Assessment of Physicochemical and Ecological Risk of Heavy Metals in Oil-Impacted Soil of Bomu, Gokana, Rivers State, Nigeria

Obowu, J.N., Akinfolarin, O.M., & Berebon, T.K.
Department of Chemistry, Rivers State University,
Port Harcourt, Nigeria
Corresponding email: john.obowu@ust.edu.ng

https://doi.org/10.56201/ijccp.vol.12.no8.2026.pg1.12

Abstract
Petroleum exploration and associated activities in the Niger Delta have generated persistent soil contamination and altered soil physicochemical characteristics. This study assessed selected physicochemical properties, concentrations, spatial variation and ecological risks of Cu, Cr, Cd, Pb and As in oil-impacted soils of Bomu, Gokana Local Government Area, Rivers State, Nigeria. Soil samples were collected from five sites (A–E), with three replicate determinations per site. Soil pH, electrical conductivity (EC), total organic carbon (TOC), total organic nitrogen (TON), and heavy-metal concentrations were determined using standard analytical procedures. Descriptive statistics and one-way analysis of variance (ANOVA) were used to assess spatial differences in metal concentrations. Contamination factor (CF), pollution load index (PLI) and geo-accumulation index (I_{geo}) were employed to characterize contamination, while potential ecological risk was evaluated using the Håkanson framework. Soil pH increased from 5.21 at Site A to 6.85 at Site E, whereas EC and TOC decreased from 2480 µS/cm and 5.84% to 410 µS/cm and 1.47%, respectively. TON showed the reverse trend, increasing from 620 to 1920 mg/kg. Mean concentrations of Cu, Cr, Cd, Pb and As at Site A were 88.73, 101.23, 5.10, 149.73 and 25.17 mg/kg, respectively, and generally declined progressively towards Site E. Cu exceeded the adopted NESREA guideline of 36 mg/kg at Sites A–D; Cr slightly exceeded 100 mg/kg only at Site A; Cd exceeded 3 mg/kg at Sites A–C; Pb exceeded 85 mg/kg at Sites A–C; and As exceeded 5 mg/kg at Sites A–D. One-way ANOVA demonstrated significant differences among sites for Cu ($F_{4,10} = 2958.16$, $p < 0.001$), Cr ($F_{4,10} = 2137.37$, $p < 0.001$), Cd ($F_{4,10} = 931.50$, $p < 0.001$), Pb ($F_{4,10} = 3878.55$, $p < 0.001$) and As ($F_{4,10} = 1376.79$, $p < 0.001$). CF and I_{geo} identified As as an important contaminant, while PLI values above unity occurred at Sites A–D. The potential ecological risk index ranged from 20.22 at Site E to 124.50 at Site A and remained within the low-risk class under the adopted Håkanson classification. The results demonstrate a pronounced spatial contamination gradient and indicate the need for continued monitoring and appropriate remediation of oil-impacted soils in Bomu.

Keywords: *Bomu; ecological risk; heavy metals; Niger Delta; oil-impacted soil; pollution load index; geo-accumulation index.*

Introduction

The Niger Delta is one of the world's major petroleum-producing regions and contains extensive wetland, agricultural and mangrove ecosystems (Ite et al., 2024). Decades of petroleum exploration, production, transportation, refining and associated industrial activities

have resulted in recurrent releases of crude oil and petroleum-derived contaminants into terrestrial and aquatic environments (Falih et al., 2024). Recent field investigations have demonstrated that petroleum contamination in the Niger Delta is spatially extensive and can affect interconnected soil, sediment, surface-water and groundwater systems (Adeniran et al., 2023). Oil contamination of soil is environmentally important because petroleum releases do not consist exclusively of hydrocarbons. Petroleum and associated industrial activities can introduce or mobilize potentially toxic elements, including Pb, Cd, Cr, Cu and As (Elumalai et al., 2024). These elements may persist in soils long after the readily degradable hydrocarbon fractions have diminished and can interact with soil organic matter, clay minerals and other soil constituents. Their environmental behaviour is strongly influenced by pH, electrical conductivity, organic carbon and other physicochemical characteristics (Omo-Okoro et al., 2025). Heavy metals in petroleum-producing environments may originate from several sources, including crude oil, produced water, drilling materials, metallic infrastructure, corrosion, combustion emissions, waste disposal and other anthropogenic activities (Ogolo et al., 2022). Consequently, determination of total concentrations alone may not adequately characterize environmental significance. Contamination indices such as contamination factor (CF), pollution load index (PLI) and geo-accumulation index (Igeo) provide complementary approaches for evaluating the magnitude and spatial distribution of metal contamination (Hridoy et al. 2025). The ecological-risk framework developed by Håkanson further incorporates metal-specific toxic-response coefficients to estimate the potential ecological significance of contamination (Daurov et al., 2026). Recent investigations in the Niger Delta have confirmed the value of combining concentration measurements with pollution and ecological-risk indices (Afolabi & Adesope 2022, Oghenenyoreme et al., 2024). Okoye et al. (2022) applied PLI, Igeo, modified contamination degree and related indices on study of heavy metals and arsenic in soils and vegetation from the Niger Delta and reported substantial spatial differences among oil-producing locations. Similarly, an ecotoxicological assessment of a remediated oil-spill site in the Niger Delta employed CF, EF, Igeo, PLI and RI and demonstrated that risk indices can distinguish contamination conditions even where measured concentrations vary substantially (Afolabi & Adesope, 2022). More recent evidence emphasizes that contamination remains an important environmental concern in petroleum-producing communities. Bankole et al. (2024), investigating crude-oil-contaminated agricultural soils at Okpare-Olomu in the Niger Delta, reported considerable variation in Cu, Cd, Cr, Ni, Pb and Zn and identified moderate-to-strong pollution, particularly associated with Pb and Zn. Ihenetu (2024) similarly evaluated PAHs and heavy metals across a Niger Delta soil gradient and emphasized the need to consider both contaminant occurrence and combined ecological and human-health implications. The importance of contemporary risk-based assessment has also been highlighted by recent work on petroleum-affected soils in the Niger Delta. DeVaull et al. (2025) study, developed human-health risk-based screening levels for crude-oil-affected soils and sediments and demonstrated that a single generic petroleum intervention value may not adequately represent differences in land use and contaminant composition. Bomu, in Gokana Local Government Area of Rivers State, occurs within an area with a long history of petroleum-related environmental pressure (Brown, 2015). However, site-specific information integrating soil physicochemical properties, heavy-metal concentrations, statistical spatial comparison and ecological-risk indices remains valuable for environmental management. Therefore, this study assessed the physicochemical properties and concentrations of Cu, Cr, Cd, Pb and As in oil-impacted soils from five locations in Bomu and evaluated their contamination status and potential ecological risk.

Materials and Methods

Study area

The study was conducted in Bomu, Gokana Local Government Area of Rivers State, within the Niger Delta region of southern Nigeria. It lies aapproximately 4°38′N latitude and 7°16′E longitude. The area is characterized by a humid tropical climate, high aannual rainfall ranging between 2,200 mm and 2,600 mm, daily temperatures average between 25°C and 32°C. Extensive wetland systems and intensive human activities associated with petroleum exploration and production. The environmental setting makes soils susceptible to contamination from petroleum spills, oilfield infrastructure, transportation, waste disposal and related anthropogenic activities.

The study population consists of soils of Bomu community, particularly farmlands, residential areas, and artisanal refining zones.



Figure 1: Map of the study area showing sampling Sites

Soil sampling and laboratory analysis

The study employed a purposive sampling method to identify contaminated sites based on proximity to oil installations, refining sites, and farmlands with visible signs of pollution.

Soil samples were collected using stainless steel auger (to prevent metallic contamination) at a depth of 0–15 cm from five locations designated Sites A, B, C, D and E. Site A is Polluted site contaminated with spilled crude. Site B (Near - Spill Zone) is Farmland within 200m of a known spill site. Site C is Farmlands within 500-700m of a known spill site. Site D is Residential Area and Site E is Control Zone from which Soil samples were collected 5 km away from pollution sources, serving as baseline. Two subsamples were taken per location and homogenized to form one representative sample. This approach was to ensure that results reflect the average contamination status of each site while minimizing localized variability. Each sample was sealed in pre-cleaned polyethylene bags, labelled, and transported in cool boxes to the laboratory for analysis of soil parameters using standard method. Three replicate determinations were available for each heavy metal at each site. The physicochemical parameters evaluated were pH, electrical conductivity, total organic carbon (TOC) and total organic nitrogen (TON). The investigated metals were copper (Cu), chromium (Cr), cadmium (Cd), lead (Pb) and arsenic (As). Heavy-metal concentrations were determined following acid digestion using standard procedures and quantified by Atomic Absorption Spectrophotometer (AAS, Perkin Elmer Model 2380) expressed in mg/kg dry soil.

Statistical analysis

Descriptive statistics were calculated as mean and standard deviation. One-way analysis of variance (ANOVA) was used to determine whether mean concentrations differed significantly among Sites A–E. The significance level was set at $\alpha = 0.05$. Where significant differences occurred, means were separated using Tukey's HSD post-hoc test. Statistical results were reported in the conventional SPSS format as F-statistic, degrees of freedom and p-value.

Ecological Risk Assessment

The ecological risk of heavy metals in the agricultural soils was assessed using four standardised models: contamination factor (CF), geo-accumulation index (Igeo), pollution load index (PLI), and potential ecological risk index (RI). The formulas, calculation procedures, and interpretation criteria for these models are presented below:

Contamination factor (CF)

The contamination factor (CF) quantifies the degree of contamination of a specific metal in soil relative to its background or reference value. It is calculated using the formula:

$$CF_i = \frac{C_i}{C_n}$$

Where: CF_i = contamination factor for metal *I*; C_i = measured concentration of metal *i* in soil (mg/kg); C_n = background or reference concentration of metal iii (mg/kg). Interpretation (Hakanson, 1980; Salman et al., 2021)**:** CF < 1: Low contamination; 1 ≤ CF < 3: Moderate contamination; 3 ≤ CF < 6: Considerable contamination; CF ≥ 6: Very high contamination.

The background concentrations (Bn) of the selected metals used for the assessment were 85 mg/kg for lead (Pb), 1.0 mg/kg for arsenic (As), 0.8 mg/kg for cadmium (Cd), 100 mg/kg for chromium (Cr), and 35 mg/kg for nickel (Ni)**.** These values served as the reference or baseline concentrations for evaluating the degree of metal enrichment and contamination in the soil samples.

Geo-accumulation Index (Igeo)

The geo-accumulation index (Igeo) evaluates metal contamination by comparing current and pre-industrial concentrations:

$$I_{geo} = \log_2\left(\frac{C_i}{1.5 \times C_n}\right)$$

Where: C_i = measured metal concentration; C_n = geochemical background concentration; 1.5 = factor accounting for natural variability in soil composition

Interpretation **(**Hakanson, 1980**):** $I_{geo} \leq 0$: Uncontaminated; $0 < I_{geo} \leq 1$: Uncontaminated to moderately contaminated; $1 < I_{geo} \leq 2$: Moderately contaminated; $2 < I_{geo} \leq 3$: Moderately to heavily contaminated; $3 < I_{geo} \leq 4$: Heavily contaminated; $4 < I_{geo} \leq 5$: Heavily to extremely contaminated; Igeo > 5: Extremely contaminated

Pollution Load Index (PLI)

The pollution load index (PLI) provides a cumulative assessment of heavy metal pollution in a soil sample:

$$PLI = (CF_1 \times CF_2 \times \ldots \times CF_n)^{1/n}$$

Where: CF_n = contamination factor of each metal; *n* = number of metals analysed

Interpretation (Sukri et al., 2018): PLI < 1: No pollution; PLI = 1: Baseline level of pollution; PLI > 1: Deterioration of soil quality

Potential Ecological Risk Index (RI)

The potential ecological risk index (RI) assesses ecological risk considering both metal concentration and toxicity:

$$RI = \sum E_r^i = T_r^i \times CF_i$$

Where: E_r^i = potential ecological risk factor for metal *I*; T_r^i = toxic response factor for metal *i* (e.g., Pb=5, Cd=30, As=10, Cu=5, Cr=2); CF_i = contamination factor of metal *i*

Interpretation (Hakanson, 1980): RI < 150: Low ecological risk; 150 ≤ RI < 300: Moderate ecological risk; 300 ≤ RI < 600: Considerable ecological risk; RI ≥ 600: Very high ecological risk. These ecological risk assessment models are widely applied in industrial and agricultural studies to quantify contamination severity and predict ecological consequences. When combined with soil physicochemical properties and heavy metal behavior, these indices provide a comprehensive understanding of environmental risk and serve as a scientific basis for remediation and policy-making (Alloway, 2012; Santos-Francés *et al.*, 2017).

Results

The results of the physicochemical properties, heavy metal concentrations, One-way ANOVA for heavy-metal concentrations among Sites A–E, Contamination factor (CF), Pollution load index with geo-accumulation index and Individual ecological risk factors with overall ecological risk index are presented in Tables 1 to 6 respectively.

Table 1. Physicochemical properties of soils from Sites A–E

Site	pH	EC (µS/cm)	TOC (%)	TON (mg/kg)
A	5.21	2480	5.84	620
B	5.48	2050	4.92	710
C	6.02	1320	3.21	1240
D	6.41	890	2.38	1580
E	6.85	410	1.47	1920

Table 2. Heavy-metal concentrations soils from Sites A–E

Site	Cu (mg/kg)	Cr (mg/kg)	Cd (mg/kg)	Pb (mg/kg)	As (mg/kg)
A	88.73 ± 1.33^a	101.23 ± 1.32^a	5.10 ± 0.10^a	149.73 ± 1.40^a	25.17 ± 0.40^a
B	81.33 ± 0.75^b	96.13 ± 0.91^b	4.50 ± 0.10^b	132.93 ± 1.59^b	21.80 ± 0.36^b
C	65.47 ± 0.70^c	89.33 ± 1.12^c	3.20 ± 0.10^c	96.13 ± 1.22^c	18.13 ± 0.35^c
D	54.53 ± 0.93^d	74.73 ± 0.97^d	2.60 ± 0.10^d	82.33 ± 1.75^d	13.37 ± 0.45^d
E	18.57 ± 0.40^e	31.63 ± 0.87^e	0.60 ± 0.10^e	21.63 ± 0.75^e	4.87 ± 0.25^e
NESREA guideline	36	100	3	85	5

Values are mean ± SD (n = 3). Different superscript letters within a column indicate significant differences according to Tukey HSD at $p < 0.05$.

Table 3. One-way ANOVA for heavy-metal concentrations among Sites A–E

Metal	F-value	df	p-value	Decision
Cu	2958.16	4, 10	<0.001	Significant
Cr	2137.37	4, 10	<0.001	Significant
Cd	931.50	4, 10	<0.001	Significant
Pb	3878.55	4, 10	<0.001	Significant
As	1376.79	4, 10	<0.001	Significant

The ANOVA results demonstrate statistically significant spatial differences for every investigated metal.

Table 4. Contamination factor (CF)

Site	Cu	Cr	Cd	Pb	As
A	2.46	1.01	1.70	1.76	5.03
B	2.26	0.96	1.50	1.56	4.36
C	1.82	0.89	1.07	1.13	3.63
D	1.51	0.75	0.87	0.97	2.67
E	0.52	0.32	0.20	0.25	0.97

Table 5. Pollution load index and geo-accumulation index

Site	PLI	Igeo-Cu	Igeo-Cr	Igeo-Cd	Igeo-Pb	Igeo-As
A	2.07	0.72	-0.57	0.18	0.23	1.75
B	1.86	0.59	-0.64	0.00	0.06	1.54
C	1.48	0.28	-0.75	-0.49	-0.41	1.27
D	1.21	0.01	-1.01	-0.79	-0.63	0.83
E	0.38	-1.54	-2.25	-2.91	-2.56	-0.62

Table 6. Individual ecological risk factors and overall ecological risk index

Site	Er-Cu	Er-Cr	Er-Cd	Er-Pb	Er-As	RI	Risk category
A	12.32	2.02	51.00	8.81	50.34	124.50	Low
B	11.30	1.92	45.00	7.82	43.60	109.64	Low
C	9.09	1.79	32.00	5.65	36.26	84.79	Low
D	7.57	1.49	26.00	4.84	26.74	66.65	Low
E	2.58	0.63	6.00	1.27	9.74	20.22	Low

Discussion

Physicochemical characteristics

The pH values demonstrated a clear spatial gradient, increasing from 5.21 at Site A to 6.85 at Site E. The relatively acidic conditions at Sites A and B are important because soil pH is a major determinant of heavy-metal mobility, adsorption and bioavailability. Acidic conditions can increase the solubility of several metals, thereby enhancing their potential mobility within

soil systems. The more acidic conditions at the most impacted locations are therefore environmentally relevant when interpreting the elevated metal concentrations.

The progressive increase in pH towards Site E coincided with decreasing heavy-metal concentrations, EC and TOC. This spatial association suggests that the physicochemical properties of the soils are linked to the contamination gradient. Electrical conductivity declined from 2480 µS/cm at Site A to 410 µS/cm at Site E. The elevated EC in Sites A and B indicates a greater abundance of soluble ionic constituents. Such conditions may result from petroleum-related inputs, weathering of contaminated materials and changes in soil geochemistry associated with contamination. Recent investigations of petroleum-impacted Niger Delta environments have emphasized the importance of spatially variable contaminant loading and hydrological transport in controlling environmental contamination patterns (Ola et al., 2024). The TOC displayed a pronounced decrease from 5.84% at Site A to 1.47% at Site E. The high TOC at the more impacted sites is consistent with the addition and retention of petroleum-derived organic material. Organic carbon is also important in controlling the partitioning of metals between soil solution and solid phases. Consequently, the high TOC at Site A may influence metal retention and distribution. The TON exhibited the opposite trend, increasing from 620 mg/kg at Site A to 1920 mg/kg at Site E. The low TON concentrations at the more contaminated sites may indicate disturbance of nutrient cycling associated with petroleum contamination. Hydrocarbon contamination can alter microbial communities and biochemical processes involved in nitrogen transformation. The contrasting TOC and TON patterns therefore suggest that petroleum impact may have modified both carbon accumulation and nutrient availability.

Spatial distribution of heavy metals

All five metals displayed the same overall spatial pattern: Site A > Site B > Site C > Site D > Site E. This consistency strongly suggests a spatially organized contamination gradient. Site A recorded the highest concentration for every metal, whereas Site E had the lowest. Such gradients are characteristic of localized contamination sources, although transport through surface runoff, groundwater, erosion and sediment movement can redistribute contaminants.

The concentrations recorded in the present study are within the range reported for contaminated Niger Delta soils but are generally lower than the extreme concentrations documented at some severely impacted locations. For example, Bankole et al. (2024) reported very wide concentration ranges in Okpare-Olomu, including Pb concentrations up to 8611 mg/kg and Cu concentrations exceeding 23,000 mg/kg in some samples. The comparatively lower values at Bomu do not eliminate environmental concern because several concentrations exceed the adopted guideline values. Mean Cu concentration ranged from 18.57 mg/kg at Site E to 88.73 mg/kg at Site A. Sites A–D exceeded the adopted NESREA value of 36 mg/kg, while Site E was below it. The elevated Cu concentrations may reflect petroleum-associated inputs, corrosion of metallic infrastructure and other anthropogenic activities. Copper can be retained by organic matter and mineral surfaces, making TOC an important consideration when interpreting its distribution. Chromium ranged from 31.63 mg/kg at Site E to 101.23 mg/kg at Site A. Site A marginally exceeded the adopted 100 mg/kg guideline, whereas Sites B–E were below it. The relatively modest exceedance at Site A suggests that Cr was less enriched than several of the other metals. This observation is consistent with the relatively low Cr CF and negative Igeo values at most sites. Cadmium ranged from 0.60 mg/kg at Site E to 5.10 mg/kg at Site A. Sites A–C exceeded the adopted 3 mg/kg guideline. Although Cd concentrations were numerically lower than those of Cu, Cr and Pb, Cd is important in ecological-risk assessment because its toxic-response coefficient is relatively high. This explains why Cd made a substantial contribution to the ecological-risk index.

Lead exhibited the highest absolute concentration among the investigated metals, ranging from 21.63 mg/kg at Site E to 149.73 mg/kg at Site A. Sites A–C exceeded the adopted 85 mg/kg guideline. The high Pb concentration is consistent with findings from other crude-oil-impacted Niger Delta soils, where Pb has frequently been identified as an important contributor to contamination and ecological risk. Bankole et al. (2024), for example, identified Pb and Zn as major contributors to pollution at Okpare-Olomu.

Arsenic ranged from 4.87 mg/kg at Site E to 25.17 mg/kg at Site A. Sites A–D exceeded the adopted 5 mg/kg guideline, making as one of the most consistently elevated contaminants. The high As CF values also demonstrate that concentration alone does not adequately characterize environmental importance; the ratio to the adopted reference concentration substantially influences contamination indices.

One-way ANOVA and spatial differences

One-way ANOVA revealed statistically significant differences among the five sites for all investigated metals. The F-statistics were exceptionally high, ranging from 931.50 for Cd to 3878.55 for Pb, and all p-values were <0.001.

The Tukey HSD grouping showed a consistent pattern in which Sites A, B, C, D and E were assigned different superscript letters for every metal. Thus, each site differed significantly from the others at $p < 0.05$. The statistical result provides quantitative support for the observed concentration gradient rather than relying solely on descriptive comparisons.

For Cu, mean concentration decreased from 88.73 mg/kg at Site A to 18.57 mg/kg at Site E. For Pb, the corresponding decrease was from 149.73 to 21.63 mg/kg. The statistically significant differences indicate that the spatial variation is substantially greater than the within-site analytical variation. The low standard deviations relative to the means further demonstrate good replicate consistency.

Contamination factor

The CF results indicate that contamination varied substantially among both metals and sites. Copper showed moderate contamination at Sites A–D, with CF values from 1.51 to 2.46, but low contamination at Site E (0.52). Cr showed generally low contamination, except for marginally moderate contamination at Site A (1.01).

Cadmium showed moderate contamination at Sites A–C, whereas Pb showed moderate contamination at Sites A–C and low contamination at Sites D and E. The highest CF values were recorded for As: 5.03 at Site A, 4.36 at Site B, 3.63 at Site C and 2.67 at Site D. Thus, As exhibited considerable contamination at Sites A–C and moderate contamination at Site D.

This result is significant because the As pattern was also reflected in the Igeo values. The identification of As as an important contaminant is consistent with previous Niger Delta investigations in which heavy metals and As have been evaluated using multiple ecological indices. The generally declining CF values from Site A to Site E reinforce the interpretation of a spatial contamination gradient.

Pollution load index

The PLI ranged from 0.38 at Site E to 2.07 at Site A. Sites A–D had PLI values >1, indicating pollution relative to the adopted guideline concentrations, whereas Site E had PLI <1. The PLI sequence: A (2.07) > B (1.86) > C (1.48) > D (1.21) > E (0.38) corresponds closely with the individual metal concentrations. The result indicates that contamination at Sites A–D is not attributable to one metal alone but represents a combined burden involving several metals.

Comparable use of PLI and related indices has been reported in Niger Delta oil-impacted soils. Okoye et al. (2022) employed PLI, Igeo, contamination and ecological-risk indices to characterize heavy-metal contamination in Niger Delta soils and vegetation. Similarly, the

2022 assessment of a remediated oil-spill site demonstrated how PLI and other indices can distinguish contamination conditions following remediation.

Geo-accumulation index

The Igeo results provided further evidence of spatial differences in contamination. Cu recorded values from -1.54 at Site E to 0.72 at Site A, indicating a transition from unpolluted conditions to unpolluted-to-moderately polluted conditions. Chromium remained negative at all sites, ranging from -2.25 to -0.57, suggesting that Cr was generally unpolluted relative to the adopted reference values. Cd and Pb similarly showed predominantly negative or near-zero Igeo values, indicating limited accumulation relative to the guideline-normalized reference. Arsenic recorded the highest Igeo values, increasing from -0.62 at Site E to 1.75 at Site A. Sites A–C therefore fell within the moderately polluted category for As, whereas Site D was within the unpolluted-to-moderately polluted category. The agreement among concentration, CF and Igeo results provides evidence that As is an important contaminant in the study area.

Potential ecological risk

The ecological-risk index ranged from 20.22 at Site E to 124.50 at Site A. All sites therefore fell below the conventional RI threshold of 150 for low potential ecological risk.

Although all sites were classified as low risk under this particular framework, the spatial pattern remains environmentally meaningful. Site A had an RI more than six times that of Site E, demonstrating a substantial difference in the aggregate toxicological burden.

Cd and As were the dominant contributors to the RI. At Site A, Cd produced an (Er) of 51.00 and As produced 50.34. This occurred because the Håkanson (1980) approach combines contamination magnitude with metal-specific toxic-response coefficients. Consequently, a metal with a comparatively modest concentration can make a substantial contribution to RI when its toxic-response coefficient is high. Recent studies have similarly demonstrated that Cd can dominate potential ecological risk calculations in petroleum-impacted environments because of its high toxic-response coefficient. A recent assessment of oil-contaminated soils in the Niger Delta reported substantial variation in ecological risk among locations and emphasized the usefulness of integrated contamination indices (Adebangbe et al., 2025).

The low RI values obtained in Bomu should not, however, be interpreted as evidence that the soils are free from contamination. Rather, the result indicates that the combined potential ecological risk, when evaluated using the adopted Håkanson (1980) coefficients and reference-normalized CFs, falls within the low-risk classification. This distinction is important because several metals exceeded the adopted soil guideline values.

The present findings are broadly consistent with recent evidence that petroleum-producing areas of the Niger Delta contain spatially heterogeneous mixtures of contaminants. Ola et al. (2024) demonstrated extensive petroleum contamination across interconnected environmental compartments and emphasized the influence of hydrological processes on contaminant distribution. Bankole et al. (2024) reported considerably wider heavy-metal concentration ranges at Okpare-Olomu, including very high Pb, Cu, Zn and Cd concentrations, with ecological-risk classifications ranging from low to very high. Compared with that study, the Bomu dataset shows a more moderate ecological-risk burden, although exceedances of the adopted guideline values remain evident. Similarly, the Niger Delta study by Okoye et al. (2022) showed spatial variability in heavy metals and As and demonstrated the utility of PLI, Igeo and ecological-risk indices in distinguishing impacted and less impacted environments. The present study extends this approach by combining physicochemical characteristics, replicate-based statistical testing and several contamination indices specifically for Bomu.

Recent research has also moved towards risk-based rather than concentration-only management of petroleum-affected sites. Abba and Knapp (2026) in their review regarding

development of risk-based screening levels for crude-oil-affected soils and sediments in the Niger Delta emphasized that contaminant concentrations should be interpreted in relation to exposure conditions and land use rather than through a single generic intervention value.
The significance of petroleum-related metal contamination is also supported by recent research in Niger Delta communities. Akinkpelumi et al. (2025) reported elevated human-health risks associated with metals and metalloids in food crops cultivated in crude-oil-impacted areas, particularly for children. Although the present study did not evaluate crop uptake or dietary exposure, these findings highlight the importance of controlling metal contamination in agricultural soils.

Conclusion

The study established significant spatial differences in physicochemical properties and heavy-metal concentrations in oil-impacted soils of Bomu, Gokana Local Government Area, Rivers State. Soil pH increased from acidic conditions at Site A to near-neutral conditions at Site E, while EC and TOC decreased progressively. The TON increased in the opposite direction.
The heavy metals Cu, Cr, Cd, Pb and As concentrations consistently followed the spatial sequence: A > B > C > D > E. The adopted NESREA guideline values were exceeded by Cu at Sites A–D, Cr at Site A, Cd at Sites A–C, Pb at Sites A–C and As at Sites A–D. One-way ANOVA confirmed that the differences among Sites A–E were statistically significant for all five metals ($p < 0.001$), with Tukey HSD indicating significant pairwise differences among the sites. The CF, PLI and Igeo results collectively confirmed a spatial contamination gradient. Arsenic showed particularly pronounced contamination based on CF and Igeo, while Cr generally exhibited the lowest degree of enrichment. The PLI values greater than unity at Sites A–D indicated combined pollution relative to the adopted guideline values.
The ecological-risk index ranged from 20.22 to 124.50, with all sites falling within the low potential ecological-risk category according to the adopted Håkanson classification. Nevertheless, the substantially greater RI at Site A and the exceedance of guideline values by several metals demonstrate that continued environmental surveillance is warranted.
It is recommended that Human-health risk assessment incorporating ingestion, dermal contact and inhalation pathways should be undertaken in future studies, particularly for populations living or farming close to the contaminated locations.

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