050	0.100
Fe	0.010	0.020	0.007	0.013
Ni	0.050	0.100	0	0.050
Zn	0.017	0.037	0.013	0.027
HQ	3.102	7.207	1.737	2.523

Table 6: Seasonal Hazard quotient (HQ) and Hazard index (HI) of heavy metals in water samples from GRA, Ondo

Heavy metals	Dry season		Wet season	
	Adults	Children	Adults	Children
As	-	-	-	-
Cd	0	1	0	1
Hg	3	6	1	1
Pb	-	-	-	-
Cr	0	0	0.333	1.000
Cu	0.05	0.1	0.025	0.025
Fe	0.007	0.013	0.01	0.023
Ni	0.05	0.100	0.05	0.05
Zn	0.01	0.023	0.01	0.023
HI	3.117	7.236	1.428	3.121

The results of Incremental Lifetime Cancer Risk (ILCR) of the heavy metals in water samples from Sabo and GRA, Ondo, in adults and children during the dry and wet seasons are presented in Tables VII and VIII.

Table 7: Incremental Lifetime Cancer Risk (ILCR) of Heavy Metals in water samples from Sabo, Ondo

Heavy metals	Dry season		Wet season	
	Adults	Children	Adults	Children
Pb	5.95×10^{-5}	1.28×10^{-4}	4.25×10^{-5}	9.35×10^{-5}
Cd	0	6.00×10^{-6}	0	0
Ni	9.10×10^{-4}	1.82×10^{-3}	0	9.10×10^{-4}
Cr	1.50×10^{-3}	3.00×10^{-3}	1.00×10^{-3}	2.00×10^{-3}
ICR	2.46×10^{-3}	1.13×10^{-2}	1.04×10^{-3}	3.00×10^{-3}

Table 8: Incremental Lifetime Cancer Risk (ILCR) of Heavy Metals in water samples from GRA, Ondo

Heavy metals	Dry season		Wet season	
	Adults	Children	Adults	Children
Pb	1.70×10^{-5}	3.40×10^{-5}	2.50×10^{-5}	5.95×10^{-5}
Cd	0	6.00×10^{-6}	0	6.00×10^{-6}
Ni	9.10×10^{-4}	1.82×10^{-3}	9.10×10^{-4}	9.10×10^{-4}
Cr	0	0	5.00×10^{-4}	1.50×10^{-3}
ICR	9.27×10^{-4}	1.86×10^{-3}	1.44×10^{-3}	2.48×10^{-3}

Physico-chemical parameters of water samples

pH is a key determinant in measuring toxicity in water. It determines the amount of solute that can be dissolved in water (Darko *et al.*, 2025). The pH of drinkable water is neutral; however, WHO recommends a pH of 6.5- 8.5 for drinking and irrigation purposes. pH values detected for all the samples were within this range. Lawson (2011) reported mean pH values of 7.03, 6.92, and 6.97 in samples collected from mangrove swamps of Lagos Lagoon, Nigeria. EC of water is an indicator of salinity and taste. Although the TDS values obtained were within the range of ≤ 500 set by WHO, high TDS implies that the water is not pure, as it contains dissolved solids (inorganic and organic materials) which often

affect the taste of water (Jaafar *et al.*, 2020). The temperature of the water samples was typical of a temperate region.

BOD is used to measure the amount of organic matter that pollutes water. BOD values show the amount of oxygen used during the process of aerobic decomposition of organic matter caused by micro-organisms. High BOD content indicates a high pollution rate (Bader *et al.*, 2010). BOD values of the water samples collected from Sabo and GRA ranged from 1.12 to 3.44 mg/L (Table 1). Oluyemi *et al.* (2010) similarly reported 0.69 to 6.74 mg/L in water sources from Ife North Local Government Area of Osun State, Nigeria. COD, on the other hand, determines the rate of oxygen consumption in water for the process of oxidizing a solution that can dissolve in water. It provides an index that helps determine the

effect of discharges on water (Jaafar *et al.*, 2020). The mean COD obtained in water samples from Sabo was 12.12 and 39.32 mg/L in the wet and dry seasons, respectively and 10.34 and 18.16 mg/L in GRA during the wet and dry seasons, respectively (Table 1). DO determines the level of water contamination due to a lack of oxygen in water and also indicates the increased use of oxygen by organic substances in water. The higher the DO, the better the quality of water and vice versa (Jaafar *et al.*, 2020). The values obtained in the sampled water varied from 4.30 to 7.30 mg/L (Table 1). Lawson (2011) also reported mean DO of 0.58 to 10.00 mg/L in water samples from the Mangrove Swamps of Lagos Lagoon, Lagos, Nigeria.

Heavy metal concentration in water samples

Water contains some natural essential heavy metals such as Zinc, Iron, Cobalt, Nickel, copper, etc., but these metals become toxic when they exceed the regulatory limit (Xu *et al.*, 2024). Non-essential heavy metals, however, have no beneficial role and are toxic even at minute concentrations.

For the non-essential heavy metals, Sabo recorded an As mean concentration of 0.059 and 0.035 mg/L, while GRA recorded 0.019 and 0.018 mg/L in the dry and wet seasons, respectively. Arsenic is a naturally occurring toxic element that is released into the environment through weathering, geothermal fluids or volcanic emissions (Adeyemi & Ojekunle, 2021; Zohra *et al.*, 2024). It can also exit into the environment as a result of human activities such as mining, use of pesticides, or leachates from solid wastes (Liu *et al.*, 2025). Similarly, Custodio *et al.* (2020) reported 21.10 to 23.00 µg/L of As in surface water from Peru, while Obasi and Akudinobi (2020) reported a high concentration of 4.13 mg/L in water sources from mining communities in Abakaliki, southeast Nigeria. The high values were attributed to mining activities taking place in that community. As the concentrations detected in the water samples were above the WHO recommended limit of 0.01 mg/L, this could pose a potential health risk to humans following consumption. Arsenic toxicity has been linked to various diseases such as cancers (skin, lungs, bladder), metabolic diseases (diabetes), neurological illnesses, reproductive and developmental issues (Adelolu *et al.*, 2021; Naujoka *et al.*, 2013; Sinha & Prasad, 2020). Mean concentration of Cd varied from 0.006 to 0.014 mg/L, with the highest concentration recorded in GRA during the dry season. Activities such as weathering of rocks, mining, metal plating and waste landfills can release Cd into water sources and soil (Irfan *et al.*, 2021). Cd concentration in all the water samples exceeded the regulatory limit of 0.003, thereby making the consumption of such water unhealthy. In a similar study conducted by Orisakwe *et al.* (2006), Cd levels in sachet water sold for consumption in Eastern Nigeria ranged from 0.002 to 0.036 mg/L, while Emmanuel *et al.* (2022) reported Cd concentrations of 0.10 to 0.35 mg/L in water sources from Anambra, Eastern Nigeria. However, Abedi-Sarvestani *et al.* (2019) reported low concentrations of ND to 0.0005 mg/L in drinking water sources from Kerman city, Iran. Chronic exposure to Cd has been linked to increased risk of chronic kidney disease, bone demineralization, osteoporosis, cardiovascular diseases, male fertility impairment and cancer (Genchi *et al.*, 2020; Satarug *et al.*, 2020).

Mercury is another heavy metal that reaches rivers, lakes, and oceans via atmospheric deposition, runoff, erosion, and leaching from soils to groundwater, then to surface waters (Aleku *et al.*, 2024; Kocman *et al.*, 2017). Hg toxicity depends on concentration

and duration of exposure (Wu *et al.*, 2016). All Hg forms are toxic, and chronic low-dose exposure from water and food can contribute to neurological, cardiovascular, immunological, hepatic and renal disorders through oxidative stress and epigenetic changes (Charkiewiuz *et al.*, 2025; Wu *et al.*, 2024). Hg was detected in the highest concentration during the dry season in both Sabo and GRA, with mean values of 0.055 and 0.094, respectively. Run-off and leaching from the dumpsites into the water bodies could have contributed to the Hg values detected in the water samples. These values were higher than the WHO recommendation of 0.006 and NSDWQ of 0.001. Similarly, Obasi and Akudinobi (2020) also reported very high values of 0.001 to 0.48 mg/kg in water sources from Lead-Zinc mining communities of Abaliki, Nigeria, while Ekpo *et al.* (2008) reported low concentrations of 0.001 to 0.002 mg/kg in water sources from the same region.

Lead, just like Cd and As, also poses a global public health problem when present in drinking water. It mainly comes from pipes and plumbing, and even low exposures can cause harm in children's brains and development (Jarvis & Fawell, 2021). There is no safe level of lead for children's neurodevelopment; even low exposure impairs cognitive development and behavior (Joseph *et al.*, 2024; Levallois *et al.*, 2018). Pb detected in the water samples varied from 0.059 to 0.221 mg/kg. High concentrations of lead in these water sources suggest that Pb is being leached from these dumpsites, which could be a result of disposing of batteries and other Pb-containing materials on the dumpsite. Lead, when ingested, can cause severe neurodevelopmental issues and low cognitive ability in children, while in adults, it has been linked to hypertension, nervous system disorders and kidney diseases (Ozoko *et al.*, 2022). Njagi *et al.* (2016), however, reported Pb values that were below the detection limit in water sources around a dumpsite in Kenya, while Ozoko *et al.* (2022) also reported Pb concentrations (0.35 µg/L to 1.90 µg/L) lower than those in this study. The nature of waste disposed of on these dumpsites must have affected the Pb concentration found in the water sources.

In Sabo, Cr had a mean concentration of 0.094 and 0.056 during the dry and wet seasons, respectively. These values are higher than the permissible limit of 0.050, while Cr was detected at lower levels of 0.004 and 0.044 in GRA during the dry and wet seasons. The high values detected in Sabo may have resulted from transport of leachates from the dumpsite to the surface water during rainfall. In line with this, Ozoko *et al.* (2022) reported Cd concentrations in leachates and surface water higher than those of groundwater in a study conducted in Eastern Nigeria. Long-term ingestion of Cr contaminated food or water could lead to gastrointestinal diseases, stomach cancer and lung cancer (Georgaki & Charalambous, 2022; Zhitkovich, 2022).

The essential heavy metals (Cu, Fe, Ni and Zn) analyzed in the water samples were below the permissible limit recommended by WHO. Decomposition of wastes such as paper, metals, electronic waste, vehicle parts and food waste can contribute to leaching of these metals to nearby water sources (Drall *et al.*, 2024; Essien *et al.*, 2022). Their mean concentrations ranged from 0.014 to 0.172 mg/L, with zinc detected at the highest concentration. Since the concentration of these metals was below the permissible limit, their consumption would not pose any health risk to humans. However, the high concentration of the non-essential heavy metals studied in the water samples would damage the potability of drinking water.

As and Pb have no ADD values because of their high toxicity level;

therefore, WHO has stipulated that no value of As and Pb is safe for consumption in adults and children (Joseph *et al.*, 2024; Neuwirth *et al.*, 2022). Cd CDI values (0.000–0.001) were equal to or below the ADD value (0.001), indicating exposure levels within the acceptable daily intake range. Hg CDI values ranged from 0.001–0.006, while the ADD was 0.001. Children's CDI during the dry season exceeded the ADD, suggesting a potential concern for mercury exposure in this group. Cr CDI values ranged from 0.000 to 0.006, with children in the dry season having CDI values twice the ADD, indicating relatively higher exposure.

Cu CDI values were lower than the ADD of 0.04, suggesting negligible risk from copper intake. Fe CDI values varied from 0.002 to 0.007; these values were far below the ADD of 0.3, indicating that iron exposure is within safe limits.

Children consistently recorded higher CDI values than adults for all metals in both seasons. This suggests that children are more exposed and more vulnerable to heavy metal toxicity because of their low body weight. Also, the CDI values were generally higher during the dry season than the wet season; this may be due to increased concentration of contaminants in water sources as a result of reduced dilution by rainfall during the dry season. However, Alade *et al.* (2025), Omotosho *et al.* (2023), and Yahaya *et al.* (2020) reported low CDI-to-ADD values in groundwater and surface water bodies collected from Lagos and Oyo State, Nigeria. This corroborates the fact that dumpsites are major contributors of HMs in water sources.

Unlikely, whereas values greater than 1 indicate a potential health risk from long-term exposure. Among the heavy metals evaluated, mercury (Hg) posed the greatest non-carcinogenic risk in both seasons. During the dry season, Hg recorded HQ values of 3.0 for adults and 6.0 for children, while in the wet season the HQ reduced to 1.0 for both groups. These values indicate that mercury exposure through drinking water may present a significant health concern, particularly for children during the dry season. Chromium (Cr) also contributed to the overall health risk. In the dry season, HQ values in Sabo were 1.0 for adults and 2.0 for children, exceeding the safety threshold. Although the values declined during the wet season to 0.667 for adults and 1.333 for children, children remained at potential risk from chromium exposure.

The HQ values for Cu, Fe, Ni, and Zn were all below the acceptable threshold of 1 in both seasons, suggesting that these metals individually are unlikely to cause non-carcinogenic health effects through consumption of sampled water. Cd showed an HQ of 1.0 only for children during the dry season in the two study areas, indicating a borderline risk.

In Sabo, the cumulative HI was 3.102 for adults and 7.207 for children during the dry season, decreasing to 1.737 and 2.523, respectively, during the wet season, while GRA recorded a cumulative HI of 3.117 for adults and 7.236 for children during the dry season, which reduced to 1.428 and 3.121, respectively, during the wet season. Since all HI values exceeded the safety threshold of 1, the findings indicate a potential non-carcinogenic health risk associated with the combined exposure to heavy metals in the water. Furthermore, children consistently exhibited higher HI values than adults, reflecting their greater vulnerability due to lower body weight and higher water intake relative to body mass.

The higher HI observed during the dry season may also be attributed to reduced water volume and limited dilution, which can concentrate dissolved heavy metals. Conversely, the lower HI values recorded during the wet season are likely due to dilution

from increased rainfall, although the overall risk remains above the acceptable limit.

The ILCR estimates the probability of an individual developing cancer over a lifetime due to exposure to carcinogenic contaminants. Generally, an ILCR value between 1.00×10^{-6} and 1.00×10^{-4} is considered acceptable or tolerable by regulatory agencies such as the USEPA. Values exceeding 1.00×10^{-4} indicate an elevated lifetime cancer risk.

Among the heavy metals assessed, chromium (Cr) contributed the highest carcinogenic risk in both seasons. During the dry season in Sabo, ILCR values were 1.50×10^{-3} for adults and 3.00×10^{-3} for children, while the values varied between 1.00×10^{-3} and 3.00×10^{-3} in GRA. These values are considerably higher than the acceptable risk threshold, indicating that chronic exposure to chromium-contaminated water may substantially increase lifetime cancer risk, particularly among children. Cd contributed minimally to cancer risk, with an ILCR of 6.00×10^{-6} observed only for children in the two study locations, while no risk was detected in adults. A similar study by Emmanuel *et al.* (2022) and Eruke *et al.* (2025) also supports ILCR being higher in children and infants compared to adults, with metals like Cd, Ni, and Pb posing the highest risk.

The cumulative ILCR values were well above the acceptable limit of 1×10^{-4} , indicating that long-term consumption of the water samples may pose a significant lifetime carcinogenic risk. The consistently higher ILCR values observed in children further emphasize their greater susceptibility to carcinogenic effects due to their lower body weight, higher water intake relative to body mass, and longer expected lifetime of exposure.

In conclusion, this study confirms that water sources around dumpsites are contaminated with HMs at concentrations exceeding WHO permissible limits, and the health risk assessment revealed that consumption of such water could be deleterious to human health. Proper waste management and continuous monitoring of water sources are therefore recommended.

Conflict of Interest Declaration

All authors declare that they have no conflict of interest

REFERENCES

- Abedi Sarvestani, R., & Aghasi, M. (2019). Health risk assessment of heavy metals exposure (lead, cadmium and copper) through drinking water consumption in Kerman city, Iran. *Environmental Earth Sciences*, 78(24), 714.
- Abugu, H. O., Egbueri, J. C., Agbasi, J. C., Ezugwu, A. L., Omeka, M. E., Ucheana, I. A., & Aralu, C. C. (2024). Hydrochemical characterization of ground and surface water for irrigation application in Nigeria: a review of progress. *Chemistry Africa*, 7(6), 3011–3036.
- Adegbite, O. & Adegbite, O. (2021). Resources and Opportunities for Competitive Industrial Systems in Nigeria's Agro-allied and Forest-based Industries. *Perspectives on Industrial Development in Nigeria: Issues, Challenges and Hard Choices* 4: 105–152.
- Adejumo, A. O., Adebayo, A. O., & Ogunleye, O. O. (2019). Assessment of heavy metals in leachates from solid waste dumpsites in South-Western Nigeria. *Environmental Research Journal*, 13(2), 45–52.
- Adelolu, S., Khan, S., & Patti, A. (2021). Arsenic Contamination of Groundwater and Its Implications for Drinking Water Quality

- and Human Health in Under-Developed Countries and Remote Communities—A Review. *Applied Sciences*. <https://doi.org/10.3390/app11041926>.
- Adeyemi, A. A., & Ojekunle, Z. O. (2021). Concentrations and health risk assessment of industrial heavy metals pollution in groundwater in Ogun State, Nigeria: *Scientific African*, 11, e00666.
- Alade, A., Jones, S., Amao, O., & Mohammed, L. (2025). Assessment of Heavy Metal Contents and Associated Health Risks in Groundwater Samples Around Federal College of Animal Health and Production Technology, Ibadan, Nigeria Students' Residential Areas. *Nigerian Journal of Applied Physics*. <https://doi.org/10.62292/njap-v1i1-2025-10>
- Aleku, D., Lazareva, O., & Pichler, T. (2024). Mercury in Groundwater – Source, Transport and Remediation. *Applied Geochemistry*. <https://doi.org/10.1016/j.apgeochem.2024.106060>.
- APHA. Standard Methods for the Examination of Water and Wastewater. 22nd Edition, American Public Health Association, American Water Works Association, Water Environment Federation. 2012.
- Ayantobo, O., Awomeso, J.A., Oluwasanya, G.O., Bada, B.S., Taiwo, A.M. (2014). Non-cancer human health risk assessment from exposure to heavy metals in surface and groundwater in Igoun-Ijesha, Southwest Nigeria. *American Journal of Environmental Sciences*, 2014, 10 (3), 301- 311.
- Bader, A. C., Hussein, H. J., & Jabar, M. T. (2022). BOD: COD ratio as an indicator for wastewater and industrial water pollution. *Int. J. Spec. Educ*, 37(3), 2164–2171.
- Bukhari, S. M. A. U. S., Shah, L., Raza, S., Nawaz, M. A., & Jamal, M. (2024). Health risks associated with the presence of heavy metals in water. In *Membrane technologies for heavy metal removal from water* (pp. 44–64). CRC Press.
- Charkiewicz, A., Omeljaniuk, W., Garley, M., & Nikliński, J. (2025). Mercury Exposure and Health Effects: What Do We Really Know?. *International Journal of Molecular Sciences*, 26. <https://doi.org/10.3390/ijms26052326>.
- Custodio, M., Cuadrado, W., Peñaloza, R., Montalvo, R., Ochoa, S., & Quispe, J. (2020). Human Risk from Exposure to Heavy Metals and Arsenic in Water from Rivers with Mining Influence in the Central Andes of Peru. *Water*, 12(7), 1946. <https://doi.org/10.3390/w12071946>
- Dak, M. (2021). BOD – Biochemical Oxygen Demand (Principle, Procedure & Application). *Biokimicroki*: <https://biokimicroki.com/bod-biochemical-oxygen-demand/>
- Darko, R. O., Nsonowah, P. P., Owusu-Sekyere, J. D., & Nyameche, M. (2025). Assessment of wastewater quality for irrigation use in the Central Region of Ghana. *Discover Environment*, 3(1), 146.
- Drall, J., Rautela, R., Jambhulkar, R., Kataria, A., & Kumar, S. (2024). Effect of heavy metal contamination due to leachate migration from uncontrolled dumpsites: A comprehensive analysis of soil and groundwater. *Journal of Environmental Management*, 373, 123473. <https://doi.org/10.1016/j.jenvman.2024.123473>.
- Ekwezuo, C. S. (2025). Understanding Precipitation Extremes over West Africa: Characteristics, Drivers and Projections (Doctoral dissertation, WASCAL).
- Emmanuel, U., Chukwudi, M., Monday, S., & Anthony, A. I. (2022). Human health risk assessment of heavy metals in drinking water sources in three senatorial districts of Anambra State, Nigeria. *Toxicology Reports*, 9, 869–875. <https://doi.org/10.1016/j.toxrep.2022.04.011>
- Emmanuel, U.C., Chukwudi, M.I., Monday, S.S., Anthony, A.I. (2022). Human health risk assessment of heavy metals in drinking water sources in three senatorial districts of Anambra State, Nigeria. *Toxicology Reports*, 9, 869–875.
- Eruke, S., Akpotayire, S. I., Okoro, S., Emmanuel, D., & P. (2025). Assessment of health hazards of selected heavy metals in surface water from a contaminated river in Aleto Eleme, Southern Nigeria. *GSC Advanced Research and Reviews*. <https://doi.org/10.30574/gscarr.2025.23.1.0118>
- Essien, J., Ikpe, D., Inam, E., Okon, A., Ebong, G., & Benson, N. (2022). Occurrence and spatial distribution of heavy metals in landfill leachates and impacted freshwater ecosystems: An environmental and human health threat. *PLoS ONE*, 17. <https://doi.org/10.1371/journal.pone.0263279>.
- Genchi, G., Sinicropi, M., Lauria, G., Carocci, A., & Catalano, A. (2020). The Effects of Cadmium Toxicity. *International Journal of Environmental Research and Public Health*, 17. <https://doi.org/10.3390/ijerph17113782>.
- Georgaki, M., & Charalambous, M. (2022). Toxic chromium in water and the effects on the human body: a systematic review. *Journal of Water and Health*. <https://doi.org/10.2166/wh.2022.214>.
- Ipeaiyeda, A. R., & Dawodu, M. (2016). Heavy metal contamination of topsoil and dispersion in roadside soil in Nigeria. *Research Journal of Environmental and Earth Sciences*, 4(2), 155–164.
- Irfan, M., Liu, X., Hussain, K., Mushtaq, S., Cabrera, J., & Zhang, P. (2021). The global research trend on cadmium in freshwater: a bibliometric review. *Environmental Science and Pollution Research*, 30, 71585–71598. <https://doi.org/10.1007/s11356-021-13894-7>.
- Jaffar, A., Thamrin, N.M., Ali, M.S., Misnan, M.F., & Yassin, A.I. (2020). The Influence of Physico-Chemical Parameters to Determine Water Quality: A Review. *Journal of Electrical and Electronic Systems Research*. <https://doi.org/10.24191/jeesr.v17i1.016>
- Jarvis, P., & Fawell, J. (2021). Lead in drinking water – An ongoing public health concern?. *Current Opinion in Environmental Science & Health*, 20, 100239. <https://doi.org/10.1016/j.coesh.2021.100239>.
- Joseph, A., Zhu, N., Sam-Uket, N., Eneh, P., Edet, U., Eriegha, O., Asanga, E., Abass, G., Rene, E., Serge, N. (2024). Metals leached from aluminium foil into *Clarias gariepinus* muscles roasted at high temperatures: Potential contamination and controlling factors. *Food Bioscience*, 62: 105151
- Kılıç, Z. (2020). The importance of water and conscious use of water. *International Journal of Hydrology*, 4(5), 239–241.
- Kocman, D., Wilson, S., Amos, H., Telmer, K., Steenhuisen, F., Sunderland, E., Mason, R., Outridge, P., & Horvat, M. (2017). Toward an Assessment of the Global Inventory of Present-Day Mercury Releases to Freshwater Environments. *International Journal of Environmental Research and Public Health*, 14. <https://doi.org/10.3390/ijerph14020138>.
- Lawson, E.O. (2011). Physico-Chemical Parameters and Heavy Metal Contents of Water from the Mangrove Swamps of Lagos Lagoon, Lagos, Nigeria. *Advances in Biological Research*, 5 (1), 08–21, 2011
- Levallois, P., Barn, P., Valcke, M., Gauvin, D., & Kosatsky, T.

- (2018). Public Health Consequences of Lead in Drinking Water. *Current Environmental Health Reports*, 5, 255–262. <https://doi.org/10.1007/s40572-018-0193-0>.
- Liu, S., Yu, X., Zhao, H., & Dai, Q. (2025). Arsenic speciation and distribution in industrially polluted estuarine sediments and their effects on bacterial communities. *Frontiers in Microbiology*, 16. <https://doi.org/10.3389/fmicb.2025.1715628>.
- Naujokas, M., Anderson, B., Ahsan, H., Aposhian, H., Graziano, J., Thompson, C., & Suk, W. (2013). The Broad Scope of Health Effects from Chronic Arsenic Exposure: Update on a Worldwide Public Health Problem. *Environmental Health Perspectives*, 121, 295–302. <https://doi.org/10.1289/ehp.1205875>.
- Neuwirth, L. S., Cabañas, E., Cadet, P., Zhu, W., & Markowitz, M. E. (2022). Cereal and juice, lead and arsenic, our children at risk: A call for the FDA to re-evaluate the allowable limits of lead and arsenic that children may ingest. *International Journal of environmental research and public health*, 19(10), 5788.
- Njagi, J. M., Akunga, D. N., Njagi, M. M., Ngugi, M. P., & Njagi, E. M. (2016). Heavy metal pollution of the environment by dumpsites: a case of Kadhodeki Dumpsite. *Int. J. Life. Sci. Scienti. Res*, 2(2), 191–197.
- Njoku, V. O. N., Arinze, C., Chizoruo, I. F., & Blessing, E. N. (2021). A Review: Effects of air, water and land dumpsites on human health and analytical methods for determination of pollutants. *Analytical Methods in Environmental Chemistry Journal*, 4(03), 80–106.
- Obasi, P. N., & Akudinobi, B. B. (2020). Potential health risk and levels of heavy metals in water resources of lead–zinc mining communities of Abakaliki, southeast Nigeria. *Applied Water Science*, 10(7), 184. <https://doi.org/10.1007/s13201-020-01233-z>
- Ogunyemi, S. A., Ayodele, J. T., & Oladipo, M. A. (2020). Heavy metal contamination in leachates and surrounding water bodies from dumpsites in South Western Nigeria. *Journal of Environmental Chemistry and Ecotoxicology*, 12(1), 12–21.
- Okorie, M.N., Okechukwu, V.U., & Omokpariola, D.O. (2024). Physicochemical properties and health risk assessment of selected heavy metals from soil and borehole water in Ifite-Awka, Anambra State, Nigeria. *Discover Applied Science*, 6: 108–123. <https://doi.org/10.1007/s42452-024-05767-8>
- Oluyemi, E.A., Adekunle, A. S., Adenuga, A. A., & Makinde, W. O. (2010). Physico-chemical properties and heavy metal content of water sources in Ife North Local Government Area of Osun State, Nigeria. *African Journal of Environmental Science and Technology* 4(10), 691–697. <http://www.academicjournals.org/AJEST>
- Omotoso, O. A., Ojo, O., Matimoju, O., Farinu, O. H., Adeboye, A. C., & Adeniran, Y. O. (2023). Assessing Human Health Risks in Asejire Lake: Implications for Water Resources in Industrialized Ibadan, Nigeria. *Journal of Sustainable Natural Resources*. <https://doi.org/10.30880/jsunr.2023.04.01.004>
- Ozoko, D. C., Onyekwelu, I. L., & Aghamelu, O. P. (2022). Multivariate and health risks analysis of heavy metals in natural water sources around Enugu dumpsite, southeastern Nigeria. *Applied Water Science*, 12(9), 224.
- Rahman, Z., & Singh, V. P. (2019). The relative impact of toxic heavy metals (THMs)(arsenic (As), cadmium (Cd), chromium (Cr)(VI), mercury (Hg), and lead (Pb)) on the total environment: an overview: environmental monitoring and assessment, 191(7), 419.
- Satarug, S., Gobe, G., Vesey, D., & Phelps, K. (2020). Cadmium and Lead Exposure, Nephrotoxicity, and Mortality. *Toxics*, 8. <https://doi.org/10.3390/toxics8040086>.
- Sharma, A., Grewal, A. S., Sharma, D., & Srivastav, A. L. (2023). Heavy metal contamination in water: consequences on human health and environment. In *Metals in water* (pp. 39–52). Elsevier.
- Sharma, S. K. (Ed.). (2014). *Heavy metals in water: presence, removal and safety*. Royal Society of Chemistry.
- Sinha, D., & Prasad, P. (2020). Health effects inflicted by chronic low-level arsenic contamination in groundwater: A global public health challenge. *Journal of Applied Toxicology*, 40, 131–87. <https://doi.org/10.1002/jat.3823>.
- Tariq, A., & Mushtaq, A. (2023). Untreated wastewater reasons and causes: A review of most affected areas and cities. *Int. J. Chem. Biochem. Sci.*, 23(1), 121–143.
- Wang, F., Li, W., Wang, H., Hu, Y., & Cheng, H. (2024). The leaching behavior of heavy metals from contaminated mining soil: The effect of rainfall conditions and the impact on surrounding agricultural lands—Science of the Total Environment, 914, 169877.
- Whitcombe, A. S. (2026). Bioaccumulation of Heavy Metals in Aquatic Organisms and Its Ecological Impact. *Cadernos de Pós-Graduação em Direito Político e Econômico*, 26(1), 2409–2414.
- Wu, Y. S., Osman, A. I., Hosny, M., Elgarahy, A. M., Eltaweil, A. S., Rooney, D. W., ... & Yap, P. S. (2024). The toxicity of mercury and its chemical compounds: molecular mechanisms and environmental and human health implications: a comprehensive review. *ACS Omega*, 9(5), 5100–5126.
- Wu, Y., Osman, A., Hosny, M., Elgarahy, A., Eltaweil, A., Rooney, D., Chen, Z., Rahim, N., Sekar, M., Gopinath, S., Rani, N., Batumalaie, K., & Yap, P. (2024). The Toxicity of Mercury and Its Chemical Compounds: Molecular Mechanisms and Environmental and Human Health Implications: A Comprehensive Review. *ACS Omega*, 9, 5100–5126. <https://doi.org/10.1021/acsomega.3c07047>.
- Xu, W., Jin, Y., & Zeng, G. (2024). Introduction of heavy metal contamination in water and soil: a review on sources, toxicity and remediation methods. *Green Chemistry Letters and Reviews*, 17. <https://doi.org/10.1080/17518253.2024.2404235>.
- Yahaya, T., Oladele, E., Fatodu, I. A., Abdulazeez, A., & Yeldu, Y. I. (2020). The concentration and health risk assessment of heavy metals and microorganisms in the groundwater of Lagos, Southwest Nigeria. *Journal of Advances in Environmental Health Research*, 8, 234–242. <https://doi.org/10.22102/jaehr.2020.245629.1183>
- Zhitkovich, A. (2011). Chromium in Drinking Water: Sources, Metabolism, and Cancer Risks. *Chemical Research in Toxicology*, 24, 1617–1629. <https://doi.org/10.1021/tx200251t>.
- Zohra, F. T., Afsin, A., Al Mamun, A., Ashikur Rahaman, M., & Mizanur Rahman, M. (2024). Source and distribution of arsenic in soil and water ecosystems. In *Arsenic Toxicity Remediation: Sustainable Nexus Approach* (pp. 27–46). Cham: Springer Nature Switzerland.