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Soil Quality, Pollution Indices and Health Risk of Metals and PAHs at a Crude-Oil Spill Site in Okpohovor, Delta State, Nigeria

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ABSTRACT

Background: Oil spillage is a major driver of soil degradation in the Niger Delta, yet integrated, site-specific assessments coupling metals, polycyclic aromatic hydrocarbons (PAHs) and quantitative risk remain scarce.

Objective: This study assessed the contamination status, source structure and ecological and human-health risk of soils at a crude-oil spill site in Okpohovor, Udu Local Government Area, Delta State, Nigeria.

Methods: Soils from five points (S1–S5) and a control station were sampled at two depths (0–15 and 15–30 cm). pH, electrical conductivity, total organic carbon, particle size and nine metals were determined by flame atomic absorption spectrophotometry, and 16 priority PAHs by GC–MS. Pollution indices, principal component analysis (PCA), one-way ANOVA with effect sizes, and BaP-equivalent, hazard-index and incremental lifetime cancer-risk models were applied.

Results: Soils were strongly acidic (pH 3.00–3.70) and sandy. All metals were below Department of Petroleum Resources (DPR) target values except cadmium (0.05–2.55 mg/kg), which reached the pollution range in 60% of samples. Clay differed significantly between sites ($F=10.133$, $p=0.013$, $\eta^2=0.890$). PCA separated a lithogenic Pb–Cr–Ni–Fe association (PC1, 32.0%) from a cadmium-driven signal. The ecological risk index (9–263) was cadmium-dominated. Σ PAH reached 81,327 $\mu\text{g/kg}$ from mixed petrogenic–pyrogenic sources; hazard indices were mostly below 1 but total cancer risk exceeded 1×10^{-6} .

Conclusion: Cadmium and carcinogenic PAHs are the priority contaminants, posing food-chain and public-health risks that warrant targeted remediation and sustained monitoring.

Introduction

Petroleum exploration and the oil spills that accompany it threaten the fragile equilibrium of terrestrial and aquatic ecosystems, and decades of exploration in the Niger Delta of Nigeria have made it one of the most chronically oil-impacted landscapes on Earth.¹ Crude-oil contamination reduces soil pore space, raises bulk density, damages soil microbial communities and degrades farmland, while introducing both petrogenic hydrocarbons and the toxic metals bound in the asphaltene and resin fractions of the oil.^{1,2}

Within the region, oil spills are the most frequent source of ambient pollution and arise from pipeline

sabotage, operational discharge, transport accidents and equipment failure.³ When a spill is followed by a fire, as occurred at the present site, the combustion of crude oil generates pyrogenic polycyclic aromatic hydrocarbons (PAHs) in addition to the petrogenic input.⁴ High-molecular-weight PAHs sorb strongly to soil organic matter and accumulate near the source, whereas low-molecular-weight PAHs are preferentially volatilised, degraded and transported over longer distances.^{5,6} Soluble petroleum components and acid-mobilised metals may also migrate into the shallow aquifers that supply drinking water.⁷

Reliable assessment couples physicochemical characterisation with quantification of potentially toxic metals and expresses contamination intensity through pollution indices, including the contamination/pollution index, enrichment factor, geoaccumulation index, contamination factor and the potential ecological risk index.⁸ PAH origins are resolved with diagnostic isomeric ratios,⁹ while toxic-equivalency and incremental lifetime cancer-risk models translate concentrations into quantitative human-health risk.¹⁰ In Nigeria, soil quality is benchmarked against the target and intervention values of the Department of Petroleum Resources (DPR),¹¹ complemented by World Health Organization and United States Environmental Protection Agency (USEPA) guidelines.¹²

Despite extensive documentation, integrated, statistically rigorous and site-specific assessments combining physicochemical properties, metal indices, PAH source apportionment and quantitative risk remain scarce for the Okpohovor spill site,^{13,14} even though comparable Niger-Delta settings show heavy PAH contamination and adverse impacts on soil quality and public health.^{15,16} The study area is illustrated in Figure 1 and the assessment framework in Figure 2. This study aimed to determine the physicochemical properties of soils, the concentrations of selected potentially toxic metals and 16 priority PAHs, and the ecological and human-health risk around the oil-spill area at Okpohovor, Udu LGA, Delta State, Nigeria.

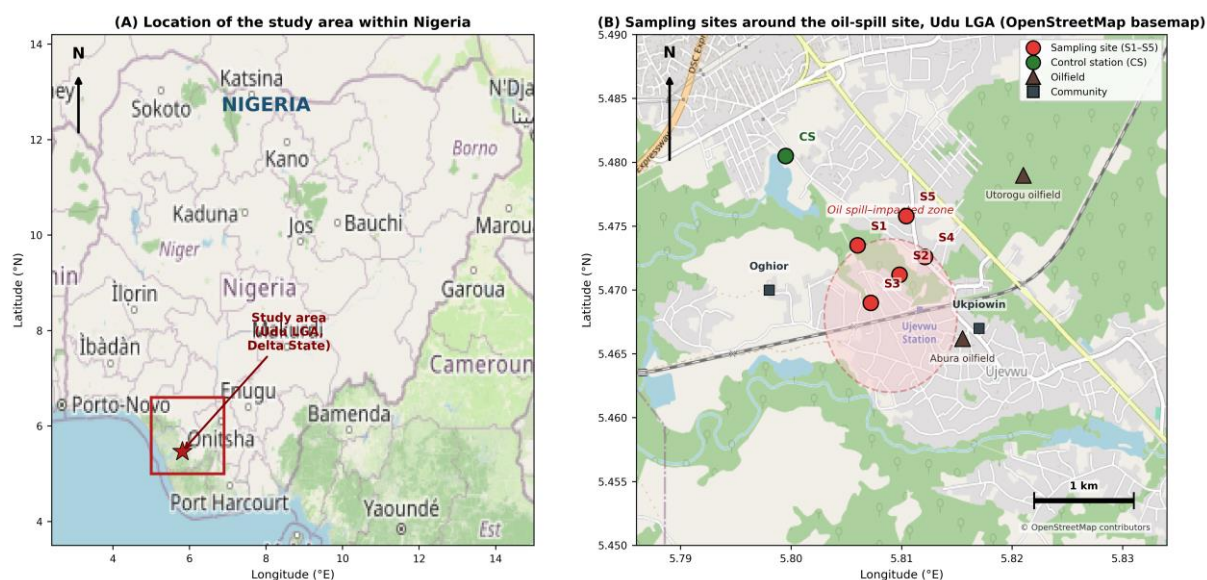


Figure 1. Study area map showing the location of the five sampling sites (S1–S5) and the control station around the oil-spill site at Okpohovor, Udu LGA, Delta State, Nigeria. (A) Location of Delta State within Nigeria. (B) Detailed map of the sampling sites, oilfields, river and road network.

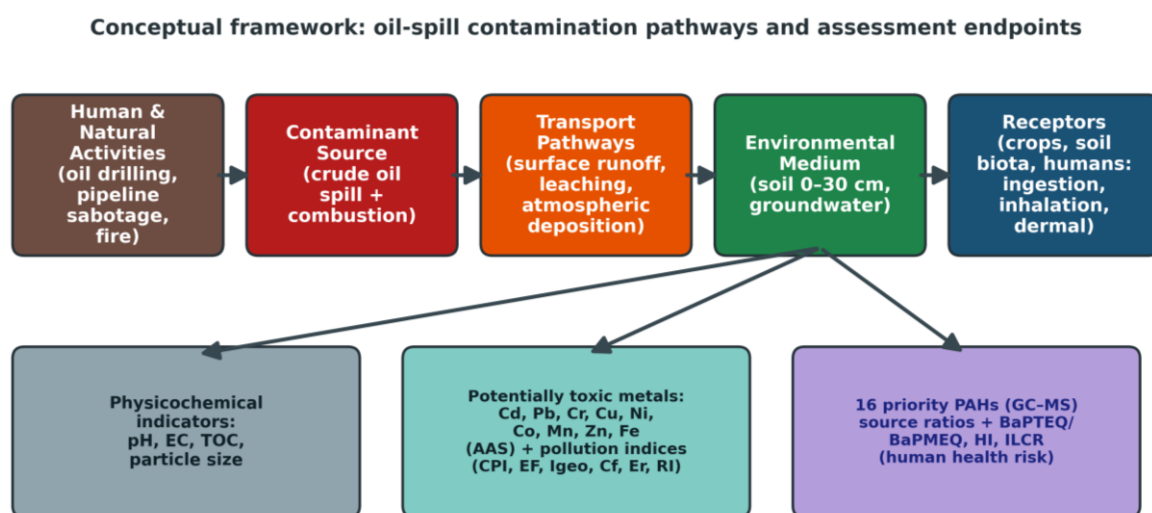


Figure 2. Conceptual framework of oil-spill contamination pathways and assessment endpoints, from human and natural activities through the contaminant source and transport pathways to the soil medium and biological receptors.

Materials and Methods

Study design and setting

An environmental monitoring and assessment design was adopted. As illustrated in Figure 1, sampling was conducted around an oil-spill site located between Oghior and Ukpuiwin towns in the Okpohovor area of Udu Local Government Area, Delta State, Niger Delta, Nigeria (approximately 5.47° N, 5.81° E; Universal Transverse Mercator zone 32N). The area receives 2,540–3,500 mm of rainfall annually, with temperatures of 23–33 °C and relative humidity peaking at 80–90% in August. Two oilfields occur within the zone—Abura (Nigerian Petroleum Development Company, developed 1974) and Utorogu (Shell, established 1961)—together with a dense network of wells and pipelines. The site experienced a spill followed by a fire that affected several host communities, contaminated a stream and destroyed farmland. The characteristics of the six sampling stations are summarised in Table 1.

Materials, samples, and data sources

Soils were collected at five points (S1–S5) surrounding the spill and at one control station (CS) on farmland approximately 1 km away, at two depths (0–15 and 15–30 cm) using a stainless-steel auger. Samples were preserved in stainless-steel vessels, transported to the laboratory, air-dried, cleared of debris, sieved (<2 mm) and stored at 4°C until analysis. Reagents were of analytical grade; certified 1000 mg L⁻¹ single-element standards (Merck/Sigma-Aldrich) were used for calibration. Metals were quantified on a Perkin-Elmer Analyst 200 flame atomic absorption spectrophotometer, and PAHs on an Agilent 7890B gas chromatograph coupled to a 5977A mass-selective detector.

Experimental variables and analytical procedures

Soil pH was measured in a 1:2 soil-to-water suspension; total organic carbon (TOC) by the Walkley–Black wet-oxidation method; particle size by the pipette method; and electrical conductivity (EC) in the soil–water suspension.¹⁷ Metals (Cd, Pb, Zn, Ni, Cu, Cr, Fe, Co, Mn) were extracted by aqua-regia digestion (10 g soil with 15 mL HNO₃:HCl, 1:3; 2 h at 125 °C) and quantified by flame atomic absorption spectrophotometry. The 16 priority PAHs were determined by USEPA Method 3550C ultrasonic extraction with hexane/dichloromethane (1:1 v/v), silica/alumina clean-up and GC–MS. Procedural blanks, matrix-spike recoveries and triplicate analyses

provided quality control, and all results were blank-corrected. Contamination intensity was evaluated with the contamination/pollution index, enrichment factor (EF), geoaccumulation index (Eq. 1), contamination factor (Cf) with degree of contamination, and the potential ecological risk index (Eq. 2):

$$I_{geo} = \log_2 [C_n / (1.5 \times B_n)] \quad (1)$$

where C_n is the measured concentration and B_n the crustal background concentration of the metal, and the factor 1.5 corrects for lithological variability.

$$RI = \sum (Tr \times Cf), \quad Cf = C_n / B_n \quad (2)$$

where RI is the potential ecological risk index, Tr the toxic-response factor and Cf the contamination factor. For PAHs, diagnostic isomeric ratios apportioned sources,⁹ and BaP toxic- and mutagenic-equivalent concentrations (BaPTEQ, BaPMEQ), the hazard index (HI) and incremental lifetime cancer risk (ILCR) for ingestion, inhalation and dermal contact were computed for children and adults using standard USEPA default exposure parameters (Table 6).^{10,12}

Data analysis

Data were analysed in Python 3.11 (NumPy, SciPy, statsmodels, scikit-learn) and cross-checked in SPSS 26. Because the design comprised five sites at two depths without field replication, the inferential statistics are treated as exploratory and effect sizes (eta-squared, η^2) are reported alongside F and exact p -values (three decimals). Normality and homogeneity of variance were checked on pooled residuals (Shapiro–Wilk and Levene's tests), and right-skewed variables were examined after log-transformation. One-way ANOVA with Tukey HSD tested between-site differences, paired t -tests compared depths, Pearson correlation quantified associations, and principal component analysis (PCA) on standardised variables resolved multivariate structure ($\alpha = 0.05$). Non-detect PAH values were treated as zero, and the control station served as a local geochemical background. As an environmental soil study with no human or animal subjects, ethical approval was not required.

Results

A total of ten composite soil samples were collected from the five points at two depths, together with a control station (Figure 1). Site characteristics are presented in Table 1 and the measured physicochemical and metal values with standard comparison in Table 2.

Table 1. Sampling-site characteristics around the oil-spill site, Okpohovor (Udu LGA), Delta State, Nigeria.

Site	Coordinates (approx.)	Land use / setting	Depths sampled	Distance to spill
S1	5.47° N, 5.81° E	Disturbed farmland, spill margin	0–15; 15–30 cm	Adjacent
S2	5.47° N, 5.81° E	Cleared crop plot near plume	0–15; 15–30 cm	Adjacent
S3	5.47° N, 5.81° E	Fallow land, drainage line	0–15; 15–30 cm	Near
S4	5.47° N, 5.81° E	Burnt zone (spill + fire)	0–15; 15–30 cm	Within plume
S5	5.47° N, 5.81° E	Riparian soil near stream	0–15; 15–30 cm	Within plume
CS	5.47° N, 5.81° E	Undisturbed farmland (control)	0–15; 15–30 cm	≈1 km

Physicochemical properties

As shown in Table 2, soil pH ranged from 3.00 to 3.70 (mean 3.33), EC from 33.0 to 199 $\mu\text{S cm}^{-1}$ (mean 69.4) and TOC from 2.33 to 3.53% (mean 3.05%). Soils were predominantly sandy (mean sand 91.5%, clay 4.89%, silt 3.62%). Clay was the only variable to differ significantly between sites ($F=10.133$, $p=0.013$, $\eta^2=0.890$), with Tukey HSD showing S1 significantly higher than S2–S5 ($p<0.05$). The strongly acidic, low-clay character is consistent with acidic petroleum-impacted soils reported elsewhere in Nigeria¹⁸ and implies limited pollutant retention.

Metal concentrations and standard comparison

Mean metal concentrations followed the order $\text{Pb} \approx \text{Cr} > \text{Co} > \text{Mn} > \text{Fe} > \text{Ni} > \text{Zn} > \text{Cd} > \text{Cu}$ (Table 2; Figure 3). As

detailed in Table 2 and illustrated in Figure 3, all metals were below DPR target values except cadmium, which met or exceeded the 0.8 mg kg^{-1} limit (pollution range) in 60% of samples and strictly exceeded it in 50%, peaking at S4 (15–30 cm). Cobalt reached 19.3 mg kg^{-1} (mean 8.07), approaching its 20 mg kg^{-1} limit at S4, while Pb (6.37–13.24), Cr (5.25–13.25), Cu (0.50–1.05), Ni (1.50–4.20), Mn (6.35–9.90), Zn (0.18–9.38) and Fe (1.59–17.0 mg kg^{-1}) remained within their reference values. Effect sizes were large for Co ($\eta^2=0.745$), Cd ($\eta^2=0.661$) and Cu ($\eta^2=0.663$). The cadmium levels were comparable to crude-oil-impacted soils at Okpare-Olomu,¹⁹ Ihwrekreka²⁰ and Umuechem,²¹ and exceeded the low baselines of the Qua Iboe oil field.²²

Table 2. Physicochemical and metal values with standard comparison (status relative to the DPR target value).

Parameter (unit)	Mean $\pm$ SD	Range	DPR / limit	WHO/EPA ref.	Status	F (p ; η^2)
pH	3.33 $\pm$ 0.21	3.00–3.70	6.0–9.0 a	6.5–8.5	Below	1.984 (0.235; 0.613)
EC ($\mu\text{S cm}^{-1}$)	69.4 $\pm$ 51.3	33.0–199	—	—	—	1.467 (0.337; 0.540)
TOC (%)	3.05 $\pm$ 0.38	2.33–3.53	—	—	—	3.029 (0.128; 0.708)
Clay (%)	4.89 $\pm$ 8.19	0–24.5	—	—	—	10.133 (0.013; 0.890)
Cd (mg kg^{-1})	1.09 $\pm$ 0.73	0.05–2.55	0.8	3 (WHO)	Exceeds	2.434 (0.178; 0.661)
Pb (mg kg^{-1})	9.68 $\pm$ 2.43	6.37–13.24	85	100 (EPA)	Within	0.694 (0.627; 0.357)
Cr (mg kg^{-1})	9.33 $\pm$ 2.35	5.25–13.25	100	100 (EPA)	Within	0.184 (0.937; 0.128)
Cu (mg kg^{-1})	0.66 $\pm$ 0.18	0.50–1.05	36	100 (WHO)	Within	2.455 (0.176; 0.663)
Ni (mg kg^{-1})	2.82 $\pm$ 0.87	1.50–4.20	35	50 (EPA)	Within	0.269 (0.886; 0.177)
Co (mg kg^{-1})	8.07 $\pm$ 5.46	3.18–19.28	20	50 (WHO)	Within	3.658 (0.094; 0.745)
Mn (mg kg^{-1})	8.10 $\pm$ 1.18	6.35–9.90	850 b	—	Within	0.549 (0.709; 0.305)
Zn (mg kg^{-1})	2.03 $\pm$ 2.66	0.18–9.38	140	300 (EPA)	Within	0.849 (0.550; 0.404)
Fe (mg kg^{-1})	7.45 $\pm$ 4.91	1.59–17.0	47000 b	—	Within	0.151 (0.954; 0.108)

Note: a general agronomic range; b crustal abundance reference value. SD, standard deviation; η^2 , eta-squared effect size.

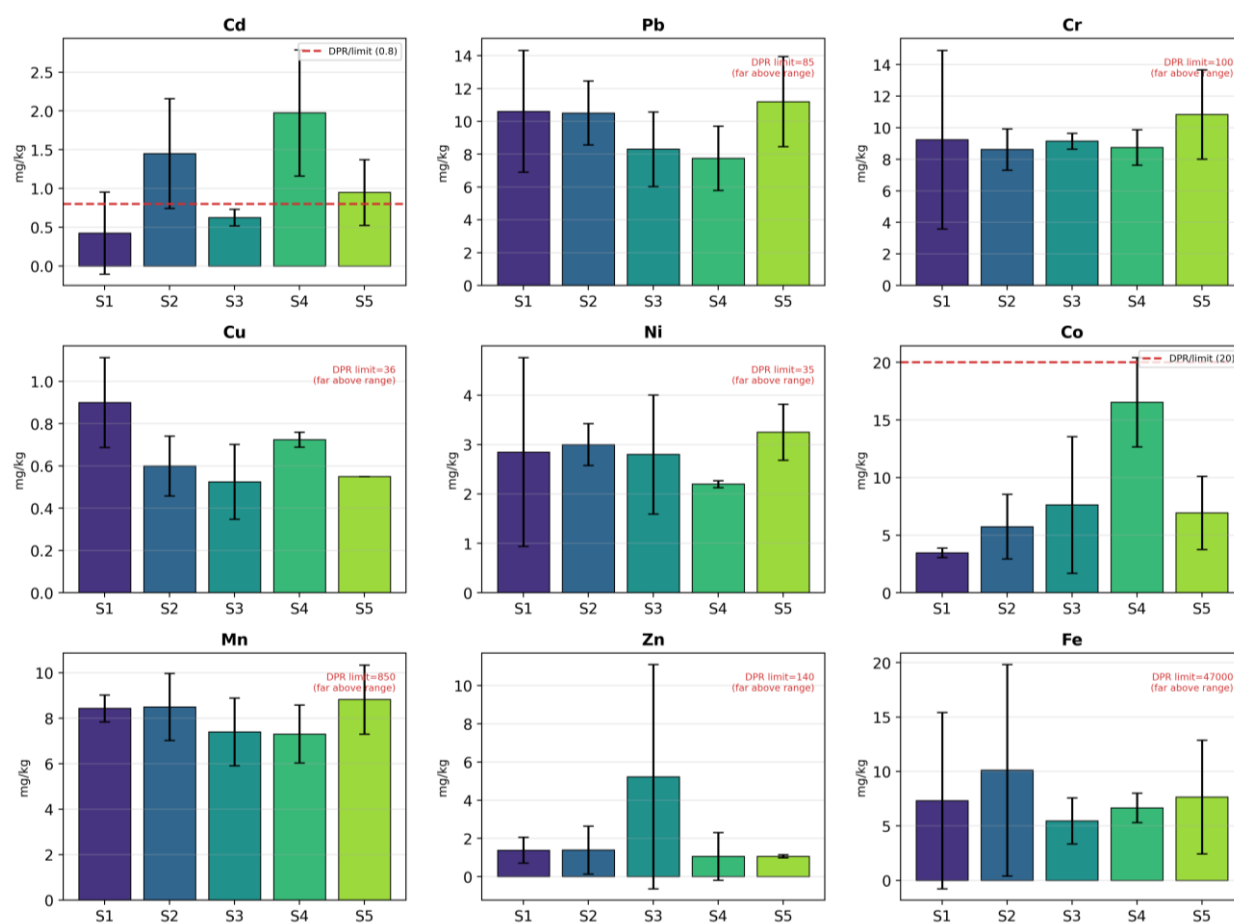


Figure 3. Mean concentrations of potentially toxic metals across sampling sites (error bars = standard deviation; $n = 2$ depths). Dashed red lines mark DPR/limit values where within plotting range; Cd exceeds its 0.8 mg kg^{-1} limit at most sites.

Pollution and ecological-risk indices

The pollution and ecological-risk indices are summarised in Table 3 and illustrated in Figure 4. As shown in Figure 4A, the contamination/pollution index placed Pb, Cr, Cu, Ni, Co and Zn in the contamination range (<1), whereas cadmium reached the pollution range (>1) at most sites, peaking at 3.19 at S4 (15–30 cm). Enrichment factors for all metals exceeded 10, indicating a non-crustal,

anthropogenic origin, with cadmium the most enriched, and the cadmium geoaccumulation index fell into classes 1–3. As detailed in Table 3 and Figure 4B–C, contamination factors followed $\text{Cd} > \text{Pb} > \text{Co} > \text{Cr} > \text{Ni} > \text{Cu} > \text{Zn} > \text{Mn}$, the degree of contamination ranged from 1.24 to 10.14, and the potential ecological risk index ranged from 9 to 263, reflecting low to considerable risk dominated almost entirely by cadmium at every site.

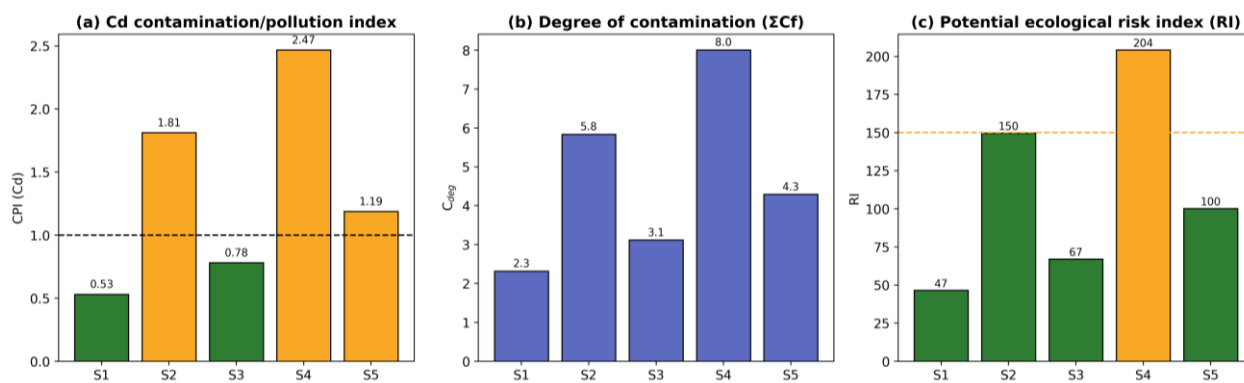


Figure 4. Pollution and ecological-risk indices across sites: (A) Cd contamination/pollution index; (B) degree of contamination (ΣC_f); (C) potential ecological risk index (RI). Colours denote quality classes.

Table 3. Summary of statistical and pollution-index results for soils of the study area.

Index	Range / key value	Dominant element	Interpretation
Contamination/pollution index (Cd)	0.06–3.19	Cd	Light to moderate Cd pollution
Enrichment factor (all metals)	>10 (Cd highest)	Cd	Anthropogenic, very-high enrichment
Geoaccumulation index (Cd)	–3.17 to 2.50	Cd	Class 1–3 (moderate–strong)
Degree of contamination (ΣCf)	1.24–10.14	Cd	Low to moderate
Ecological risk index (RI)	9–263	Cd	Low to considerable
PC1 / PC2 variance	32.0% / 19.7%	Pb–Cr–Ni–Fe / Cu–Mn	Lithogenic vs mixed
Strongest correlation	Pb–Ni $r=0.865$, $p=0.001$	—	Common lithogenic source

Multivariate structure and correlations

As illustrated in Figure 5B, Pearson correlation revealed a strong lithogenic cluster among Pb, Cr, Ni and Fe: Pb–Ni ($r=0.865$, $p=0.001$), Cr–Ni ($r=0.839$, $p=0.002$), Pb–Cr ($r=0.793$, $p=0.006$), Ni–Fe ($r=0.707$, $p=0.022$), Pb–Fe ($r=0.734$, $p=0.016$) and Cr–Fe ($r=0.688$, $p=0.028$) were all significant. Cadmium was decoupled from this group, correlating positively with cobalt ($r=0.620$, $p=0.056$) and

negatively with clay ($r=-0.560$), while TOC correlated negatively with Zn ($r=-0.642$, $p=0.045$). As shown in Figure 5A and summarised in Table 3, PCA extracted four components explaining 79.5% of the variance: PC1 (32.0%) was dominated by positive loadings of Pb, Ni, Cr and Fe (lithogenic), whereas cadmium loaded oppositely, consistent with a separate petroleum-related source; PC2 (19.7%) contrasted Cu–Mn–clay with Co–Zn–EC.

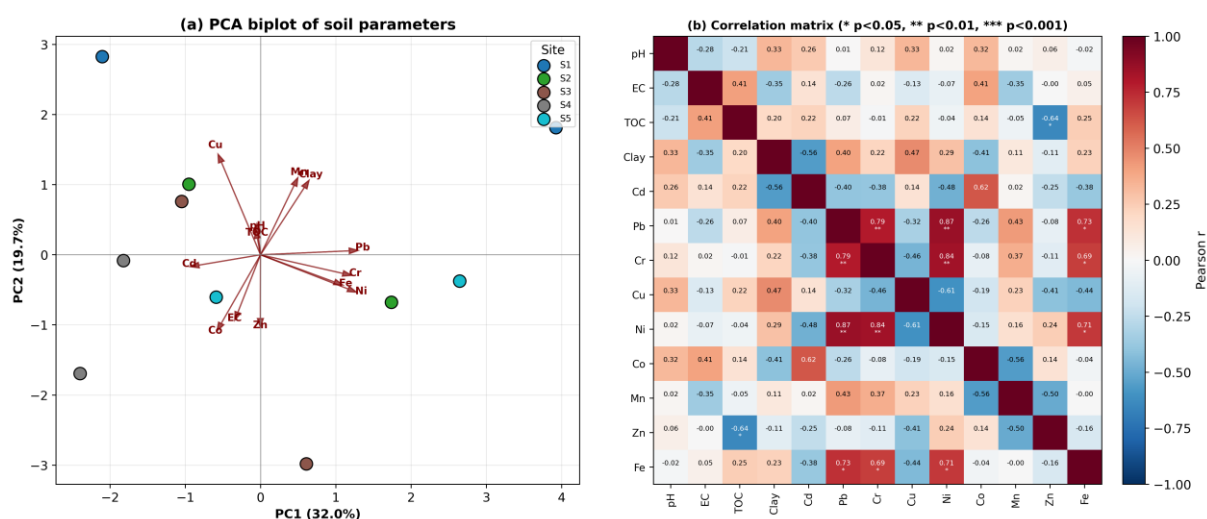


Figure 5. (A) PCA biplot of soil parameters showing the lithogenic Pb–Cr–Ni–Fe association on PC1 and the decoupled Cd vector; (B) Pearson correlation matrix (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

PAH concentrations and source apportionment

As presented in Table 4 and Figure 6, the sum of 16 priority PAHs (ΣPAH) ranged from 1,343 to 36,450 $\mu g\ kg^{-1}$ at 0–15 cm and from 416 to 81,327 $\mu g\ kg^{-1}$ at 15–30 cm, the highest burden occurring at S1 (15–30 cm). High-molecular-weight PAHs dominated, with the ring-size order $4 > 3 > 5 > 6 > 2$ rings, reflecting both the preferential degradation of low-ring PAHs and the single-hop

deposition of particle-bound high-molecular-weight PAHs near the source. Except for S2 (15–30 cm), all soils fell into the heavily contaminated category ($>1,000\ \mu g\ kg^{-1}$), consistent with the heavy PAH burdens reported for crude-oil-impacted soils and sediments in the Niger Delta.^{2,15} As shown in Table 5, diagnostic isomeric ratios indicated mixed petrogenic and pyrogenic origins, matching the spill-then-fire history of the site.⁴

Table 4. Ring-size distribution and concentration ranges of PAHs in soils of the study area.

Ring class	Σ range ($\mu g\ kg^{-1}$)	% of ΣPAH	Representative congeners
2-ring	266–908	1.1–16.8	Naphthalene
3-ring	2–36,185	0.1–44.5	Acy, Ace, Flu, Phen, Ant
4-ring	235–30,071	9.8–52.3	Flt, Pyr, Chry, BaA
5-ring	20–12,595	3.8–57.6	BbF, BkF, BaP, DahA
6-ring	140–6,576	2.3–73.6	IndP, BghiP
ΣPAH (total)	416–81,327	100	16 priority PAHs

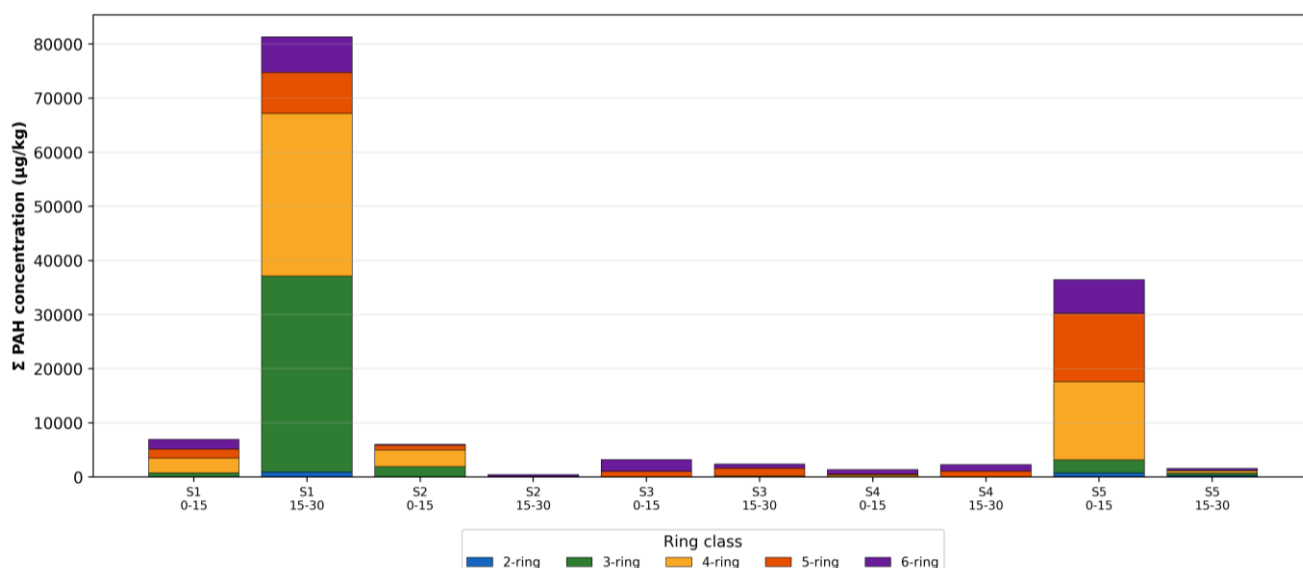


Figure 6. Ring-size distribution of PAHs across sampling sites and depths, showing the dominance of 4-ring and 3-ring congeners and the elevated burden at S1 (15–30 cm) and S5 (0–15 cm).

Table 5. Diagnostic PAH isomeric ratios and inferred sources in soils of the study area.

Isomeric ratio	Diagnostic value	Indicated source	Sites
Flt/(Flt+Pyr)	>0.5 / <0.4	Biomass / petroleum	S1; S5
Ant/(Ant+Phen)	>0.1	Combustion	S1, S2, S5
BaA/(BaA+Chry)	>0.35	Coal/biomass combustion	S1, S2, S4, S5
IndP/(IndP+BghiP)	0.2–0.5	Petroleum combustion	S1, S3, S4
Total index	>4.0 / <4.0	High-temp / petroleum comb.	S1,S2,S4,S5 / S3

Human-health risk of PAHs

The exposure parameters used in the human-health risk model are listed in Table 6. As illustrated in Figure 7B, BaPTEQ concentrations ranged from 3.90 to 8,799 µg kg⁻¹ and BaPMEQ from 17.1 to 6,419 µg kg⁻¹, driven mainly by BaA, BaP, IndP and DahA, and exceeded the Dutch target value (33 µg kg⁻¹) and Method B clean-up level (137 µg kg⁻¹) at all sites except S2 (15–30 cm). As shown in Table 7, the hazard quotients followed

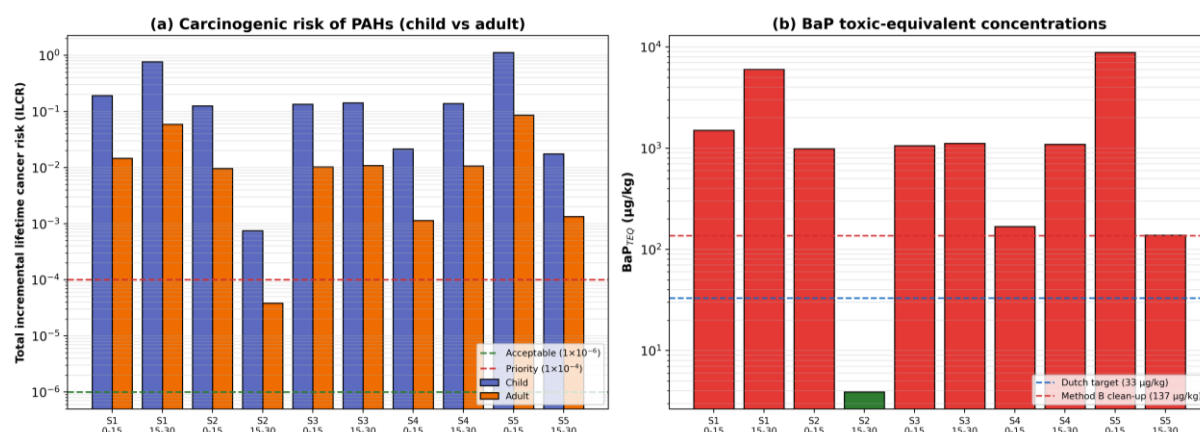
HQ_{ingestion}>HQ_{dermal}>HQ_{inhalation}, and hazard indices were generally below 1 except at S1 (15–30 cm) and S5 (0–15 cm). Incremental lifetime cancer risk (ILCR) followed ingestion>dermal>inhalation, with total cancer risk of 7.51×10⁻⁴ to 1.12 for children and 3.81×10⁻⁵ to 8.60×10⁻² for adults (Figure 7A); all values exceeded the USEPA acceptable threshold of 1×10⁻⁶ and most exceeded the 1×10⁻⁴ priority level, with children carrying the higher risk.

Table 6. Exposure parameters used in the PAH human-health risk assessment.

Parameter	Symbol	Value (child / adult)	Source
Soil ingestion rate (mg day ⁻¹)	IngR	200 / 100	USEPA RAGS
Inhalation rate (m ³ day ⁻¹)	InhR	7.6 / 20	USEPA default
Skin surface area (cm ²)	SA	2800 / 5700	USEPA default
Soil adherence factor (mg cm ⁻²)	AF	0.2 / 0.07	USEPA default
Body weight (kg)	BW	15 / 70	USEPA default
Exposure frequency (day yr ⁻¹)	EF	350 / 350	USEPA default
Exposure duration (yr)	ED	6 / 24	USEPA default
BaP cancer slope factor ((mg kg ⁻¹ day ⁻¹)-1)	CSF	7.3	USEPA IRIS

Table 7. Representative non-carcinogenic (HI) and carcinogenic (ILCR) risk of PAHs for children and adults.

Site (depth)	HI child	HI adult	ILCR child	ILCR adult
S1 (0–15)	0.148	0.019	1.91×10^{-1}	1.46×10^{-2}
S1 (15–30)	11.3	1.41	7.67×10^{-1}	5.89×10^{-2}
S2 (0–15)	0.577	0.072	1.26×10^{-1}	9.64×10^{-3}
S2 (15–30)	0.020	0.002	7.51×10^{-4}	3.81×10^{-5}
S4 (15–30)	0.001	0.000	1.39×10^{-1}	1.07×10^{-2}
S5 (0–15)	2.30	0.288	1.12	8.60×10^{-2}

**Figure 7.** Human-health risk indicators for PAHs: (A) total incremental lifetime cancer risk (ILCR) for children and adults against the acceptable (1×10^{-6}) and priority (1×10^{-4}) thresholds; (B) BaP toxic-equivalent concentrations against the Dutch target and clean-up values.

Discussion

The oil-spill soils at Okpohovor displayed a coherent contamination signature dominated by cadmium among the metals and by high-molecular-weight PAHs among the organics, set against a strongly acidic, sandy and organic-enriched matrix (Table 2). The strong acidity (mean pH 3.33) is characteristic of Niger-Delta soils and enhances cadmium mobility and bioavailability; the pH values were even lower than those reported for comparable acidic oil-impacted soils.¹⁸ At pH near 3.3, cadmium partitions into exchangeable, readily mobilised forms, so the total concentrations in Table 2 approximate the bioavailable fraction—precisely the condition under which soil-to-crop transfer and leaching are maximised. The low clay content further limits retention, leaving a mobile matrix in which both metals and PAHs can migrate to depth and toward shallow groundwater.²³

Cadmium was the only metal to reach the pollution range relative to its DPR target value, doing so in 60% of samples, with a maximum of 2.55 mg kg⁻¹ (Table 2; Figure 3). This is comparable to ranges reported for crude-oil-impacted soils at Umuechem²¹ and Ihwrekreka²⁰ but lower than the extreme values at Okpare-Olomu.¹⁹ The enrichment factors (>10) and cadmium geoaccumulation classes 1–3 (Table 3) confirm an anthropogenic rather than crustal origin, attributable to the oil spill and associated activities.

The multivariate analysis (Figure 5; Table 3) sharpened this interpretation. The significant Pb–Cr–Ni–Fe correlations and their co-loading on PC1 define a

lithogenic association derived from the soil parent material, whereas cadmium's decoupling from this cluster and its alignment with cobalt indicate a distinct, petroleum-related source associated with the crude oil and the combustion residues of the fire. It is the source-specific enrichment of a single highly toxic element, not the bulk metal load, that drives the risk, and the correlation matrix corroborates this structure independently of the fragile higher components.

The ecological risk index (9–263; Figure 4C) was governed almost entirely by cadmium owing to its high toxic-response factor. Its mobility under acidic conditions, efficient transfer into food crops and established nephrotoxicity make this enrichment a credible food-chain and public-health concern for the farming communities around the site.¹⁶ The PAH results (Table 4; Figure 6) reveal an even more pressing organic-contamination problem, with Σ PAH reaching 81,327 µg kg⁻¹ and mixed petrogenic and pyrogenic sources (Table 5) matching the documented spill-then-fire history,⁴ comparable to other Niger-Delta crude-oil-impacted sites.^{2,15}

The human-health calculations (Table 7; Figure 7) translate these burdens into tangible risk. BaPTEQ values exceeding the Dutch clean-up level at almost every site denote a high carcinogenic propensity, and the ILCR estimates—exceeding 1×10^{-6} in every sample and 1×10^{-4} in most—signal unacceptable long-term cancer risk, particularly for children, whose lower body weight raises their exposure per unit body mass. These ILCR values are screening-level indices that flag unacceptable exposure

rather than literal probabilities; a sensitivity check excluding the most contaminated sample did not change the conclusion. Ingestion was the dominant pathway, implying that consumption of crops grown on these soils and hand-to-mouth contact are the principal routes of concern, consistent with quantitative PAH risk assessments at other Niger-Delta sites.¹⁰

Bringing the control station into the quantitative framework strengthens attribution: control concentrations were consistently lower, and recomputing the enrichment and geoaccumulation indices against the local background yielded the same cadmium-dominated verdict, confirming robustness to the choice of background. From a regulatory standpoint, 60% of samples reached the pollution range for the DPR cadmium target¹¹ and PAH cancer risk exceeded international thresholds,¹² warranting attention from the responsible authorities and the operators of the Abura and Utorogu fields. Because the risk is ingestion-dominated, the most direct protective measures reduce soil-to-crop and hand-to-mouth transfer—restricting cultivation on the worst plots, liming to immobilise cadmium and capping hotspots—alongside phyto- and bioremediation suited to the sandy, organic-rich matrix. These findings extend the wider tropical and developing-country evidence base by demonstrating, for a single named spill site, how source-resolved multivariate analysis converts below-limit bulk concentrations into actionable, element-specific risk management.

The strengths of this study are its integrated design and the addition of multivariate statistics and effect sizes that provide source discrimination beyond absolute concentrations, linked directly to regulatory thresholds. Its limitations include the limited replication (five sites, two depths), which constrained statistical power so that several large effect sizes did not reach significance; the single-campaign design, which cannot resolve seasonal change, an effect shown to be substantial in comparable Niger-Delta soils;^{1,10} the absence of bioavailability assays; and reliance on default exposure parameters, which introduces uncertainty into absolute risk while leaving the site ranking robust.

Conclusion

Soils at the Okpohovor oil-spill site, Udu LGA, Delta State, are strongly acidic and sandy and carry a clear anthropogenic contamination signature. All metals were below DPR target values except cadmium, which reached the pollution range ($CPI \geq 1$) in 60% of samples and dominated the ecological-risk index (9–263, low to considerable). Multivariate analysis separated a lithogenic Pb–Cr–Ni–Fe association from a petroleum-related cadmium source, and soils were heavily contaminated with PAHs of mixed petrogenic and pyrogenic origin. Although non-carcinogenic hazard indices were mostly below 1, incremental lifetime cancer risk exceeded acceptable thresholds across the site, especially for children. These results call for targeted phyto- and bioremediation, soil pH amendment to limit cadmium mobility, and sustained monitoring by local

authorities and field operators, with periodic seasonal sampling and bioavailability assessment to refine risk management.

Declarations

Ethical Approval. The study involved environmental soil sampling only, with no human or animal subjects.

Conflict of Interest. The authors declare no conflict of interest.

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Author Contributions. M. Eguvbe conceived the study, designed the methodology and drafted the manuscript; S.E. Ogoron, E.W. Odali, I.F. Ogwu and C.J. Ossai performed field sampling, laboratory investigation and data curation; A.A. Ogbuta contributed to PAH analysis and interpretation; C.M.A. Iwegbue and G.E. Nwajei provided supervision, validation and critical review. All authors reviewed and approved the final version.

Data Availability. The data underlying the findings, including the complete per-sample concentration matrix and the scripts used to compute the pollution and risk indices, are available from the corresponding author upon reasonable request.

Use of Artificial Intelligence. During the preparation of this work, the authors did not use an AI-assisted tool. The authors reviewed and edited the content and take full responsibility for it.

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