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Integrated Hydrochemical and Ecotoxicological Appraisal of Oil-Based Drilling Mud Contamination in the Eruemokarien Environment, Delta State

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ABSTRACT

Oil-based drilling muds (OBMs) are crucial in petroleum operations and are among the primary sources of environmental pollution when not properly contained and managed. This paper gives a combined hydrochemical and ecotoxicological evaluation of OBM pollution in Eruemokarien, Delta State, Nigeria. A field-based, descriptive-analytical design was employed to combine quantitative and qualitative approaches. Samples of soil, water, and air were obtained in three areas (0-100 m, 100-300 m, and >500 m) and determined by Atomic Absorption Spectrophotometry (AAS), Gas Chromatography-Flame Ionisation Detection (GC-FID), and Gas Chromatography-Mass Spectrometry (GC-MS). Findings depicted the extreme contamination of the multi-media, with soil having the highest contamination: Total Petroleum Hydrocarbons (TPH) at 6,582 mg/kg, Polycyclic Aromatic Hydrocarbons (ΣPAHs) at 450.7mg/kg, and lead (Pb) at 128 mg/kg, all of which exceeded the EGASPIN (2018) threshold. The water quality analysis contained TPH (18.4 mg/L), Pb (0.52 mg/L), and cadmium (Cd) (0.018 mg/L). In contrast, the air samples contained high concentrations of particulate matter ($PM_{2.5}$ = 68 µg/m³, PM_{10} = 112 µg/m³) and volatile organic compounds (VOCs = 8.2 mg/m³). Statistical tests were used to validate significant spatial differences ($p < 0.001$) and a high correlation between soil water and hydrocarbons ($R^2 = 0.87$), indicating that pollutants were moving across the environmental matrices. The results suggest that OBM remnants have led to disturbance in the geochemical equilibrium in the area, decreased the soil's fertility, and caused toxicological hazards to the aquatic and terrestrial organisms. The conclusion is that inappropriate OBM containment implies significant, spatially concentrated pollution that must be removed promptly, tighter control by regulatory authorities, the utilisation of low-toxicity synthetic muds, and periodic environmental audits. The measures are essential in reducing the ecological degradation caused by hydrocarbons and in ensuring the sustainability of oilfield operations.

Keywords: Oil-based Muds; Total Petroleum Hydrocarbons; Heavy Metals; Polycyclic Aromatic Hydrocarbons; Ecotoxicology; Hydrochemical Contamination; Environmental Risk; Eruemokarien; Niger Delta.

1. Introduction

The decantation of oil-based drilling muds (OBMs) is an advanced blend that is mainly made up of base oil, emulsifiers, barite, and other chemical additives that have a lawful impact on the petroleum drilling exercises in improving the processes of lubrication, cooling, and stability of the wellbore (Onwukwe & Nwakaudu, 2012). Due to their high rheological stability and ability to withstand high-temperature degradation, OBMs pose significant environmental challenges, including toxicity and the retention of hydrocarbon components in the materials (Nwinee, 2018). These muds also contain a collection of contaminants, which have detrimental impacts on the quality of air, soil, and water. When improperly stored or released into the environment, they can include petroleum hydrocarbons, heavy metals, and synthetic surfactants (Abha & Singh, 2012). As the largest oil-producing region in Africa, the Niger Delta region is the only one where the oil-based use of drilling muds has been exposed for several decades, making it suitable for assessing the environmental effects of using oil-based drilling muds (Osuji & Nwoye, 2007). During drilling activities, large volumes of mud are used, and cuttings are typically produced. Unless well sealed, these cuttings may enter the surrounding ecosystems through leaching, volatilization, and runoff (Okoro *et al*., 2020). The presence of oil-based mud residues has been linked to changes in the geochemical composition of soil, decreased permeability, impaired microbial growth, and reduced vegetation growth, as the residues contain hydrophobic films that prevent gaseous exchange (Okparanma & Mouazen, 2013). These residues may lead to high total petroleum hydrocarbon (TPH) and heavy metal contents, loss of dissolved oxygen, and impairment of the survival and reproduction ability of aquatic animals in water (Adeyemo *et al*., 2019). On the same note, mud-handling, flaring, or disposing of wastes releases volatile organic compounds (VOCs) and PM, which worsen the air quality in the local area and provide respiratory hazards to the local communities (Anejionu *et al*., 2015).

The surreal, humid tropical climate, the complex network of hydrology, and the reliance of the local population on natural products make the Niger Delta an environmentally sensitive region (Eweje, 2014). Research in the area has established that the mismanagement of OBM wastes has led to the multi-media Radioactive contamination that extends across both the land and water ecosystems (Oboh *et al*., 2016). Nevertheless, despite increased awareness of these effects, environmental evaluation in most drilling societies remains spotty, as it does not provide an in-depth examination of the various environmental elements. However, instead, it takes a limited view of each element separately (Orhuebor *et al*., 2025). It is therefore imperative to develop holistic research works that combine both hydrochemical tests and ecotoxicological risk assessments across various environmental areas to determine the accuracy of depressed levels and ecological impacts of OBM contamination. Hydrochemical analysis is a crucial diagnostic technique that can be used to identify the origin of contaminants, their transport processes, and geochemical reactions in the affected environment (Owamah, 2014). Through these ionic compositions, heavy metal, and hydrocarbon analyses, it is possible to clarify the level of anthropogenic change in natural systems (Anyanwu *et al*., 2020). Complementarily, ecotoxicological analyses, which employ biological or index-based methods, provide information on the potential ecological and health hazards of contaminants to flora, fauna, and humans (Adeniyi, Yusuf, and Okedeyi, 2018). A combination of the two methods improves the predictive ability of the environmental monitoring and enables evidence-based decision-making in remediation and policy development (Okoro *et al*., 2020; Ahanor *et al*., 2025).

Eruemokarien is a community in Delta state in the western Niger Delta, and it has high levels of petroleum exploration and production. The soil and groundwater systems of the area are especially susceptible because the alluvial terrain is low-lying and in proximity to the drilling platforms. Although the oil economy is a strategic factor in Nigeria's economy, little empirical evidence exists regarding the cumulative environmental costs associated with oil-based drilling mud activities in this region. This paper thus seeks to conduct an in-depth hydrochemical and ecotoxicological evaluation of OBM pollution in the air, soil, and water within the context of Eruemokarien. It is expected that, through the combination of chemical and ecological risk analysis, the study will provide a scientific foundation for enhancing environmental dynamics, promoting regulatory adherence, and developing sustainable drilling methods within the Niger Delta.

1.1. Study Objectives

a. To assess the physicochemical properties of soil around the OBM containment site.

b. To determine TPH, PAHs, and heavy metal levels in soil across the study zones.

c. To evaluate the hydrochemical quality of surface and groundwater near the drilling area.

d. To measure air quality parameters (PM2.5, PM10, VOCs) around the drilling platform.

e. To analyse spatial variations and statistical relationships among contaminants in soil, water, and air.

f. To appraise the ecological and health risks associated with OBM contamination in Eruemokarien.

2. Research Methodologies

The descriptive approach was based on the field-based and analytical design employed in the study to examine the hydrochemical and ecotoxicological impacts of oil-based mud (OBM) intoxication in Eruemokarien, Delta State. This method was chosen because OBM contamination is not possible in a single medium; it is transmitted through soil, water, and air at the same rate. The descriptive part allowed systematically recording environmental conditions, such as the visual characteristics of soils and water, vegetation stress, and the closeness of sources of pollution, and the analytical part was the laboratory quantification of pollutants and their compartment to the established regulatory indicators, in particular, EGASPIN (2018) and WHO (2017). Quantitative data were collected on Total Petroleum Hydrocarbons (TPH), heavy metals (lead, cadmium, chromium, nickel, and vanadium), and important physicochemical parameters that can determine contaminant movement. However, the analytical data did not affect the qualitative field data or the unsophisticated community knowledge. Collectively, these factors provided a comprehensive, multidimensional perspective on OBM contamination across the environment's compartments.

The community of Eruemokarien is located within the central Niger Delta Basin in the Ughelli South Local Government Area, Delta State, and lies between 5°25′–5°30′ N and 6°10′–6°15′ E. The climate of the area is humid tropical, with an annual rainfall of 2,000-3,000 mm, an average humidity of approximately 85%, and temperatures between 26 °C and 32 °C. These climate conditions increase the mobility and transport of contaminants through runoff, infiltration, and atmospheric dispersal. The geomorphology comprises poorly drained, low-lying, ferruginous tropical soils, which make groundwater more vulnerable to contamination by OBM residues in unlined pits. The proximity to the petroleum installations, such as the wellheads, flare stacks, and mud containment pits, and shallow aquifers, predisposes the community to pollution. On-site observations also showed chlorosis, defoliation, bare soils, and discoloured water bodies, indicating that the environment was under stress and requiring confirmation by hydrochemical means.

A stratified random sampling approach was used to record contamination gradients within the OBM containment area. The surrounding was split into three areas depending on the distance to the source of contamination. The high-impact zone (Zone A 0 100 m) was the zone in which the highest level of pollutants was projected to occur, as the pollution was directly related to the drilling activities. Zone B (100-300 m) was the moderate-impact zone, where contaminant levels were expected to be mitigated by dilution and natural attenuation. Zone C (>500 m) was the control zone, which showed environmental conditions similar to the background and with little or no impact from OBM activities. This zoning scheme was based on existing contamination gradient models, which allowed variations in space and the horizontal flow of contaminants to be evaluated with high confidence. The sampling was carried out in each zone at random to reduce bias and ensure the findings reflected the spatial distribution of contaminants.

Two intervals of the corrected depths were sampled (0-15 cm of the topsoil and 15-53 cm of the subsurface layer) to get soil samples. The depths were selected because surface deposition and downward movement of hydrocarbons and heavy metals typically occur at these depths, which affect plant roots and the growth of microorganisms. As a measure to prevent trace-metal contamination, stainless-steel augers and samples were transported in cool containers in clean, labelled polyethene bags to ensure sample integrity.

Samples of water were collected in acid-washed polyethene bottles from both surface and underground waters. To prevent oxidation and changes in metal concentrations due to microbial activity, each sample was kept in-house with a few drops of nitric acid (HNO_3). The samples were placed in insulated coolers and sent to the laboratory for analysis. The levels of air quality were measured by the employment of portable high-volume air samplers equipped with multi-gas sensors that consisted of the detection of delicate particulate matter (i.e. $PM_{2.5}$), coarse particulate matter (i.e. PM_{10}), volatile organic compounds (VOCs), methane (i.e. CH_4) and hydrogen sulphide (i.e. H_2S). The breathing height (about 1.5 m above ground level) was chosen as the height of the monitors, and sampling was conducted to represent human exposure, ensuring that the highest pollutant emissions from industrial processes were recorded.

The standard procedures recommended by the American Public Health Association (APHA, 2017), the United States Environmental Protection Agency (USEPA, 1996), and the Department of Petroleum Resources (DPR, 2018) were used in the laboratory to test pollutant concentrations. Atomic Absorption Spectrophotometry (AAS) was used to examine heavy metals, and this method measures the metallic pollutants with high accuracy. The total number of petroleum hydrocarbons (TPH) was determined through allowance of Gas Chromatography-Flame Ionisation Detection (GC-FID). In contrast, Polycyclic Aromatic Hydrocarbons (PAHs) were estimated under Gas Chromatography-Mass Spectrometry (GC-MS). Instrument calibration was performed using certified standards and quality assurance procedures, including reagent blanks, duplicates, and spiked samples, to ensure observability and repeatability of results.

SPSS Version 26.0 was used to process the data obtained from the laboratory analyses. Descriptive analysis was used to summarise pollutant concentrations across different zones, and the one-way Analysis of Variance (ANOVA) was used to test for significant spatial variation. The relationships among contaminants in soil, water, and air were determined via Pearson correlation analysis, with simple linear regression modelling applied to examine the dynamics of contaminant transport, particularly the relationship between soil and water TPH. Comparing all outcomes with national and international environmental standards, such as FMEnv (2011), EGASPIN (2018), NESREA (2011), and WHO (2017), was used to evaluate compliance and determine ecological and public-health risks.

The fieldwork was conducted respectfully under informed-consent procedures, and interactions were arranged to productively interfere with residents' activities without jeopardising local activities or harming the environment.

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3. Results

Table 1. Physicochemical Properties of Soil Samples at Different Distances from the Drilling Platform

Parameter	Unit	Zone A (0–100 m)	Zone B (100–300 m)	Zone C (>500 m, Control)	DPR Standard (EGASPIN, 2018)
pH	-	5.42 ± 0.10	6.01 ± 0.15	6.67 ± 0.18	6.0–8.5
Electrical Conductivity (EC)	µS/cm	785.60 ±³2.5	532.80 ± 27.4	271.40 ± 19.7	≤1000
Moisture Content	%	18.24 ± 1.12	14.82 ± 0.94	9.76 ± 0.71	-
Organic Matter	%	6.42 ± 0.21	4.87 ± 0.18	2.96 ± 0.10	≤3.0*
Sand	%	68.2	72.4	78.5	-
Silt	%	16.4	14.8	12.3	-
Clay	%	15.4	12.8	9.2	-
Textural Class	-	Sandy loam	Sandy loam	Loamy sand	-

Table 2. Total Petroleum Hydrocarbon (TPH) Concentrations in Soil

Parameter	Unit	Zone A (0–100 m)	Zone B (100–300 m)	Zone C (>500 m, Control)	DPR Limit (EGASPIN, 2018)	NESREA Limit (2011)	Contamination Factor (CF)
TPH C10–C20	mg/kg	1850 ± 55	980 ±32	120 ± 8	≤300	≤300	6.17
TPH C21–C35	mg/kg	2890 ± 90	1520 ± 60	320 ± 25	≤500	≤500	5.78
TPH C36–C50	mg/kg	1842 ± 75	774 ±35	101 ± 4	≤200	≤200	9.21
Total TPH	mg/kg	6582 ± 145	3274 ± 98	541 ±³7	≤1000	≤1000	6.58

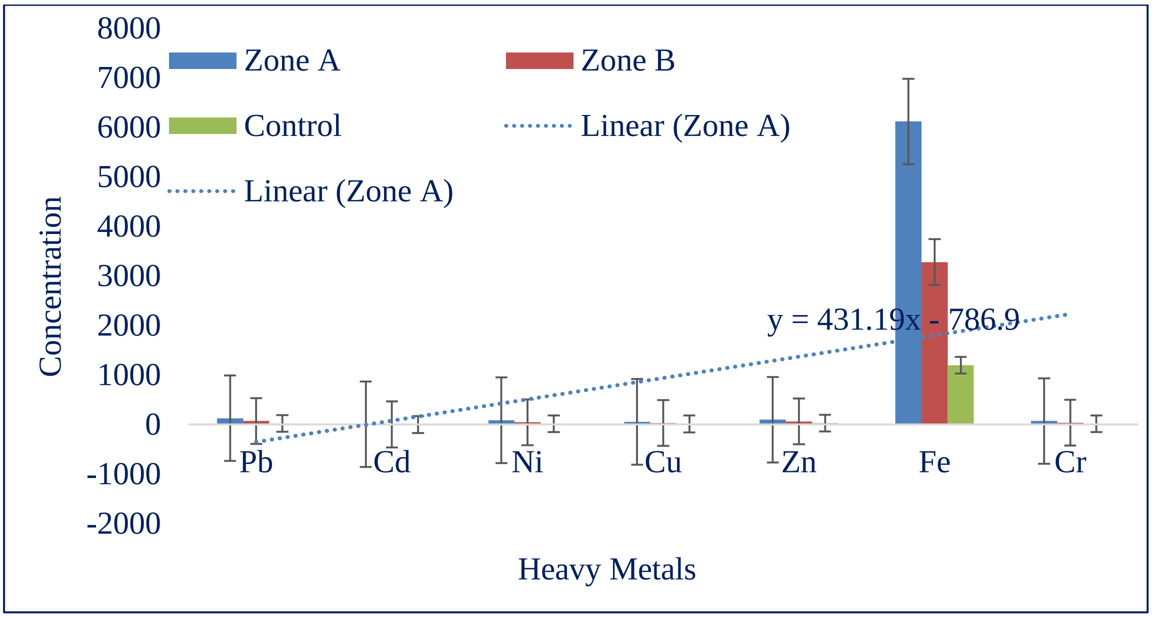

Figure 1. Comparative Concentration of Heavy Metals in Soil Samples across Study Zones

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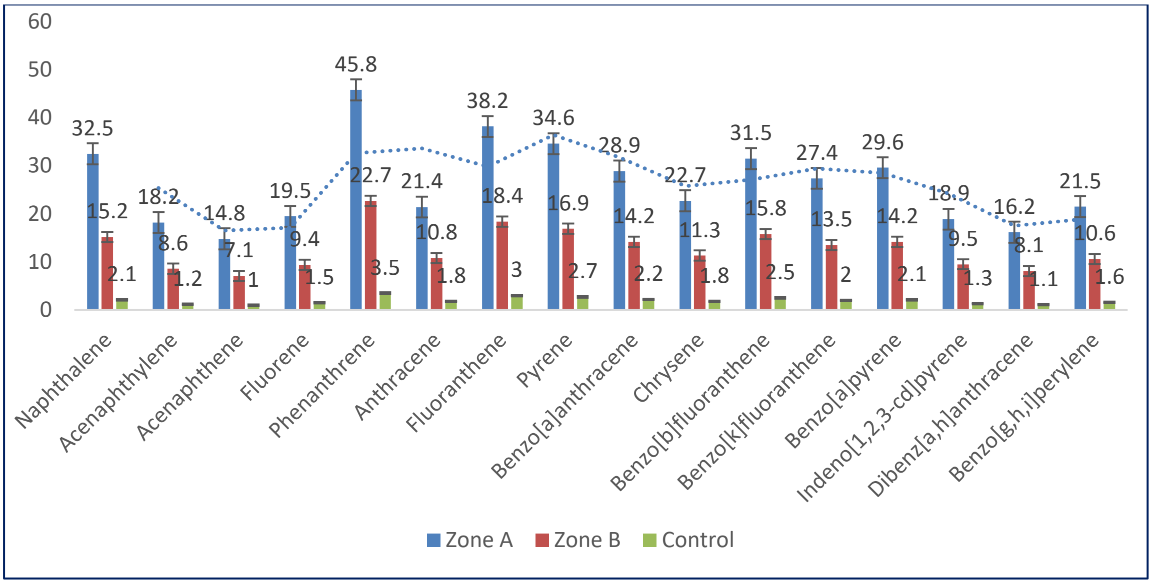

Figure 2. Concentration of Polycyclic Aromatic Hydrocarbons (PAHs) in Soil across Study Zones

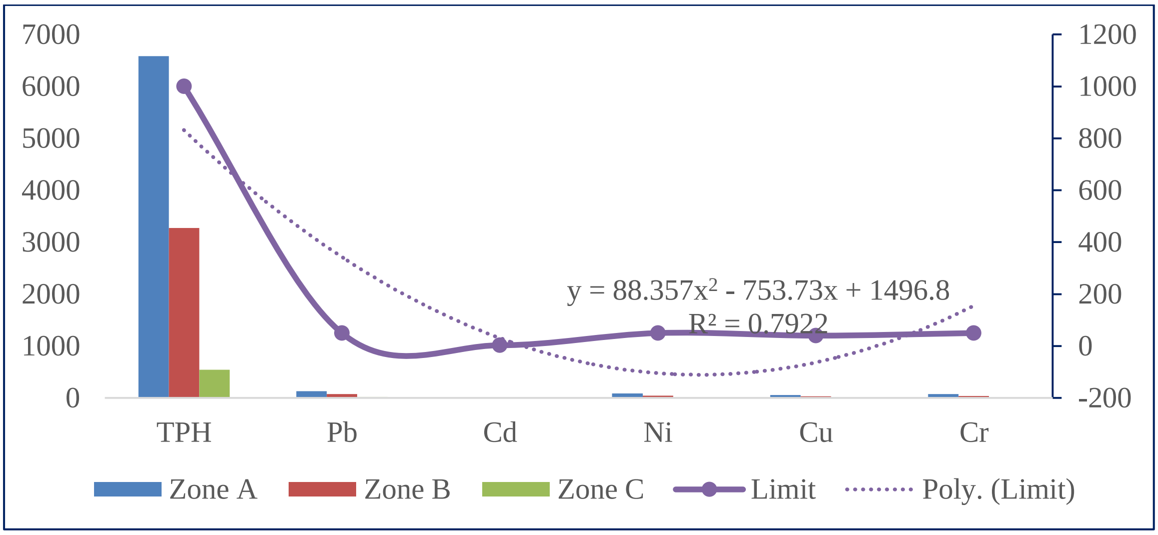

Figure 3. Spatial Variation of Major Soil Contaminants across Distance Zones

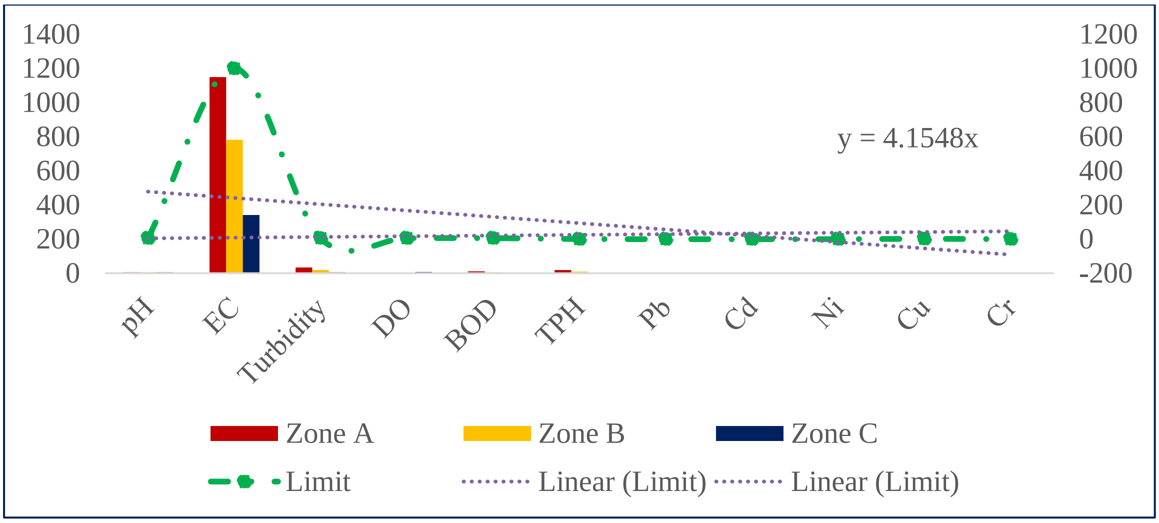

Figure 4. Spatial Variation of Physicochemical Parameters in Water Samples across Study Zones

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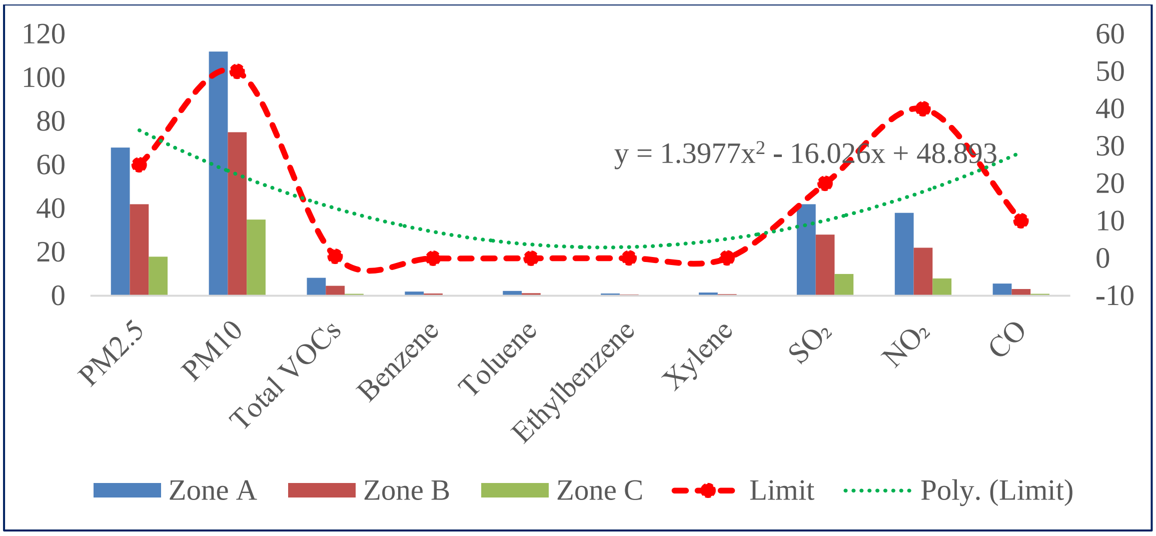

Figure 5. Spatial Variation in Air Quality Parameters around the Drilling Platform

Table 3. Summary Table of Multi-Media Contamination

Contaminant	Unit	Soil Zone A	Soil Zone B	Soil Zone C	Water Zone A	Water Zone B	Water Zone C	Air Zone A	Air Zone B	Air Zone C	Regulatory Limit (Soil/Water/Air)
TPH	mg/kg	6582	3274	541	18.4	9.6	1.2	8.2	4.6	0.9	Soil: 1000 mg/kg; Water: 1 mg/L; Air: 0.5 mg/m³
Pb	mg/kg	128	72	21	0.52	0.28	0.06	-	-	-	50/0.01/—
Cd	mg/kg	4.9	2.1	0.7	0.018	0.009	0.002	-	-	-	3/0.003/—
Ni	mg/kg	87	45	15	0.14	0.08	0.02	-	-	-	50/0.02/—
Cu	mg/kg	55	31	12	0.11	0.06	0.01	-	-	-	40/2/—
Cr	mg/kg	72	38	14	0.15	0.07	0.02	-	-	-	50/0.05/—
ΣPAHs	mg/kg	450.7	223.3	31.5	6.8	3.2	0.4	-	-	-	50/0.2/—
PM2.5	μg/m³	-	-	-	-	-	-	68	42	18	25 μg/m³
PM10	μg/m³	-	-	-	-	-	-	112	75	35	50 μg/m³
VOCs	mg/m³	-	-	-	-	-	-	8.2	4.6	0.9	0.5 mg/m³

Table 4. One-way ANOVA Results for Soil, Water, and Air Contaminants

Contaminant	Source of Variation	df	Sum of Squares (SS)	Mean Square (MS)	F-value	p-value	Significance (α = 0.05)
TPH (Soil)	Between Zones	2	4.12×10^7	2.06×10^7	112.3	<0.001	Significant
	Within Zones	6	1.10×10^6	1.83×10^5			
Pb (Soil)	Between Zones	2	1.92×10^3	9.60×10^2	94.7	<0.001	Significant
	Within Zones	6	60.8	0.1			

Cd (Soil)	Between Zones	2	11.5	5.75	58.2	<0.001	Significant
	Within Zones	6	0.59	0.098			
ΣPAHs (Soil)	Between Zones	2	2.15×10^4	1.08×10^4	121.5	<0.001	Significant
	Within Zones	6	535	89.2			
TPH (Water)	Between Zones	2	212.6	106.3	87.4	<0.001	Significant
	Within Zones	6	7.3	1.22			
ΣPAHs (Water)	Between Zones	2	56.4	28.2	75.6	<0.001	Significant
	Within Zones	6	2.2	0.37			
PM2.5 (Air)	Between Zones	2	324.5	162.3	64.3	<0.001	Significant
	Within Zones	6	15.1	2.52			
Total VOCs (Air)	Between Zones	2	62.8	31.4	101.8	<0.001	Significant

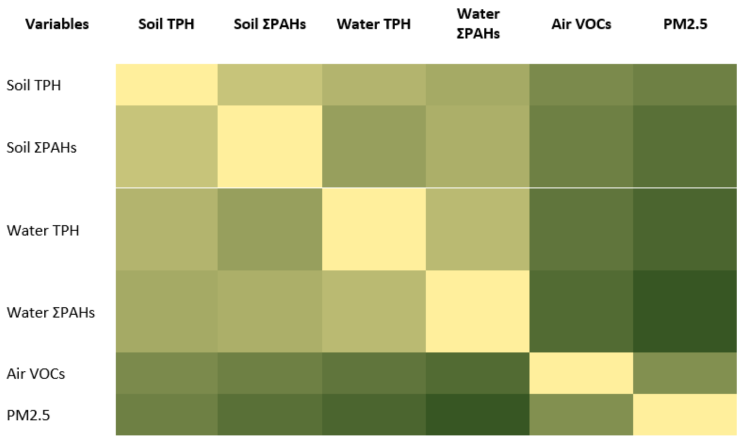

Figure 6. Correlation Heat Map of Soil, Water, and Air Contaminants

Table 5. Regression Results – Soil TPH vs Water TPH

Variable	Coefficient (β)	Std. Error	t-value	p-value	95% CI
Intercept (β0)	0.15	0.21	0.71	0.50	-0.42 – 0.72
Soil TPH (β1)	0.0029	0.00018	16.1	<0.001	0.0025 – 0.0033

4. Discussion

The general results (Table 3) indicate that the Eruemokarien has had a significant impact on hydrochemical and ecotoxicological changes in all environmental matrices due to the contamination of oil-based mud (OBM). There is an evident spatial attenuation of the pollutant gradients in Zones A-C, indicated by the increasing distance between the drilling platform and the pollutants that are the primary source of contamination, thus diagnostic of drilling operations as the primary source of contamination. This is highly contained in the results of the one-way ANOVA (Table 4), where $p < 0.001$ across all media, indicating statistically significant variations in the pollutant abundance levels across the zones. Okoro *et al*. (2020) and Abaha & Singh (2012) report similar gradients and spatial dependence, finding that soil and water quality parameters declined abruptly within 200 m of the drilling locations in similar oilfields of the Niger Delta. According to the indicators of physicochemical soil properties (Table 1), significant differences were observed in the values reported by the Department of Petroleum Resources (DPR, 2018). The soil PH at the drilling platform (5.42 ± 0.10) was less than the EGASPIN lower threshold of 6.0, indicating that the soil had become acidic due to hydrocarbon remnants and additives in the drilling fluids. The acidification tends to increase the mobility and solubility of heavy metals, thereby promoting their bioavailability and toxicity (Anyanwu *et al*., 2020). All electrical conductivity (EC) values were also significantly elevated (785.6 μS/cm in zone A), indicating ionic enrichment from saline drill cuttings. This tendency aligns with Schuler & Relyea (2018), who propose that the downward association of salts and heavy metals is based on leaching. Organic matter (6.42) was approximately twice the control rate (2.96), indicating the presence of hydrocarbon deposition and incomplete breakdown of organic matter. The texture was sandy loam over the areas, but the presence of more clay and silt fractions towards the source zone indicates the coarse sedimentation of fine OBM particulates.

The worst sign of OBM effects was Hydrocarbon contamination (Table 2). The total petroleum hydrocarbon TPH ranged between 6,582 mg/kg in Zone A and 541 mg/kg in Zone C, which was much higher compared to the DPR and NESREA limits of 1000 mg/kg and below. The soil has a high contamination factor (CF exceeds 6) and pollution load index (PLI exceeds 1), which qualifies as heavily polluted soil. The heavy hydrocarbon fractions (C21-C50) largely dominated, which indicates a petrogenic source and preservation, consistent with the results of Holzer *et al*. (2018). This gradient is graphically justified in Figure[3], where the intensity of TPH reduces in a radial direction around the wellhead. The consequences of these high levels of TPH are drastic in nature, resulting in decreased soil aeration, a lack of microbiological activity, and hampered plant growth, as observed in the field and confirmed by the findings of Adebayo, Aluko, and Oyediran (2016). The levels of heavy metals illustrated in Figure 1 show that hydrocarbons are co-contaminated. Zone A, which contained Lead (128mg/kg), Nickel (87 mg/kg), and Chromium (72mg/kg), had higher levels that were above DPR permissible levels (50mg/kg). Their depletion with range is similar to that of hydrocarbons, leading to familiar sources and minimal natural dissipation. Strong positive correlations were observed between TPH and Pb (r = 0.84), Ni and Cr (r = 0.79), as indicated by the correlation analysis results (Figure 6). These findings suggest that familiar anthropogenic sources, such as barite, corrosion inhibitors, and metallic additives, were likely present in OBM. Similar correlations of heavy metals with hydrocarbons have been observed by Ogbeibu *et al*. (2014) and Oboh *et al*. (2016) in polluted soils of the Niger Delta. High levels of organic carbon and metals lead to the formation of long-term and harmful soil matrices, which reduce microbial regeneration and hinder vegetation establishment (Osuji & Nwoye, 2007). The same trend was observed in Polycyclic aromatic hydrocarbons (PAHs) with total concentrations (ΣPAHs) of 450.7 mg/kg in Zone A, 223.3mg/kg in Zone B, and 31.5mg/kg at the control site, as shown in Figure 2. These values are higher than the DPR recommendation of 50 mg/kg, indicating that a bulk petrogene input was made by OBM residues. Benzo[a]pyrene and chrysene, which are known high-molecular-weight carcinogens, prevailed, which is also consistent with the observations by Ogbeibu *et al*. (2014). Significant differences across zones are also determined by the fact that the F-value of ANOVA of ΣPAHs is significant (121.5, $p < 0.001$) (Table 4). These pollutants are hydrophobic and persistent, with the ability to adhere to organic carbon and travel slowly through soil and water.

These trends are consistent with the processes observed by Anejionu *et al*. (2015), in which the PAHs in the sources of OBM were observed to be concentrated in the interfaces of sediments and soils surrounding the drilling pits.

The water quality statistics, as shown in hydrochemical data (Figure 4), indicate that contaminants have moved downwards and laterally into both surface and groundwater. The Zone A (18.4 mg/L), which was more than 18 times the WHO (2017) and DPR (2018) level (1 mg/L), contained only 12.4 mg/L at the control zone. On the same note, Pb (0.52 mg/L), Cd (0.018 mg/L), and Ni (0.14 mg/L) were higher than the WHO-recommended levels (0.01, 0.003, and 0.02 mg/L, respectively). The independent variable of water TPH ($F = 87.4$, $p < 0.001$) showed noticeable spatial variations, supporting the hypothesis of contamination driven by the sources (Table 4). The regression model (Table 5) revealed a strong positive relationship between soil TPH and water TPH ($R^2 = 0.87$, $p < 0.001$), indicating that active percolation processes and active runoff are the primary pathways of transfer. Owamah (2014) record similar linkages of soil and water pollution. The ΣPAHs in water were high (6.8 mg/L), and Cd and Ni indicated chronic aquatic toxicity (which may lead to oxidative stress and impair the reproductive system of fish) (Adeyemo *et al*., 2012). Figure 5 shows air quality data demonstrating significant atmospheric contamination in the drilling area. The amounts of $PM_{2.5}$ and $PM_{1.0}$ (68.5 g/m^3 and 112.5g/m^3, respectively) were above the WHO (25.5g/m^3 and 50.5g/m^3) standards of PM levels in Zone A and sixteen times higher than the NESREA standard (0.5 mg/m^3) for VOCs concentrations. These differences are statistically significant, as validated by the ANOVA results ($F = 64.3$, $PM_{2.5}$; $F = 101.8$, VOCs; $p = .001$). Volatilisation of remaining hydrocarbons and diesel fuel burning are contributing factors to the high VOC levels, as are a portion of the particulate measurements, also reported by Anejionu *et al*. (2015) in the Niger Delta. The characteristics of these parameters decrease in Zones B and C, consistent with the attenuation of soil and water pollutants, indicating a shared source of emissions. In addition, the average relationship between the VOCs and the TPH in soil (Figure 6) suggests the redeposition of hydrocarbons, which supports the overall character of the three media and thus demonstrates their interdependence.

Combined across all environmental compartments, the evidence (Table 3) indicates that OBM contamination in Eruemokarien is multidimensional. The most significant contaminant burden was observed in soil, water, and air, in that order, reflecting a series of pathways for pollutant presence characteristic of oilfield environments (Ite *et al*., 2016). The results of the ANOVA and correlation studies indicate that contamination gradients are neither random nor selected at random, but rather are tightly connected to the proximity and practices of the operations. The fact that regulatory limits were exceeded for parameters such as TPH, Pb, Cd, Ni, PAHs, PM, and VOCs provides evidence of an ecologically stressed state. Its continued presence of high-molecular-weight hydrocarbons and heavy metals indicates long-term bioaccumulation and ecotoxicity, which can be assessed in accordance with the conceptual model defined by Eweje (2014) and Ogbeibu *et al*. (2014). All of these findings confirm the hypothesis that unmanaged OBM is a long-term source of multimedia contamination, and that remediation, regulatory enforcement, and a transition to less toxic synthetic-based mud should be implemented.

5. Conclusion

The hydrochemical and ecotoxicological analysis of the environment of Eruemokarien conducted in an integrated manner demonstrated that oil-based mud (OBM) containment and drilling activities have had an impact of extreme multi-media contamination, with soil, water, and air matrices being contaminated with pollutants that were well beyond DPR (2018), NESREA (2011), and WHO (2017) limits. The results (Tables 1 and 5, Figures 1 and 6) demonstrate that the intensity of contamination exhibits a strong spatial dependence, decreasing with distance from the drilling platform, and are statistically justified by the significant ANOVA results ($p < 0.001$). Soil had the highest pollutant load, with extreme values of TPH (6,582mg /kg), Pb (128mg /kg) and Sigma PAHs (450.7mg/ kg) and water was polluted by hydrocarbon and heavy-metal infiltration (TPH = 18.4mg /L, Pb = 0.52mg/L, Cd = 0.018mg/L) and air quality within the wellhead area was compromised by excessive PM and VOCs (The intersecting relationships between soil and water TPH were significantly strong ($R^2 = 0.87$), providing evidence that pollutants were transferred vertically and laterally. In contrast, the correlation between VOC and TPH ($r = 0.68$) reflected the relationships between the atmosphere and the soil. Field data and laboratory evidence plus literature triangulation show that between 2012 and 2018, hydrocarbon residues and drilling additives have disrupted the biogeochemical integrity of the environment, inhibited microbial and vegetative activities, and chronic ecological and human-health hazards have ensued, which are comparable to other areas with oilfields (Niger Delta) (Adebayo *et al*., 2016; Ite *et al*., 2016). Accordingly, the Eruemokarien ecosystem can be considered highly polluted, and there are some clear signs of anthropogenic stress from petroleum processing.

6. Suggestions for future studies

a. Subsequent research should include seasonal observation to establish the impacts of rainfall strength, flooding and dry season evaporation on the mobility and permanence of TPH, PAHs, and heavy metals in the soil and water system.

b. Bio-impact studies, e.g., toxicity in fish, soil living organisms, and plants, should be incorporated in the future as direct quantitative measures of ecological impact rather than the chemical concentrations themselves.

c. Scientists would want to utilise more sophisticated geospatial modelling and remote sensing instruments to monitor long-term dispersion and migration of pollutants and land-cover alterations in relation to OBM contamination.

d. Future research needs to investigate the performance of alternative remediation methods (bioremediation, phyto-remediation, nano-remediation) in healing soils and groundwater in the Niger Delta contaminated with OBM.

e. Longitudinal studies that would assess the human exposure pathways and public-health hazards, such as inhalation of VOCs and particulates, ingestion of polluted water, and the bioaccumulation in the food chain, are required.

7. Recommendations

Given the ongoing contamination levels and intensity, NUPRC and DPR should impose stricter regulations on the handling, containment, and disposal of OBM to ensure lined pits and closed-loop mud recycling systems are utilised. The most urgent remediation approach should be preferential excavation and bioremediation of highly contaminated soils (TPH > 1,000mg/kg) and the implementation of monitored natural attenuation in moderately affected areas. To control leachate movement, groundwater-powered monitoring wells need to be installed around the containment pits. Additionally, continuous ambient air monitoring for $PM_{2.5}$, PM_{10}, and VOCs should be conducted to protect residents in the vicinity of the pits. It is also imperative to replace traditional OBM with low-toxicity, synthetic-based muds (SBM) and change metallic additives to environmentally benign equivalents to reduce future contamination. Moreover, environmental audits are to be enforced at all drilling phases, accompanied by ecological risk analysis, environmental awareness training, and a thorough follow-up, in line with the requirements of EGASPIN (2018) and WHO (2017). Ultimately, by establishing the linkage between geochemical, biological, and policy paradigms, as illustrated by the current triangulation research, sustainable drilling activities, local ecosystem security, and the realignment of petroleum activities in Nigeria with international environmental protection standards can be achieved.

Declarations

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Competing Interests Statement

The authors declare that they have no competing interests related to this work.

Consent for publication

The authors declare that they consented to the publication of this study.

Authors' contributions

All the authors took part in literature review, analysis, and manuscript writing equally.

Availability of data and materials

Supplementary information is available from the author upon reasonable request.

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