

Ecotoxicological status, source apportionment and human health risk assessment of potential toxic element in surface water and sediments of creeks along Bonny River, Nigeria

Omobolaji O. Afolabi^{a,*}, Peter B. Okwori^b, Olushola I.T. Yemi-Jonathan^b, Elekwachi Wali^c, Maureen C. Ugwu^d, Chimzurun D. Ugwa^a, Victoria O. Emelu^b, Toochukwu T. Ugwuechendu^a, Lilian C. Bosco-Abiahu^e, Sunny O. Asomaku^b

^a Institute of Natural Resources, Environment and Sustainable Development, University of Port Harcourt, Nigeria

^b Disaster Risk Management and Development Studies, University of Port, Harcourt, Nigeria

^c Department of Geography, University of Nigeria, Enugu State, Nigeria

^d Department of Geography and Environmental Management, University of Port Harcourt, Nigeria

^e Department of Environmental Management, Federal University of Technology Owerri, Nigeria

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ABSTRACT

Potentially toxic elements (PTEs) are naturally available in the environment; however, anthropogenic activities encourage their high concentration, posing environmental and human health risks. The ecotoxicological status, source apportionment and health risk assessment of PTEs (Iron (Fe), Nickel (Ni), Cadmium (Cd), Selenium (Se), Zinc (Zn), Lead (Pb), Chromium (Cr) and Copper (Cu)) in creeks (Fibiri and Iwoama) along Bonny River were examined through laboratory analysis (American Public Health Association standard), indicators and statistical techniques. The PTEs concentration of surface water and sediment for both creeks exceeded the WHO allowable limit, and the surface water trended as $Cr > Pb > Fe > Ni > Cd > Zn > Cu > Se$ for Fibiri creeks, $Fe > Cr > Pb > Ni > Cd > Zn > Cu > Se$ for Iwoama creek while the sediment trended as $Fe > Pb > Ni > Cr > Zn > Cd > Cu > Se$ for both creeks. The contamination factor (CF) of the creek's sediment showed low CF (Zn and Cu), moderate CF (Ni, Pb and Cr) and very high CF (Fe and Cd), while risk index status ranged from low risk (Ni, Zn, Pb, Cr and Cu), moderate risk (Fe) and significantly high risk (Cd). The human health risk revealed that children could be exposed to potential non-carcinogenic effect ($HI > 1$) with Zn (1.64 and 2.03), and the Total Carcinogenic Risk (TCR) for children indicated high carcinogenic risk ($TCR > 1 \times 10^{-4}$) for Ni, Pb, Cr and Cd of the creeks' environmental mediums. The similarity in the trend and status of the creeks suggested that both environments are exposed to similar anthropogenic activities impact.

Introduction

Potentially toxic elements (PTEs) consist of metals, semimetals, and non-metals that are naturally present in the human environment as a result of weathering action of parent materials, which may or may not have any biological importance to living organisms (Carvalho et al., 2022; Pan et al., 2018). PTEs are environmentally concerned due to their persistence, toxicity, bioaccumulation, and biomagnification (Marín et al., 2022). At high concentrations, they pose health risks to organisms, including humans (Afolabi et al., 2022). Various anthropogenic actions such as mineral resources development, metal processing and smelting,

industrial emissions, application of fertilisers and pesticides, sewage irrigation, and landfill systems have increased the concentration of PTEs in the global environment over the years and accumulated in environmental media (Chen et al., 2015; Afolabi and Eludoyin, 2021). Although, natural phenomena such as metal corrosion, atmospheric deposition, soil erosion of metal ions, volcanic eruptions and weathering can contribute to the concentration of PTEs in the environment (Omutange et al., 2022; Goher et al., 2019; Sharma et al., 2021).

In aquatic environments, PTEs are introduced through various sources, including human activities, and their concentration can be detected in the waters, sediments, and aquatic organisms, exhibiting

* Correspondent author.

E-mail address: omobolaji_afolabi@uniport.edu.ng (O.O. Afolabi).

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different geochemical behaviour and biological toxic effects (Zeng et al., 2013). The accumulation of these elements and their enrichment in food chains can present risks to aquatic ecosystems, such as loss of biodiversity and degradation of environmental quality, as well as risks to human health (Green and Planchart, 2018; Gall et al., 2015; Hou et al., 2019). Generally, health risk arises primarily from chronic exposure to PTE through ingestion of water, soil, and food (Chen et al., 2018).

PTE levels and sources must be routinely and accurately monitored for adequate and sustainable water quality management (Custodio et al., 2020). In this sense, multivariate statistical analyses such as Principal Component Analysis (PCA), Hierarchical Cluster Analysis (HCA), and Pearson Correlation Coefficient (PCC) have been used to find relationships between elements and determine their sources (Ustaoglu and Islam, 2020; Zhang et al., 2016). Elements with strong relationships may have common origins and similar transport behaviours (Kükrer, 2018; Lu et al., 2016). The quality indices are used to assess the risks that PTE can present to the aquatic environment, such as the contamination factor (CF), enrichment factor (EF), accumulation index (Igeo), risk index (RI) and modified ecological risk index (MRI) (Tepe and Aydin, 2017; Li et al., 2015; Palma et al., 2015).

Various anthropogenic activities such as urbanisation and industrialisation have significantly increased the concentration of PTEs in the aquatic environment (Martin et al., 2015; Ali et al., 2016) with various degrees of impact (Ahmeed et al., 2015). In aquatic environments, sediment serves as a sinker of many of the PTEs, and is also used to monitor the environment to evaluate the extent of PTEs concentration (Islam et al., 2015). The impact of anthropogenic activities on the

aquatic environment can be assessed based on the water and sediment of the ecosystem (Saleem et al., 2015), and the outcome can support the management of the environment (Afolabi et al., 2022).

PTEs are commonly found in the environment due to various anthropogenic activities, and aquatic environments are not excluded. Studies have reported PTEs present in the aquatic environment of Nigeria, and the outcomes were linked to anthropogenic activities (Babatunde et al., 2015; Bubun et al., 2018; Akankali et al., 2019; Achi et al., 2021). Bonny River is one of the major river networks in the Niger Delta region of Nigeria, with numerous creeks, which all empty into the Atlantic Ocean at Bonny Island (Dublin-Green, 1988). The region is known for its oil and gas exploitation and exploration activities which have contributed to the country's foreign exchange; however, the region has suffered various levels of environmental pollution. The oil and gas-related activities of have led to various environmental impacts due to oil spillage, gas flaring, industrial waste discharge, urban waste and agricultural runoff (Jamabo & Chinda, 2010; Babatunde et al., 2015; Moslen & Miebaka, 2017; Nwankwoala & Omofuophu, 2020). Many of the studies from the creeks of Bonny Rivers concentrated on the preliminary quantifications of PTEs in the ecosystem; however, the present further applied various ecotoxicological indices in quantifying the PTEs in the ecosystem. In this regard, the specific objectives of the study were to (i) evaluate the ecotoxicological status of PTEs in creeks of Bonny Rivers based on CF, EF, Igeo, RI and MRI, (ii) identify the source allocations of PTEs using statistical techniques; and (iii) assess the associated health risk associated with the environment.

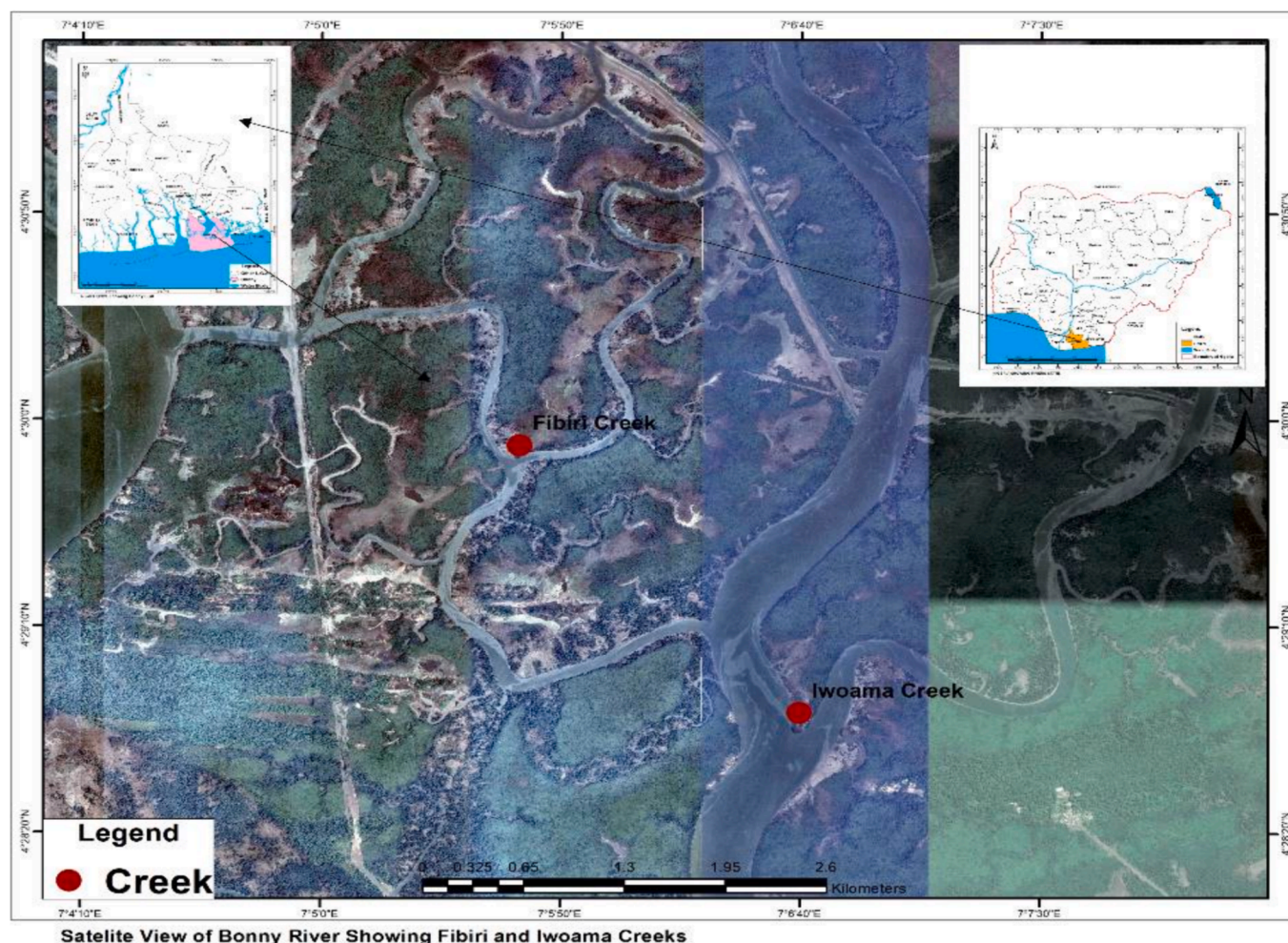


Fig. 1. Overview of the Study Area along the Bonny Rivers, Nigeria.

Method and materials

Study area

The study was conducted among creeks around Bonny River, Rivers State, Nigeria. The creeks included in the study were Fibiri Creek (04°29' 28.430" N and 07°01' 23.540" E) and Iwoama Creek (04°28' 43.080" N and 07° 6' 51.180" E) (Fig. 1). The Bonny River plays a significant role towards various socio-economic activities of the people in the environment; however, the river has been heavily impacted by oil spillage, industrial waste discharge and over-exploitation of the natural resources. As an aquatic environment, it is about 100 km long and over 30 km wide and makes up the eastern wing of the Niger Delta (Okorundu et al., 2021) traversing the shorelines of various Niger Delta states.

Sample collection and laboratory analysis

The samples were collected in September 2022, based on the method described by Ogbonna et al. (2021) and Pan et al. (2018). For the surface water, a sterilised transparent bottle was plunged into the water about 30 cm deep, and the bottle was filled to the brim and covered before bringing out the bottle. This was repeated at four different points (sub-composites) about 25 m apart, all in the opposite direction of water flow. All the sub-composites (4) were mixed to form a composite sample for each creek and placed in an ice box before transporting to the laboratory. The sediment samples were collected at low tides using Eckman grab at about 20–30 cm from each creek. Similarly, four sub-composites were collected at 25 m apart to make a composite for the creeks, and the samples were placed in self-sealing polythene bags previously decontaminated in HCl and immediately transported to the laboratory for further analysis.

The composite samples were analysed for relevant physicochemical; pH, and PTEs; Iron (Fe), Nickel (Ni), Cadmium (Cd), Selenium (Se), Zinc (Zn), Lead (Pb), Chromium (Cr) and Copper (Cu). All the parameters were analysed based on American Public Health Association standard-APHA (APHA, 2012) and American Standard for Testing Materials-ASTM (ASTM, 2012) accepted standard procedures and analytical method described by Afolabi et al. (2022), while the PTEs concentration was determined by absorption spectrometer (Perkin Elmer 3100 model, New Jersey, USA).

Quality assurance/control (QA/QC) ensures that analyses are done at standard procedures, triplicate analyses and mean estimation for accuracy and precision. All analyses were subjected to quality reagents while instruments were sterilized, soaked in 10 % HNO₃ in 1 % HCl solution, washed adequately with deionized water, and desiccated. Detection limits, including LOD and LOQ, were estimated as LOD = 3 σ/S, LOQ = 10 σ/S, respectively, where σ is the SD (standard deviation) of analytical blank measurement (n = 18). At the same time, S is the slope of the calibration curve (y = mx + b) (Ahmad et al., 2021).

Data analysis

Ecotoxicological status of sediment

The commonly used indicators such as CF, EF, Igeo, RI and MRI have been adopted to assess the environmental medium's contamination/pollution status (Afolabi and Adesope, 2022; Afolabi et al., 2023). To estimate the CF and EF values, the geochemical background values (BGV) used by Afolabi and Adesope (2022) and Turekian & Wedepoh (1961) for surface sediment, which include; Cr (35), Ni (20), Cu (45), Fe (47), Cd (0.3), Zn (95) and Pb (20). Also, the Fe concentration was used as the ratio of the elemental concentration of sediment normalized to a reference. The toxicological response factor (Tr) was required for Risk index (RI) estimation, and the Tr value of the PTEs for the study include; Pb (5), Cd (30), Cr (2), Ni (5), Fe (1) and Cu (5) (Aja et al., 2021). The formulae for the indicators and their values classification for the estimation of the ecotoxicological status of sediment samples from the

creeks are presented in [Supplementary Table ST1](#).

Source apportionment analysis for surface water and sediment

The source and distribution of PTEs across the surface water and sediment were analysed through statistical tools such as Pearson's Correlation Coefficient (PCC) and Principal Component Analysis (PCA) using the Statistical Package for the Social Sciences (SPSS) version 21 platform.

Health risk assessment for surface water and sediment

The health risk due to exposure to PTEs in surface water and sediment can be analysed through the daily dose (ADD), the non-carcinogenic target hazard quotient (THQ), hazard index (HI), and Total/lifetime carcinogenic risk (LCR) coefficients for adults and children (Kumar et al., 2018; Afolabi et al., 2023). According to Edokpayi et al. (2018), there are three (3) major human exposure pathways to PTEs risk: inhalation via nose and mouth, direct ingestion, and dermal absorption through skin exposure. These exposure pathways are commonly estimated for surface water (ingestion (ing) and dermal (derm) absorption) and sediment (inhalation (inh), ingestion and dermal absorption) (Afolabi et al., 2022; 2023).

Average daily dose (ADD)

Exposure doses for determining human health risk through these three pathways have been described in the literature (Kamunda et al., 2016; Boateng et al., 2019) and can be calculated using Equation 1–3 as adapted from the US EPA risk assessment guidance for superfund (RAGS) methodology (USEPA, 1989; 2013; Edokpayi et al., 2018).

$$ADD_{ing} = C_{S,water/Sediment} \times \frac{IngR \times EF \times ED}{BW \times AT} \times 10^{-6} \quad (1)$$

$$ADD_{inh} = C_{Sediment} \times \frac{InhR \times EF \times ED}{PEF \times BW \times AT} \quad (2)$$

$$ADD_{derm} = C_{S,water/Sediment} \times \frac{SA \times AF \times ABF \times EF \times ED}{BW \times AT} \times 10^{-6} \quad (3)$$

where;

ADD = Average daily dose through ingestion/inhalation/dermal absorption of soil (mg/kg/day); C_{soil} = concentration of the heavy metals in soil (mg/kg); IngR: Ingestion rate; InhR: Inhalation rate; EF: Exposure Frequency; ED: Exposure Duration; PEF: Particle Emission Factor; BW: Body Weight; AT: Averaging Time; SA: Exposed Skin Area; AF: Skin Adherence Factor and ABF: Dermal Absorption Factor. All values are presented in [Supplementary Table ST2](#).

i. Target Hazard Quotient (THQ) and Hazard Index (HI)

Total hazard quotient: THQ is the ratio of ADD (that is, exposure through ingestion/inhalation/dermal absorption of surface water and sediment) and RfD (chronic reference dose for each metal in mg/kg BW/day), which is typically used to estimate the potential non-carcinogenic risk of PTEs exposure to humans in different pathways (Alsafran et al., 2021; Afolabi et al., 2022).

$$THQ = \frac{ADD (Ingestion \times Inhalation \times Dermal)}{RfD} \quad (4)$$

where THQ < 1 considers the exposed population experience no significant health risk.

Hazard Index (HI): HI is the sum of all expected HQs (non-carcinogenic risks) through different pathways and is employed to compute the total potential non-carcinogenic risks of various contaminants (Alsafran et al., 2021; Afolabi et al., 2022). The RfD for the PTEs were provided in [Supplementary Table ST3](#).

$$HQ = \frac{ADD}{Rfd}; HI = \sum HQ = HQ_{ing} + HQ_{inh} + HQ_{derm} \quad (5)$$

When the value of $HI \leq 1$ indicates no significant risk of non-carcinogenic effects; however, when $HI > 1$, there is a probability of non-carcinogenic effects occurring, and the probability increases with a rising value of HI (Alsafran et al., 2021; Afolabi et al., 2022).

ii. Carcinogenic Risk (CR) Coefficients

The estimation is that carcinogenic PTEs determine the health risk through different exposure pathways. It is calculated based on the formula below;

$$CR = ADD (Ing \times Inh \times Derm) \times CSF \quad (6)$$

$$TCR = \sum CR = CR_{ing} + CR_{inh} + CR_{derm} \quad (7)$$

where CSF: Cancer Slope Factor. $TCR < 10^{-6}$, $TCR > 1 \times 10^{-4}$, and 1×10^{-6} to 1×10^{-4} indicate no carcinogenic risk, high risk of developing cancer, and acceptable risk to humans, respectively. The CSF for the carcinogenic PTEs were provided in Supplementary Table ST4.

Result and discussion

PTEs concentration in surface water and sediment

The concentration of PTEs in surface water and sediment of the study areas (Fibiri and Iwoama Creeks) was presented in Table 1. The pH of the water ranged from 6.28 for Iwoama Creek to 7.06 for Fibiri Creek. The pH values for both creeks were within the WHO acceptable limit and lower than the value reported by Onojake et al. (2015). The PTEs concentration for both creeks exceeded the WHO allowable limit, and those reported by Onojake et al. (2015), and the concentrations trended as $Cr > Pb > Fe > Ni > Cd > Zn > Cu > Se$ for Fibiri Creeks and $Fe > Cr > Pb > Ni > Cd > Zn > Cu > Se$ for Iwoama creek. For the sediment, the pH ranges from 4.43 for Fibiri Creek to 4.39 for Iwoama Creek, which both values below the WHO limit and indicate acidic status. The outcome indicates PTEs' environmental pollution, as Pan et al. (2022) reported. Afolabi and Adesope (2022) reported a similar pH-acidic (5.13) for a study conducted on sediment from a nearby oil spill site. The PTEs concentration for both creeks exceeded the WHO allowable limit, and those reported by Bubu et al. (2015) and Okorundu et al. (2021), and the concentrations trended as $Fe > Pb > Ni > Cr > Zn > Cd > Cu > Se$ for both creeks. The outcome indicated that the creek's surface water is polluted with the PTEs and can be detrimental to the environment, aquatic organisms and human health. Naturally, Fe is among the prevailing element frequently in high sediment concentrations than other PTEs (Ustaoğlu and Islam, 2020). Excessive concentrations of PTEs are attributed to anthropogenic activities such as industrial discharge and engagement of resources from the environment, which increases the

health risk such as anaemia and cancer (Tiware et al., 2015; Bazrafshan et al., 2015), nervous system and kidneys (Mugica et al., 2002), allergies, cardiovascular and kidney diseases, lung fibrosis, and lung and nasal cancer (Afolabi and Adesope, 2022).

Ecotoxicological status of sediment

The ecotoxicological status of the Creeks sediment based on the CF, EF, Igeo, RI and MRI were analysed and presented in Table 2. The Creeks CF status ranged from low contamination (Zn and Cu), moderate contamination (Ni, Pb and Cr) and very high contamination (Fe and Cd) and trended as $Cd > Fe > Pb > Ni > Cr > Cu > Zn$. The CF status of Zn and Cu reported therein is similar to those reported by Bubu et al. (2017) for sediment along Bonny River, while Enuneku et al. (2018) reported similar status for Fe and Pb for sediment along Benin River, Southern Nigeria. Emmanuel et al. (2018) reported similar status for Cd from the River Benue, North-Central Nigeria study. According to Yahaya et al. (2020), the high contamination status of Fe and Cd can be linked to abundance availability in the earth's crust and human-related activities, respectively. The EF status of the sediments indicated that all PTEs such as Ni, Zn, Pb, Cr and Cu have zero enrichment, less enrichment for Fe, while the Cd of Fibiri Creek showed moderated enrichment compared to less enrichment for Cd of Iwoama Creek. The EF showed similarity to the study conducted by Afolabi et al. (2023), while Ohiagu et al. (2020) suggested that $EF > 1$ can be linked to human-related activities while $EF \leq 1$ could be due to natural phenomena such as weathering. The Igeo status of the Creeks' sediment revealed that all the PTEs have a 'no pollution' status (where $I_{geo} \leq 0$: No Pollution). Bubu et al. (2017) reported a similar outcome for Igeo status for PTEs for sediment along Bonny River, indicating that any of the PTEs do not pollute the sediment of the studied location. The Creeks RI status ranged from low risk (Ni, Zn, Pb, Cr and Cu), moderate risk (Fe) and significantly high risk (Cd) and trended as $Cd > Fe > Pb > Ni > Cr > Cu > Zn$. The MRI status of the Creeks indicated that all the PTEs are within the low-risk status except for Cd, which showed considerable risk. Based on different ecotoxicological indices adopted by the study to determine the status of PTEs in creeks sediment, it was observed that Cd possesses significant concern due to its high contamination and considerably high ecological risk.

Source apportionment analysis for surface water and sediment

The source and distribution of PTEs across the surface water and sediment were analysed through PCA, PCC, rotation component matrix of HM, and screen plot, which are summarised and presented in Tables 3-4 and Fig. 2. Pearson correlation mix indicated that Fe has a significantly strong positive relationship (>0.5) with Ni, Se, Zn and Cu with correlation (r) of 0.985, 0.759, 0.981 and 0.526, respectively and a weak positive relationship (<0.4) with Cd with $r = 0.082$. Furthermore, a strong positive relationship between Pb and Cr but a negative relationship with other PTEs. According to Afolabi et al. (2023), PTEs of

Table 1
Concentration of PTEs in Surface Water (SW) and Sediment (S).

Parameter	Fibiri Creek SW(mg/l)	S(mg/kg)	Iwoama Creek SW(mg/l)	S(mg/kg)	Ref ₁	Ref ₂ ^a	Ref ₃	WHO _{SW}	BGV
pH	7.06	4.43	6.28	4.39		7.76		6.5–8.5	—
Fe	60.3	1526.6	105.6	1557.4	15.07	2	11.12	0.3	47 ^a
Ni	43.9	47.8	43.0	48.4	—	0.25	0.189	0.07	20 ^a
Cd	13.5	14.2	13.3	12.8	—	0	1.025	0.03	0.15 ^a
Se	5.6	5.9	5.6	6.9	—	—	—	—	—
Zn	9.7	29.1	9.4	36.0	9.11	0.25	0.036	5.0	95 ^b
Pb	61.3	52.9	60	54.9	3.95	0.23	0.437	0.01	20 ^a
Cr	91.2	42.1	87.7	48.4	—	1.75	—	0.1	35 ^a
Cu	6.9	7.2	7.6	8.6	1.31	0.42	0.160	2.0	15.1 ^a

Ref₁: Bubu et al. (2017); Ref₂: Onojake et al. (2015) for SW, Ref₃: Okorundu et al. (2021), BGV: Background Value (^aAfolabi and Adesope, 2022; ^bTurekian and Wedepohl, 1961).

Table 2
Ecotoxicological Status of Sediment.

	Fibiri Creek					Iwoama Creek				
	Cf	Ef	I _{geo}	RI	MRI	Cf	Ef	I _{geo}	RI	MRI
Fe	32.5	1	−0.17	32.5	1	33.1	1	−0.17	33.1	1
Ni	2.39	0.07	−1.68	11.95	0.35	2.42	0.07	−1.68	12.1	0.35
Cd	94.7	3	−2.21	2841	90	85.3	2.7	−2.26	2559	81
Zn	0.31	0.009	−1.89	0.31	0.009	0.38	0.01	−1.82	0.38	0.01
Pb	2.65	0.08	−1.64	13.25	0.4	2.73	0.08	−1.64	13.65	0.4
Cr	1.2	0.04	−1.74	2.4	0.08	1.38	0.04	−1.68	2.76	0.08
Cu	0.47	0.01	−2.52	2.35	0.01	0.56	0.02	−2.4	2.8	0.1

Table 3
Pearson’s Correlation Coefficient (PCC) Analysis.

	Fe	Ni	Cd	Se	Zn	Pb	Cr	Cu
Fe	1.000							
Ni	0.985	1.000						
Cd	0.082	0.029	1.000					
Se	0.759	0.799	−0.578	1.000				
Zn	0.981	0.985	−0.106	0.870	1.000			
Pb	−0.970	−0.921	−0.278	−0.592	−0.906	1.000		
Cr	−0.993	−0.964	−0.190	−0.678	−0.950	0.991	1.000	
Cu	0.526	0.517	−0.764	0.890	0.652	−0.385	−0.447	1.000

Table 4
Rotation component matrix of PTEs across the Environmental Mediums.

	PC 1	PC 2
Cr	−0.997	
Pb	−0.988	
Fe	0.987	0.160
Ni	0.965	0.202
Zn	0.939	0.338
Cd	0.240	−0.970
Cu	0.388	0.894
Se	0.648	0.750
Eigenvalues	5.874	1.996
% of Variance	67.305	31.076
Cumulative %	67.305	98.381

strong correlation indicated similar sources and distribution patterns noted among Fe, Ni, Se, Zn and Cu. According to Bai et al. (2023), the complex relationship of PTEs were influenced by several attributes or sources which makes coherent conclusion of the PCC. A situation with

complex relationship or sources were suitable for further traceability study using principal component analysis (Liu et al., 2022).

The significance correlation of the PTEs was presented in [Supplementary Table ST5](#).

The principal component (PC1) of the PTEs have strong positive correlations for Fe: 0.987, Ni: 0.965, Zn: 0.939 and Se: 0.648 except for Cr and Pb with negative correlation (−0.997 and −0.988) and Cd and Cu with weak positive correlation (0.24 and 0.388). Liu et al. (2022) classified sources of metals based on the degrees of positive loading with loading values as strong positive loading (0.75–1.0), moderate positive loading (0.5–0.75), and weak positive loading (0.3–0.5). Therefore, PTEs in PC1 such as Fe, Ni, Zn and Se are presumed to be an anthropogenic source related with oil exploration and exploitation taking place around the study area. This submission is similar to the finding of Zeng et al. (2022) which deduced anthropogenic sources of metalloids through PCA analysis (Factor I). The weak positive and negative value of Cd, Cu, Cr and Pb in the PCI further confirm the influence of multiple sources which was a confirmed by the similar study of Chen et al.

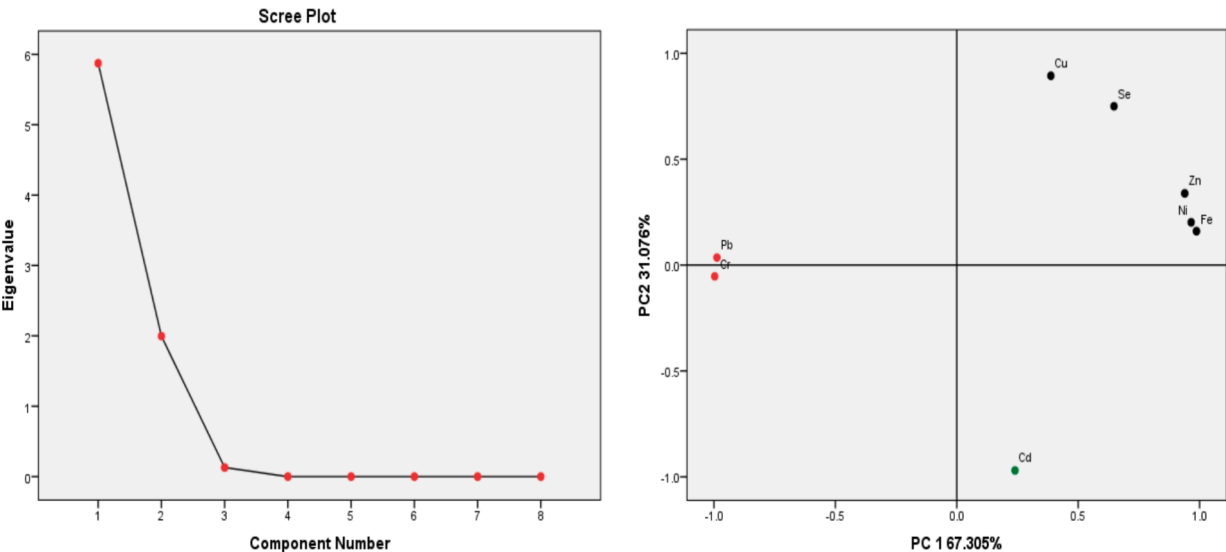


Fig. 2. Scree plot of eigenvalues after PCA and rotated component matrix of PTEs.

(2022). The eigenvalues indicated that the PC1 has > 1 and constitutes 67.305 % of the total variance capable of explaining the factor and it was deduced that PTEs of strong correlations might come from similar sources or similar transport pathway (Hu et al., 2020; Chen et al., 2022).

The principal component (PC2) indicated 31.076 % of the variance, where all the PTEs showed weak and negative correlations except for Cu and Se (0.894 and 0.750). The eigenvalues indicated that the PC2 has > 1 , constituting 98.381 % of the total variance. From the outcome, PTEs such as Fe, Ni, Se, Zn and Cu with strong correlation indicate similar sources and patterns, and it is lithogenic and further explains their weak and negative correlation with Cd, Pb and Cr. Similarly, PTEs such as Cd, Pb and Cr with weak or negative correlation indicate similar sources and patterns, and it is anthropogenic, which substantially explains the lack of correlation with Fe, Ni, Se, Zn and Cu. This submission is similar to studies such as Zeng et al. (2022) and Wang et al. (2020) which indicated that metals such as Ni in the environment can originated from lithogenic material. The outcome corroborated with Ustaoglu et al. (2020), which indicated that a strong correlation between and among elements could indicate similar sources and distribution patterns, while a lack of correlation implies the opposite. Overall, the main industry around the creeks is oil and gas sectors which could contribute to the diffusion and pollution PTEs from atmospheric deposition, transport (ship) vehicles, and rivers (Xu et al., 2013; Shen et al., 2019; Zeng et al., 2022).

Health risk assessment for surface water and sediment

The ADD based on the three exposures (ADD_{ing}, ADD_{inh}, and ADD_{derm}) were estimated for the PTEs sourced from the creek's surface water and sediment and presented in Supplementary Table ST6. The THQ, HI

and TCR for all the PTEs across the environmental medium were presented in Table 5 for Fibiri Creek and Table 6 for Iwoama Creek. The THQ for the creeks indicated “no significant health risk-NSHR” for all the PTEs for surface water and sediment. The outcome is similar to those Afolabi et al. (2023) reported, where all the reported elements showed NSHR in adults and children. The HI reported that the creeks showed the non-carcinogenic PTEs (Fe, Zn and Se) indicated “no significant risk of non-carcinogenic effect-NSRNC” except for HI of Zn reported for children at Fibiri Creek (1.64) and Iwoama Creek (2.03) indicating a “potential non-carcinogenic effect-PNCE”. The HI outcome showed that children are more exposed to the PNCE than adults due to their consistent oral consumption through hand and mouth (Kusin et al., 2018; Alsafran et al., 2021).

The estimated TCR revealed that the risk is higher with children than adults and with sediment than with surface water. For Fibiri Creek, the TCR for adults ranged from “no carcinogenic risk-NCR to acceptable risk to human-ARH”, while the TCR for children indicated “high carcinogenic risk-HCR” for Ni (2.87×10^{-4}), Pb (2.33×10^{-4}) and Cr (1.34×10^{-4}) for surface water and Ni (7.01×10^{-4}), Cd (2.46×10^{-4}), Pb (6.5×10^{-4}) and Cr (1.35×10^{-3}) for the sediment. A similar trend was observed at the Iwoama Creek, where all the TCR for the adult indicated NCR to ARH and TCR for children showed HCR for Ni (2.89×10^{-4}), Pb (2.42×10^{-4}) and Cr (1.45×10^{-4}) for surface water and Ni (6.06×10^{-4}), Cd (2.42×10^{-4}), Pb (6.76×10^{-4}) and Cr (1.34×10^{-3}) for the sediment. The outcome showed similarity with the study conducted by Aendo et al. (2022) while the carcinogenic PTEs are capable of lung and nasal cancer (Guo et al., 2019), respiratory disorder, perinatal jaundice, and congenital disabilities (Banu et al., 2018) and allergies, cardiovascular and kidney diseases, and lung fibrosis (Kinuthia et al., 2020). Chronic exposure to low Pb levels can limit the intelligence capacity of

Table 5

The THQ, HI and TCR for Surface Water and Sediment of Fibiri Creek.

Fibiri Creek													
	PTEs	Surface Water						Sediment					
		THQ	Remark	HI	Remark	TCR	Remark	THOR	Remark	HI	Remark	TCR	Remark
Adult	Fe	8.45×10^{-10}	NSHR	1.52×10^{-4}	NSRNC	—	—	2.56×10^{-13}	NSHR	3.84×10^{-3}	NSRNC	—	—
	Zn	5.9×10^{-8}	NSHR	1.15×10^{-3}	NSRNC	—	—	1.29×10^{-14}	NSHR	3.43×10^{-3}	NSRNC	—	—
	Se	1.42×10^{-7}	NSHR	1.97×10^{-3}	NSRNC	—	—	3.31×10^{-14}	NSHR	2.07×10^{-3}	NSRNC	—	—
	Ni	2.38×10^{-7}	NSHR	—	—	8.59×10^{-6}	ARH	5.57×10^{-14}	NSHR	—	—	5.18×10^{-5}	ARH
	Cd	9.75×10^{-6}	NSHR	—	—	3.9×10^{-6}	ARH	2.28×10^{-11}	NSHR	—	—	4.12×10^{-6}	NCR
	Pb	6.87×10^{-5}	NSHR	—	—	6.34×10^{-6}	ARH	6.51×10^{-11}	NSHR	—	—	7.79×10^{-6}	NCR
	Cr	1.24×10^{-5}	NSHR	—	—	3.06×10^{-5}	ARH	3.30×10^{-10}	NSHR	—	—	1.42×10^{-5}	ARH
	Cu	1.32×10^{-9}	NSHR	—	—	—	—	2.21×10^{-17}	NSHR	—	—	—	—
Children	Fe	3.03×10^{-6}	NSHR	3.01×10^{-3}	NSRNC	—	—	1.32×10^{-9}	NSHR	1×10^{-1}	NSRNC	—	—
	Zn	2.13×10^{-4}	NSHR	5.47×10^{-1}	NSRNC	—	—	1.19×10^{-10}	NSHR	1.64	PNCE	—	—
	Se	5.1×10^{-5}	NSHR	5.13×10^{-2}	NSRNC	—	—	2.57×10^{-10}	NSHR	5.4×10^{-2}	NSRNC	—	—
	Ni	5.33×10^{-5}	NSHR	—	—	2.87×10^{-4}	HCR	4.41×10^{-12}	NSHR	—	—	7.01×10^{-4}	HCR
	Cd	2.18×10^{-3}	NSHR	—	—	7×10^{-6}	NCR	1.27×10^{-9}	NSHR	—	—	2.46×10^{-4}	HCR
	Pb	1.53×10^{-2}	NSHR	—	—	2.33×10^{-4}	HCR	5.56×10^{-9}	NSHR	—	—	6.5×10^{-4}	HCR
	Cr	2.77×10^{-3}	NSHR	—	—	1.34×10^{-4}	HCR	3.43×10^{-13}	NSHR	—	—	1.35×10^{-3}	HCR
	Cu	2.96×10^{-7}	NSHR	—	—	—	—	2.87×10^{-15}	NSHR	—	—	—	—

NSHR: No Significant Health Risk, NSRNC: No Significant Risk Of Non-Carcinogenic Effect, PNCE: Potential Non-Carcinogenic Effect, ARH: Acceptable Risk for Humans, HCR: High Carcinogenic Risk, NCR: No Carcinogenic Risk.

Table 6
The THQ, HI and TCR for Surface Water and Sediment of Iwoama Creek.

Iwoama Creek													
	PTEs	Surface Water						Sediment					
		THQ	Remark	HI	Remark	TCR	Remark	THOR	Remark	HI	Remark	TCR	Remark
Adult	Fe	2.59×10^{-9}	NSHR	1.27×10^{-3}	NSRNC	—	—	2.72×10^{-13}	NSHR	3.15×10^{-3}	NSRNC	—	—
	Zn	5.6×10^{-8}	NSHR	1.11×10^{-3}	NSRNC	—	—	2.44×10^{-14}	NSHR	4.25×10^{-3}	NSRNC	—	—
	Se	1.42×10^{-7}	NSHR	1.97×10^{-3}	NSRNC	—	—	5.32×10^{-14}	NSHR	2.43×10^{-3}	NSRNC	—	—
	Ni	2.29×10^{-7}	NSHR	—	—	4.65×10^{-5}	ARH	1.29×10^{-19}	NSHR	—	—	5.24×10^{-5}	ARH
	Cd	9.46×10^{-6}	NSHR	—	—	3.85×10^{-6}	ARH	168×10^{-11}	NSHR	—	—	3.72×10^{-6}	NCR
	Pb	6.58×10^{-6}	NSHR	—	—	6.21×10^{-6}	ARH	1.89×10^{-19}	NSHR	—	—	5.67×10^{-6}	NCR
	Cr	1.15×10^{-5}	NSHR	—	—	2.95×10^{-5}	ARH	5.02×10^{-10}	NSHR	—	—	1.63×10^{-5}	ARH
	Cu	1.61×10^{-9}	NSHR	—	—	—	—	3.78×10^{-17}	NSHR	—	—	—	—
Children	Fe	9.25×10^{-6}	NSHR	6.91×10^{-3}	NSRNC	—	—	1.32×10^{-9}	NSHR	1.02×10^{-1}	NSRNC	—	—
	Zn	2×10^{-4}	NSHR	5.3×10^{-1}	NSRNC	—	—	1.19×10^{-10}	NSHR	2.03	PNCE	—	—
	Se	5.07×10^{-4}	NSHR	5.12×10^{-2}	NSRNC	—	—	2.57×10^{-10}	NSHR	6.35×10^{-2}	NSRNC	—	—
	Ni	5.11×10^{-5}	NSHR	—	—	2.89×10^{-4}	HCR	4.41×10^{-12}	NSHR	—	—	6.06×10^{-4}	HCR
	Cd	2.1×10^{-3}	NSHR	—	—	6.85×10^{-6}	ARH	1.27×10^{-9}	NSHR	—	—	2.42×10^{-4}	HCR
	Pb	1.46×10^{-3}	NSHR	—	—	2.42×10^{-4}	HCR	5.56×10^{-9}	NSHR	—	—	6.76×10^{-4}	HCR
	Cr	2.55×10^{-3}	NSHR	—	—	1.45×10^{-4}	HCR	3.43×10^{-13}	NSHR	—	—	1.34×10^{-3}	HCR
	Cu	3.6×10^{-7}	NSHR	—	—	—	—	2.87×10^{-15}	NSHR	—	—	—	—

NSHR: No Significant Health Risk, NSRNC: No Significant Risk Of Non-Carcinogenic Effect, PNCE: Potential Non-Carcinogenic Effect, ARH: Acceptable Risk for Humans, HCR: High Carcinogenic Risk, NCR: No Carcinogenic Risk.

children (Kinuthia et al., 2020).

Conclusion

Our study comprehensively demonstrated that PTEs such as Fe, Pb, Ni, Cr, Zn, Cd, Cu and Se in the environmental medium of creeks along Bonny Rivers, Nigeria, exceed the WHO allowable limit indicating possible pollution of the environment. This was further inquired through ecotoxicological studies which revealed that Cd among the PTEs poses a significant concern due to its high contamination and considerably high ecological risk, and its source was linked to anthropogenic activities in the environment. The human health risk revealed that children are exposed to potential non-carcinogenic effects with Zn and high carcinogenic risks with Ni, Pb, Cr, and Cd. Using PCA for apportionment model, the PTEs sources were more anthropogenic; although, the aspect of lithogenic was not exclude while other form depositions are influence by local industrial activities in the area. Environmental sustainability practices through surveillance and remediation action are encouraged to prevent further deterioration of the environment.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.wsee.2024.06.001>.

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