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Environmental Assessment of Oil-Based Mud Impacts on Soil and Water in Eruemokohwarien, Delta State, Nigeria

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Abstract

This research determined the environmental impacts of contained OBM on the soil and water quality at the drilling area and the environment in and around the drilling area. Field samples from the affected and control sites were analyzed using Atomic Absorption Spectrophotometry (AAS) to assay heavy metals, Gas Chromatography-Mass Spectrometry (GC-MS) to analyze hydrocarbons. Findings bequeathed excellent indications of environmental degradation: Both total petroleum hydrocarbons (TPH) and polycyclic aromatic hydrocarbons (PAHs) in the soil and the water were above the WHO and NESREA standards; heavy metals/ Pb, Cd, Cr, Ni, Zn / were highly enclosed in the drilling regions in contrast to the controls regions; the soil was hydrophobic, low microbial functioning and low fertility; turbidity, oil coats and contaminants in the water samples were high. High correlations exist between soil and water contaminants, indicating the movement of contaminants through the environmental media. The research concludes that the OBM containment systems in Eruemokohwarien are not very efficient and pose a danger to the environment. It suggests the strict implementation of the EGASPIN standards, the adoption of modern remediation technologies, such as thermal desorption and cuttings reinjection, and the implementation of environmental monitoring, including community participation, to ensure sustainable drilling operations and ecological restoration.

Keywords: Oil-Based Mud, Environmental Contamination, Hydrocarbons, Heavy Metals, Niger Delta, Egaspin Standards, Soil-Water Pollution.

Introduction

Crude oil exploration and production is one of the most critical industrial processes behind the modern civilisation that contributes to energy security, industrial growth and socio-economic growth in the world. Drilling fluids otherwise known as muds are important in the production of petroleum especially through oil drilling as an indispensable stage in the petroleum production process. These fluids have a number of technical purposes like lubrication and cooling of the drill bit, suspension and transportation of rock cuttings to the surface, hydrostatic pressure maintenance to prevent formation blowouts and stabilisation of the wellbore under different geology pressures (Amanullah and Al-Tahini, 2009). Three major drilling fluids have been created over the years such as water-based muds (WBMs) and oil-based muds (OBMs) and synthetic-based muds (SBMs) with their own merits and consideration to the environment. Of them, OBMs have become highly popular in complex drilling projects, particularly in deep, high-pressure, and high-temperature wells, because they are highly lubricious, inhibit shale, and resist thermal degradation (Okiongbo et al., 2020). These attributes render OBMs indivisible in the contemporary petroleum engineering in which operations efficiency and precision and drilling is of prime importance. Nonetheless, their use and disposal have posed a major global problem in terms of environmental cost despite their undisputed technical advantages. The persistent organic pollutants (POPs) are brought into the environment through the base oils of OBMs which are usually based on diesel, mineral oils or low-toxicity paraffinic hydrocarbons, but this leaks into the environment despite poor management (Okedere et al., 2021). Complex chemical additives, such as emulsifiers, weighting agents, such as barite, corrosion inhibitors and the viscosifiers improve the performance of drilling but they also raise the toxic load of the discharged mud residue. Repeatedly discharged to soil, air, and water, OBMs lead to the influx of hydrocarbons, heavy metals, and other chemical contaminants into the natural physicochemical and biological balance in the nature of ecosystems (Nwinee, 2018). As a result, OBMs have increased the effectiveness of drilling operations and minimised the frequency of mechanical errors, but they are persistent and poorly degradable, which means that they are among the most eco-unfriendly works of by-products of petroleum extraction (Onuoha et al., 2022). Regulatory frameworks, including those of the United States Environmental Protection Agency (Yarandi et al., 2019) and the European Environment Agency (Anejionu, et al., 2015), now focus on waste reduction, treatment, and zero-discharge on the OBM residues, but compliance levels are sporadic especially in the developing countries where the policies are not well enforced.

Oil-based muds (OBMs) have been known to

be indispensable in the high-technology drilling since long ago due to their enhanced thermal stability, lubricity, and ability to reduce the swelling of a shale; but the very composition and permanence of these byproducts make them one of the most toxic substances that petroleum companies produce. OBM used in drilling activity generates volumes of waste cuttings and the left-over muds which, on not contained or otherwise levels off, may lead to vast pollution of the immediate environmental media. Although the containment systems, including lined pits, closed-loop mud systems, and cuttings re-injection technologies, are meant to reduce such risks, the experience of oil-producing areas, including the Niger Delta, indicates that the technologies are not effective, as they are frequently poorly designed, not well maintained, or fail, or they are intentionally discharged in the course of cost-cutting activities (Onuoha et al., 2022; Nwankwoala and Ememu, 2018). As such, even contained OBMs can drain off hydrocarbons, heavy metals, and other toxic substances in the soils, water bodies, and the atmosphere. Hydrocarbon residues and metallic additives like lead (Pb), chromium (Cr), cadmium (Cd), nickel (Ni), and zinc (Zn) are likely to be retained in the environment due to their hydrophobicity and bio-degrading recalcitrance and end up causing long-term contamination and bioaccumulation in ecosystems (Nwinee, 2018). This type of contamination changes physicochemical and biological characteristics of the soil, decreases the quality of water with oil films and dissolved hydrocarbons, and worsens the quality of air with volatile organic compounds (VOCs) and particulate matter due to drying mud and gas flaring (Saeedi et al., 2020).

AIM AND OBJECTIVES

The aim is to assess the effect of contained oil-based mud on soil and water, with following objectives to:

i. evaluate the physicochemical characteristics of soil and water within and around drilling sites utilizing contained oil-based mud,
ii. determine the concentrations of Total Petroleum Hydrocarbons (TPH) and Polycyclic Aromatic Hydrocarbons (PAHs) in soil and water in the study area.
iii. quantify the levels of selected heavy metals (such as lead, cadmium, chromium, nickel, and zinc) in soil and water within the study area.

RESEARCH METHODS

The research methods adopted in this study are outlined below.

Soil Sample Collection and Analysis

Sample Collection and Preparation

The samples of the soils were taken with stainless-steel auger in the same sampling zones at a depth of 015 cm and 1530 cm. Three subsamples of five meters at each of the sampling places then mixed well to get a single composite sample information about that particular point. The approximate weight of each sample was 500 grams. To the laboratory, the samples were taken

in the form of acid-washed polyethylene bags, closed, and labelled with date, time, depth, as well as GPS coordinates, and kept in a cool box at 4C.

Each of the soil samples was dried at ambient temperature (25 = -2o C) in the laboratory over 48 hours to get the sample dry without interfering with the chemical composition of the samples. The sample was crushed a few times using a porcelain mortar and pestle, sieved to 2 mm mesh to remove any debris, and put into airtight glass jars awaiting analysis. Also, various analyses were conducted on subsamples of each of the prepared composites, which had to include parameters such as physicochemical, heavy metals, total petroleum hydrocarbons (TPH), and polycyclic aromatic hydrocarbons (PAHs).

Determination of Soil Physicochemical Parameters

a. Soil pH:

i. 10 g of air-dried soil was weighed into a 50 mL beaker.
ii. 25 mL of distilled water was added (1:2.5 soil-to-water ratio).
iii. The mixture was stirred with a glass rod for 5 minutes and allowed to stand for 30 minutes.
iv. The pH of the supernatant was measured using a digital pH meter (Hanna HI 2211) calibrated with buffer solutions of pH 4.0, 7.0, and 9.0.

b. Electrical Conductivity (EC):

i. The same soil suspension used for pH was stirred again, and the EC was measured using a Hanna EC meter, standardized with a 0.01 M KCl solution.
ii. The result was recorded in µS/cm.

c. Moisture Content:

i. 10 g of soil was weighed into a pre-weighed aluminum dish (W_1).
ii. The sample was oven-dried at 105°C for 24 hours, cooled in a desiccator, and reweighed (W_2).

$$\text{Moisture Content (\%)} = \frac{W_1 - W_2}{W_1}\ x\ 100$$

d. Organic Carbon:

i. Determined using the Walkley–Black wet oxidation method.
ii. 1 g of soil was placed in a conical flask, followed by 10 mL of 1 N $K_2Cr_2O_7$ and 20 mL of concentrated H_2SO_4.
iii. The mixture was swirled and allowed to stand for 30 minutes.
iv. 100 mL of distilled water, 10 mL of phosphoric acid, and 1 mL of diphenylamine indicator were added.
v. The mixture was titrated against 0.5 N ferrous ammonium sulfate until the color changed from violet to green.
vi. Organic carbon (%) was calculated using standard conversion factors.

e. Cation Exchange Capacity (CEC):

i. 10 g of soil was leached with 1 M ammonium acetate solution (pH 7.0).
ii. The ammonium ions replaced the exchangeable cations in the soil.

iii. The leachate was collected, and the concentration of cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) was determined using AAS.
iv. Total CEC was obtained as the sum of all exchangeable cations, expressed in cmol(+)/kg.

Determination of Heavy Metals in Soil

a. Digestion:

i. 1 g of dried soil was weighed into a 250 mL digestion flask.
ii. 10 mL of aqua regia (HNO_3: HCl, 1:3) was added, and the mixture was heated on a hot plate at 120°C until the solution became clear and reduced to about 5 mL.
iii. The digest was cooled, filtered through Whatman No. 42 filter paper, and diluted to 50 mL with distilled water.

b. Analysis:

i. The digest was analyzed using an Atomic Absorption Spectrophotometer (AAS, PG-990 model) for Pb, Cd, Ni, Cr, Cu, Zn, and Fe.
ii. Calibration curves were prepared using certified standard solutions.
iii. Each sample was analyzed in duplicate to ensure accuracy, and results were expressed in mg/kg dry weight.

Determination of Total Petroleum Hydrocarbons (TPH)

a. **Extraction:**

i. 10 g of soil was weighed into a 250 mL extraction flask.
ii. 50 mL of dichloromethane (DCM) was added and extracted using a Soxhlet apparatus for 6 hours at 60°C.
iii. The extract was concentrated using a rotary evaporator to about 5 mL.

b. **Clean-Up:**

i. The concentrated extract was passed through a silica gel column (10 cm × 1 cm i.d.) preconditioned with n-hexane.
ii. The hydrocarbon fraction was eluted with 20 mL of n-hexane, and the eluate was concentrated to 2 mL.

c. **Quantification:**

i. The purified extract was analyzed using Gas Chromatography with Flame Ionization Detection (GC-FID) following USEPA Method 8015B.
ii. Injector and detector temperatures were maintained at 250°C and 300°C, respectively.
iii. The oven temperature was programmed from 60°C (2 min hold) to 280°C at 10°C/min.
iv. TPH concentrations were quantified by integrating total chromatographic peaks and expressed in mg/kg.

Determination of Polycyclic Aromatic Hydrocarbons (PAHs)

a. **Extraction and Cleanup:**
    i. The same DCM extracts used for TPH were cleaned with florisil column chromatography.
    ii. The PAH fraction was eluted with n-hexane: DCM (3:1).
b. **Analysis:**
    i. Quantitative analysis was carried out using Gas Chromatography–Mass Spectrometry (GC–MS) (Agilent 7890B/5977A) as per USEPA Method 8270D.
    ii. Injector temperature: 280°C; column: HP-5MS capillary (30 m × 0.25 mm × 0.25 μm); carrier gas: helium at 1 mL/min.
    iii. Oven program: 70°C (2 min hold) → 290°C at 8°C/min (hold 10 min).
    iv. Individual PAHs (e.g., naphthalene, anthracene, benzo[a]pyrene, chrysene) were identified by comparing retention times and mass spectra with standards.

Water Sample Collection and Analysis

Sample Collection and Preservation

Surface water, (creeks and ponds), was sampled and ground water, (wells, boreholes), was sampled with water 1 L acid-washed polyethylene bottles. The sample water was used 3 times to rinse the bottles prior to collection. Surface water sampling and groundwater sampling were conducted 30 cm beneath the surface and 10 minutes of pumping were used to agitate the water before sampling respectively. For each sample:

a. 100 mL was acidified with 2 mL concentrated HNO_3 (for metals),
b. 100 mL preserved with n-hexane (for hydrocarbons), and
c. the remainder stored for physicochemical analysis.

Samples were kept at 4°C in coolers and analyzed within 24 hours.

Physicochemical Analysis of Water

a. pH and Temperature: measured in situ using a portable multiparameter probe (Hach HQ40d).
b. Electrical Conductivity (EC) and Total Dissolved Solids (TDS): measured with a Hach Conductivity/TDS meter.
c. Turbidity: determined using a nephelometric turbidity meter (Hach 2100P).
d. Dissolved Oxygen (DO): measured using a DO meter following the Winkler method.
e. Biochemical Oxygen Demand (BOD_5): water samples were incubated at 20°C for 5 days, and DO reduction was used to calculate BOD.
f. Chemical Oxygen Demand (COD): measured using the dichromate reflux method—10 mL sample + 5 mL $K_2Cr_2O_7$ + 15 mL conc. H_2SO_4, digested for 2 hours at 150°C.
g. Anions (SO_4^{2-}, NO_3^-, PO_4^{3-}, Cl^-): analyzed using a UV–visible spectrophotometer (Shimadzu UV-1800) after reagent color development (e.g., turbidimetric method for SO_4^{2-}, cadmium reduction for NO_3^-).

Heavy Metals and Hydrocarbon Determination in Water

a. **Heavy Metals:**
   - 100 mL of each sample was digested with 10 mL HNO_3:HCl (3:1) and heated to near dryness.
   - The digest was filtered and diluted to 50 mL.
   - Concentrations of Pb, Cd, Ni, Cu, Zn, Cr, and Fe were determined using AAS.

b. **TPH and PAHs:**
   - 100 mL of water was extracted with 20 mL of n-hexane by vigorous shaking for 10 minutes.
   - The extract was dried over anhydrous sodium sulfate and concentrated to 2 mL.
   - TPH and PAHs were analyzed by GC-FID and GC–MS, respectively, using the same conditions as soil extracts.

RESULTS AND DISCUSSION

Physicochemical Characteristics of the Soil Samples

Table 1 displays the physicochemical properties of soil samples in three study zones, indicating that spatial variability is extensive because each zone is located near the drilling platform. The pH level in zone A was 5.42, and in zone C was 6.67, indicating that the drilling location is in increasingly more acidic conditions. This acidity is also possibly caused by the oxidation processes of hydrocarbons and chemical additives in the oil-based mud (OBM), which introduce organic acids to the soil structure. The alkalinity of the area surrounding the drilling location also indicates active chemical weathering and microbial degradation of hydrocarbons, as found by Jiang, et al., (2022) in the context of oilfields. Zone A recorded the highest level of electrical conductivity (EC) (785.6 µS/cm) due to the buildup of soluble ions and salts from OBM returns. It was found to decrease over distance, indicating less contamination. The contents of moisture and organic matter were similar, with high levels towards the platform due to the retention of hydrocarbons and inadequate aeration. The composition of the texture revealed that the acceptable content of the soils in Zone A was greater than in the control zone (clay and silt), indicating that the soil in Zone A was more textured (finer). All the data points to the conclusion that OBM activities have had a considerable impact on soil chemical and physical characteristics in the area around the platform. They made the soils more acidic, salty, and rich in organic material, which has implications for lower fertility and slower attenuation by natural processes.

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	-

Petroleum Hydrocarbon (TPH) in Soil

Table 2 indicates that the total petroleum hydrocarbon (TPH) had the highest concentration of 6,582 mg/kg in Zone A and the lowest concentration of 541mg/kg in Zone C, which is higher than the Department of Petroleum Resources (DPR) and the NESREA regulations (1,000 mg/kg) of all the contaminated zones. The outcomes show a distinct distance-related reduction in concentration of TPH, which validates the local contamination in the region of the drilling. The chemical composition of OBM is also reflected in the preponderance of medium- to heavy-chain hydrocarbons (C21-C50) around the well site, which consists of the long-chain hydrocarbons that are less volatile and more resistant to degradation. The contamination factors (CFs) of the various fractions vary between 5.78 and 9.21, suggesting that the soils are highly contaminated and that the accumulation of hydrocarbons is an old event. Such results are consistent with those provided by Bafe et al., (2023) and Onojake, et al., (2020), who have detected the same TPH enrichment in the area of active drilling operation in the Niger Delta. Long-term ecological effects could be the high TPH levels that inhibit soil microbial activity, decrease oxygen movement, and impede nutrient cycling. Moreover, the persistence of heavier hydrocarbon fractions indicates little capability for natural degradation, making remediation necessary. Overall, the results show that the isolation of OBM containment areas is the best predictor of hydrocarbon contamination severity, and Zone A soils present significant risks to environmental and human health.

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

Metal Level in Soil

The concentrations of heavy metal summed up in Table 3 indicate high levels of contamination at the vicinity of the drilling platform and the values of Lead (Pb), Nickel (Ni), and Chromium (Cr) are high that is well above the DPR and NESREA threshold, 128 mg/kg, 87mg/kg, and 72mg/kg respectively. These metals are found in high levels and are correlated with drilling equipment, lubricants, and OBM additives that have metallic stabilisers. There were also increases in Cadmium (Cd) and Copper (Cu), where Cd (4.9 mg/kg) was greater than its maximum level of 3mg/kg. The level of Zinc (Zn) was moderately elevated but not excessive. In contrast, the element of Iron (Fe) was naturally high because of the presence of ferruginous soils of the Niger Delta. The contamination factors (CFs >1) deny mild or extreme pollution, specifically to Pb and Cd, which is extremely ecotoxicologically dangerous. The decrease in space between Zone A and C shows the decreased input of the metal as the distance increases between the drilling platform and Zone C. Onojake, et al., (2017) also reported similar tendencies, which supported the conclusion that the activities of the OBMs are significant contributors to the enrichment of the adjacent soils with metal. The presence of high metal concentrations in Zone A suggests that these metals may be mobile enough to reach the groundwater and could bioaccumulate in local crops. This necessitates environmental remediation and adherence to tighter waste disposal procedures.

Table 3: Heavy Metal Concentrations in Soil Samples and Contamination Indices

Metal	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, Zone A)
Pb	mg/kg	128 ± 5.6	72 ± 3.8	21 ± 2.1	50	70	2.56
Cd	mg/kg	4.9 ± 0.3	2.1 ± 0.2	0.7 ± 0.1	3	3	1.63
Ni	mg/kg	87 ± 4.2	45 ± 2.5	15 ± 1.3	50	50	1.74
Cu	mg/kg	55 ± 2.8	31 ± 1.7	12 ± 1.1	40	50	1.38
Zn	mg/kg	98 ± 5.1	62 ± 3.2	28 ± 2.0	100	150	0.98
Fe	mg/kg	6120 ± 150	3280 ± 120	1200 ± 80	-	-	-
Cr	mg/kg	72 ± 3.5	38 ± 2.0	14 ± 1.2	50	50	1.44

PAHs Concentrations in Soil

Table 4 shows the amounts of 16 priority PAHs in the soils of the three zones with severe organic contamination around the drilling platform. Total PAHs (ΣPAHs) in Zone A (450.7 mg/kg) were well above the DPR/NESREA limit (50 mg/kg) of the same, whereas in Zone B (223.3 mg/kg) and C (31.5 mg/kg) they recorded 223.3 and 31.5 mg/kg, respectively. The findings indicate a high dominance of high-molecular-weight PAHs, including Phenanthrene (45.8mg/kg), Fluoranthene (38.2mg/kg), Pyrene (34.6mg/kg), and Benzo[a]pyrene (29.6mg/kg), pointing to both the petrogenic (OIL) (OBM residues) and pyrogenic (combustion) sources. These substances are hydrophobic, durable, and cancer-causing, implying severe effects on the environment and health. The sharp decline in the concentrations of PAH with the distance indicates restricted motility and partial or partial biospitability of lighter PAHs. The results align with Yarandi, et al., (2019) and Onojake, et al., (2020), who

had similar findings of the PAH enrichment around the drilling activities. The occurrence of carcinogenic PAHs, Benzo [a]pyrene and Dibenz [a,h]anthracene, around the platform raises concerns about possible bioaccumulation in food and water. Accordingly, the table confirms the direct relationship between the proximity and the concentration and composition of the PAH which validates the localised but intense contamination that needs immediate soil remedial action.

Table 4: Concentrations of Selected PAHs in Soil Samples

PAH Compound	Zone A (0–100 m)	Zone B (100–300 m)	Zone C (>500 m, Control)	DPR Limit (mg/kg)	NESREA Limit (mg/kg)
Naphthalene	32.5 ± 1.4	15.2 ± 0.8	2.1 ± 0.2	5	5
Acenaphthylene	18.2 ± 0.9	8.6 ± 0.4	1.2 ± 0.1	5	5
Acenaphthene	14.8 ± 0.6	7.1 ± 0.3	1.0 ± 0.1	5	5
Fluorene	19.5 ± 0.8	9.4 ± 0.5	1.5 ± 0.1	5	5
Phenanthrene	45.8 ± 2.1	22.7 ± 1.2	3.5 ± 0.2	10	10
Anthracene	21.4 ± 1.0	10.8 ± 0.6	1.8 ± 0.2	5	5
Fluoranthene	38.2 ± 1.9	18.4 ± 1.0	3.0 ± 0.2	10	10
Pyrene	34.6 ± 1.7	16.9 ± 0.9	2.7 ± 0.2	10	10
Benzo[a]anthracene	28.9 ± 1.5	14.2 ± 0.8	2.2 ± 0.1	10	10
Chrysene	22.7 ± 1.1	11.3 ± 0.6	1.8 ± 0.1	10	10
Benzo[b]fluoranthene	31.5 ± 1.6	15.8 ± 0.9	2.5 ± 0.2	10	10
Benzo[k]fluoranthene	27.4 ± 1.4	13.5 ± 0.7	2.0 ± 0.1	10	10
Benzo[a]pyrene	29.6 ± 1.5	14.2 ± 0.8	2.1 ± 0.1	5	5
Indeno[1,2,3-cd]pyrene	18.9 ± 0.9	9.5 ± 0.5	1.3 ± 0.1	10	10
Dibenz[a,h]anthracene	16.2 ± 0.8	8.1 ± 0.4	1.1 ± 0.1	5	5
Benzo[g,h,i]perylene	21.5 ± 1.1	10.6 ± 0.6	1.6 ± 0.1	10	10
ΣPAHs (Total)	**450.7 ± 12.3**	**223.3 ± 7.5**	**31.5 ± 2.1**	50	50

Soil Contaminant Concentration Distances

A spatial overview of all the key soil contaminants in terms of TPHs, heavy metals, and PAHs is presented in Table 5, which demonstrates the gradients of concentration with respect to the location of the drilling platform. A distinct trend is observed in the table, with all parameters at their highest, where a steady decrease towards the control zone follows Zone A. As an example, TPH at 0 100 m was decreased by 6,582 mg/kg, and at above 500 m was reduced by 450.7 mg/kg, and total PAHs were decreased by 6,582 mg/kg. The same followed with the heavy metals, where Pb, Ni, and Cr concentrations declined critically with distance. The trends attest to the distance-related gradient contamination and support the hypothesis that the load of pollutants reduces as a result of causes related to dilution, dispersion, and adsorption. The stability of this trend in parameters suggests that the source of pollution prevails as the residues of OBM and the drilling wastes. This type of localised contamination, albeit at a profound level, would be consistent with the spatial analysis provided by Hamdan, and Salam, (2020)

in other oilfield settings. As highlighted in the table, Zone A is a severe contamination hot zone, and its numbers are much higher than the regulations, whereas Zone C is relatively unpolluted. This testifies to the necessity of the spatial zoning and buffer zones of the drilling areas in order to preserve the integrity of the soil and the ecosystems surrounding it.

Table 5: Summary of Soil Contaminant Concentrations by Distance

Contaminant	Unit	Zone A (0–100 m)	Zone B (100–300 m)	Zone C (>500 m)	DPR/NESREA Limit
TPH (Total)	mg/kg	6582 ± 145	3274 ± 98	541 ± 37	1000
Pb	mg/kg	128 ± 5.6	72 ± 3.8	21 ± 2.1	50
Cd	mg/kg	4.9 ± 0.3	2.1 ± 0.2	0.7 ± 0.1	3
Ni	mg/kg	87 ± 4.2	45 ± 2.5	15 ± 1.3	50
Cu	mg/kg	55 ± 2.8	31 ± 1.7	12 ± 1.1	40
Cr	mg/kg	72 ± 3.5	38 ± 2.0	14 ± 1.2	50
ΣPAHs	mg/kg	450.7 ± 12.3	223.3 ± 7.5	31.5 ± 2.1	50

Physicochemical Characteristics of Water Samples

Table .6 indicates that the water sources surrounding the drilling platform have enormous amounts of hydrocarbon and metal contaminants. The pH values (5.38 -6.58) show that there are acidic environments, particularly in Zone A, which are a result of OBM leachates. The highest EC (1,150 µS/cm) was measured at Zone A, indicating the high solubility of ionic additives as well as hydrocarbon residue, and surpassed the WHO as well as DPR values. Turbidity and BOD scores were also significantly high, signalling that it was an organically loaded and suspended solids characteristic of oil-contaminated waters. In the case of Zone A, dissolved oxygen (DO) was at 3.2 mg/L, which is a critically low level, indicating the lack of oxygen due to microbial degradation of hydrocarbons. TPH concentrations (18.4 mg/L in Zone A) and PAHs (6.8 mg/L) were much higher than the limits, which proved to be a direct intrusion of hydrocarbons. The concentration of heavy metals like Pb (0.52 mg/L) and Cd (0.018 mg/L) was also on the higher side than WHO limit, and it could lead to bioaccumulation and toxicity of aquatic organisms. The data reveal that pollutant concentration is steady with distance thus confirming the spatial contamination gradient found in soils. The results are consistent with the research of Jiang, et al., (2022) and Onojake, et al., (2020) that defend the fact that OBM disposal and surface runoff are the primary sources of water pollution in the drifting field.

Table 6: Physicochemical Properties of Water Samples

Parameter	Unit	Zone A (0–100 m)	Zone B (100–300 m)	Zone C (>500 m, Control)	WHO (2017)	DPR/NESREA Limit
Ph	-	5.38 ± 0.12	5.92 ± 0.15	6.58 ± 0.13	6.5–8.5	6.5–8.5
EC	µS/cm	1150 ± 45	782 ± 32	342 ± 20	≤1000	≤1000
Turbidity	NTU	34.2 ± 1.5	18.4 ± 0.9	5.2 ± 0.3	≤5	≤5
DO	mg/L	3.2 ± 0.2	5.1 ± 0.3	7.2 ± 0.3	≥6	≥6
BOD	mg/L	12.5 ± 0.8	6.8 ± 0.4	3.1 ± 0.2	≤6	≤6

Parameter	Unit	Zone A (0–100 m)	Zone B (100–300 m)	Zone C (>500 m, Control)	WHO (2017)	DPR/NESREA Limit
TPH	mg/L	18.4 ± 1.2	9.6 ± 0.8	1.2 ± 0.1	≤1	≤1
Pb	mg/L	0.52 ± 0.03	0.28 ± 0.02	0.06 ± 0.01	0.01	0.01
Cd	mg/L	0.018 ± 0.002	0.009 ± 0.001	0.002 ± 0.001	0.003	0.003
Ni	mg/L	0.14 ± 0.01	0.08 ± 0.01	0.02 ± 0.01	0.02	0.02
Cu	mg/L	0.11 ± 0.01	0.06 ± 0.01	0.01 ± 0.01	2	2
Cr	mg/L	0.15 ± 0.01	0.07 ± 0.01	0.02 ± 0.01	0.05	0.05
ΣPAHs	mg/L	6.8 ± 0.3	3.2 ± 0.2	0.4 ± 0.1	0.2	0.2

Results of the Regression: Soil TPH and Water TPH

Table 7 is the linear regression model of the predictive relationship between the soil and water TPH concentrations. The regression coefficient of soil TPH (= 0.0029, 0.001) indicates not only a strong positive relationship but also a statistically significant one. In other words, the higher the soil TPH levels in terms of hydrocarbon content, the higher its water TPH levels. An R^2 value of 0.89 indicates that 89% of the variation in water TPH can be attributed to soil TPH, while only 11% is due to the deviation of runoff or existential degradation rates. The high power of explanation is based on the fact that direct hydrocarbon migration in soil to surface or underground water occurs due to factors such as the use of sandy-loam soils in the area, which are easily permeable, and the high levels of rainfall in the region. The positive slope also suggests continuous leaching possibilities over time. The finding is congruent with research by Jiang, et al., (2022), who indicated the same soil-water hydrocarbons associations in drilling locations. The test for multicollinearity is not significant; none of the standard errors are high, so the model is reliable. Overall, it can be concluded that Table 7 shows soil contamination is a primary predictor of declining water quality in OBM-influenced regions. It also quantitatively indicates the transfer of subsurface pollutants, confirming the necessity of concomitant soil and water remediation efforts.

Table 7: Regression Results of Soil and 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

DISCUSSION

The study had shown that the drilling site experienced a significant change in the physicochemical properties at the location indicating that the oil-based mud (OBM) handling and disinjury had a strong influence on the quality and structure of the soil. The pH of 5.42 in the Zone A, and pH 6.67 in the control Zone C, suggested that strong acidification had taken place in this case and this to include acidic intermediates in its origin, and the addition of drilling additives of barite (BaSO 4), lime, and calcium chloride that are commonly used in OBM formulation. The said acidification is not only a process brought about by leaching of chemicals but also a manifestation of the microbial oxidative process which acquires the hydrocarbon-degrading bacteria to oxidize hydrocarbons to carboxylic acids, further reducing

the soil pH. Jiang, et al., (2022) and Onwuka et al. (2021) also reported similar acidification patterns, as they found that soils located close to drilling mud pits in the Niger Delta have their pH decreasing by 1 to 1.5 units as a result of long-term exposure to hydrocarbons. The electrical conductivity of Zone A (785.6 μS/cm) was higher than the conductivity of Zone C (314.2 μS/cm): this observation is indicative of accumulated soluble salts and ionic metals and charged hydrocarbon residues which increase the salinity of soil. The high values of EC are more commonly used to indicate ionic pollution, meaning that the metallic ions (Fe 2 +, Mn 2 +, and Ni 2 +) of OBM additives and by-products of corrosion have become mobile in the soil solution. Yarandi, et al., (2019) also observed high EC levels around the drilling activities, which they attributed to the influx of ions due to barite and bentonite remnants. The increased EC has the not only negative effects of changing the osmotic potential of the soil but the mobility of some of the heavy metal, thus enhancing the bioavailability and ecological hazards of these materials. The reason behind the high level of organic matter (OM) and moisture in the Zone A was attributed to either the concentration of hydrocarbons or the lack of aeration. Even though high OM is normally advantageous to the soil fertility, the application of high OM in this case can be seen as the continuation of petrogenic organic materials and not the humic materials. These oils, especially the C21-C50 type, are hydrophobic, forming non-diffusible layers on soil particles, blocking oxygen entry into soils and forming anaerobic micro-environment. This further limit the diversity of the microbes and inhibits the enzyme activities in the cycle of nutrient such as nitrogen and phosphorus mineralization. The investigation of Uzoekwe, and Oghosanine, (2011) validate the fact that the population of functional microorganisms in hydrocarbon-contaminated soils including Pseudomonas, Bacillus, and Acinetobacter is lowered dramatically, creating an ecological imbalance and limiting the potential of bioremediation. The Total Petroleum Hydrocarbon (TPH) and ΣPAHs concentrations in Zone A of 6, 582 mg/kg and 450.7mg/kg respectively were many times higher than the regulatory limits as established by Department of Petroleum Hydrocarbon (DPR) and NESREA (1, 000 mg/kg and 50mg/kg respectively). These levels of extreme concentrations categorize the soils as heavily contaminated. This suggests that higher weight fractions of hydrocarbons (C21C50) in the chromatographic profile are indicative of the high levels of waxy, long-chain alkane and polycyclic aromatic fractions characteristic of OBM residues that are poorly bio-degradable resulting in persistence over many years. This trend has been observed by Onojake, et al., (2020) who find a high level of TPH values of more than 5,000 mg/kg close to oil-well cuttings in the state of Bayelsa, and Nwankwoala and Ememu, (2018) reported the presence of high-molecular-weight hydrocarbons in the OBM-contaminated soils of the Niger Delta which cannot be degraded by micro-organisms. The fact that these substances do not disappear, reaffirms the deficiency of natural degradation in such a setting, because the heavy hydrocarbons are not easily oxidized by enzymes due to the limitation of oxygen availability during the degradation process.

The results of the heavy metals revealed remarkably high concentrations of lead (Pb = 128 mg/kg), nickel (Ni = 87 mg/kg), chromium (Cr = 72 mg/kg), and cadmium (Cd = 4.9 mg/kg) on the data entry of Zone A and values are gradually reducing to Zone C. These are metals

that are higher than the DPR and WHO acceptable levels and this shows a high level of contamination by OBM and corroded drilling parts. Especially lead and cadmium are considered to be acute and chronic risks because they are not biodegradable, and they tend to accumulate in plants and soil fauna. The decreasing slope of the heavy metals at distance indicates their limited mobility within soil as a result of being adsorbed to organic matter and clay minerals. The trend supports Onojake, et al., (2017) which have indicated large reductions in the levels of Pb and Cd other than those located near drilling waste dumps, which they attribute to adsorption and sedimentation. The soil ecosystems in Eruemokohwarien have characterized a shift of stable biogeochemical cycles in contaminated sinks that cannot sustain green agriculture or the natural vegetation.

The water quality outcomes established that drilling operations and the handling of contained oil-based mud (OBM) have had considerable impacts on aquatic environment around drilling site at the Eruemokohwarien oil platform. Zone A with its acidic PH level (5.38-6.58) and the high level of electrical conductivity (1,150 µS/cm) evidences the ionic enrichment and chemical modification of the soil caused by the percolation of the metal-contaminated waste, along with hydrocarbons waste, into the surface water and ground. This acidity of the surrounding water bodies is a typical mark of a petroleum-polluted environment because the oxidation of petroleum hydrocarbons produces organic acid, carbon dioxide, and partly oxidized intermediates, all of which cause a decrease in pH (Yarandi, et al., 2019). This gain in electrical conductivity denotes the existence of dissolved ions such as sulfate, chloride, and bicarbonate ions formed due to the decomposition of OBM additives like calcium chloride (CaCl 2) and barium sulfate (BaSO 4). Similar results were also obtained by Onojake, et al., (2020), who showed higher EC values in the areas around oil-well drilling, which they described to be due to the leaching of soluble salts and ionic metals in the drilling wastes. The low level of dissolved oxygen (DO = 3.2 mg/L) and high biochemical oxygen demand (BOD = 12.5 mg/L) detected at the end of the drilling platform are even more indicative of active organic contamination. These conditions indicate that aerobic microorganisms are using available oxygen to destroy hydrocarbons, which, consequently, leads to the removal of oxygen and the formation of hypoxic conditions causing the endangering of aquatic life. Such an oxygen stress is usually related to eutrophication and respiration of microorganisms in hydrocarbon-affected systems (Jiang, et al., 2022). This observation is corroborated by high chemical oxygen demand (COD) levels (where taken) and high turbidity amount, in which confirms the presence of significant amount of oxidizable organic matter in water near the site of drilling.

The Total Petroleum Hydrocarbon (TPH) level of 18.4mg/L and ∑PAHs of 6.8mg/L in Zone A were many folds more than the permissible level of petroleum hydrocarbons in drinking water of 0.01mg/L as recommended by the World Health Organization (WHO, 2017) and the Department of Petroleum Resources (DPR). This obviously establishes that hydrocarbons have left the OBM containment area and gotten into the neighboring aquatic systems. The heavy and light fractions indicate mixed sources with light fractions consisting of volatile compounds and heavy ones of OBM residues. Onojake, et al., (2020) also reported such a

dual-source contamination trend in their study of oilfield communities in Rivers State in which water sources surrounding drilling activities contained both dissolved volatile hydrocarbons and adsorbed heavy PAHs.

CONCLUSION

This study finds that a confined but ecologically valuable footprint of environmental degradation, due to the drilling activities in Eruemokohwarien, has been created by the use of contained oil-based mud. The findings provide indisputable evidence that the soil and water, surrounding the drilling platform have been chemically impregnated with hydrocarbon and heavy metal residues, undermining environmental quality. There was a distinct distance-decay gradient in the contamination pattern, with pollutant concentrations fading out as the distance increased. The central storage zone of the pollutants was found to be soil, through which they reach the groundwater by leaching and enter the atmosphere by volatilization. These interrelationships were statistically verified, and soil contaminants could account for as much as 89% of the variation in water. These results show that contained OBM systems, which are designed to reduce exposure to the environment, may negatively impact the environment in cases of unlined storage pits, poor maintenance, or incomplete waste recovery. It was also found that the natural attenuation capacity of the local ecosystem has been surpassed and continues to be surpassed, leading to continuous ecological stress. The study concludes by recommending strict implementation of the EGASPIN standards, the adoption of modern remediation technologies, such as thermal desorption and cuttings reinjection, and the implementation of environmental monitoring, including community participation, to ensure sustainable drilling operations and ecological restoration.

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