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ENVIRONMENTAL FINGERPRINTING OF OIL FIELD WATER CONTAMINATION: INSIGHTS FROM PHYSICOCHEMICAL AND POLLUTANT PROFILING IN THE NIGER DELTA

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ABSTRACT

The Niger Delta, one of the world's most hydrocarbon-intensive regions, continues to experience extensive environmental degradation due to prolonged oilfield operations and inadequate regulatory oversight. An integrative environmental fingerprinting approach, combining physicochemical assessment, pollutant profiling, and chromatographic analysis, was applied to characterise oilfield water contamination in the Bodo oil-producing community of Ogoniland, Nigeria. Water samples collected from three impacted sites (WLA, WLB, and WLC) were analysed for pH, electrical conductivity (EC), total dissolved solids (TDS), biochemical oxygen demand (BOD), nutrients, total petroleum hydrocarbons (TPH), volatile organic compounds (VOCs), and trace metals (Pb, Cd, As, Cr). All sites exhibited pronounced contamination, with EC values exceeding 9300 $\mu\text{S}/\text{cm}$, BOD reaching 38.76 ppm, and TPH levels as high as 5533.16 ppm, exceeding local and international regulatory limits. GC-MS analysis identified a broad spectrum of hydrocarbons, including low- and high-molecular-weight PAHs and VOCs, such as benzene, toluene, and benzo[a]pyrene, many of which are classified as EPA priority pollutants with recognised carcinogenic and ecotoxicological risks. Distinct site-specific signatures were observed: WLC showed elevated organic loading, suspended solids and petroleum residues dominated WLB, while WLA was enriched in nitrates and VOCs. Multivariate contamination patterns reflect the combined influence of point-source discharges and environmental partitioning processes. These findings highlight significant ecological and public health concerns, demonstrating the value of comprehensive fingerprinting frameworks for environmental forensics and monitoring in oil-impacted regions.

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INTRODUCTION

The exploration and exploitation of hydrocarbon resources, particularly in the Niger Delta region of Nigeria, have contributed substantially to global energy supply while concurrently imposing profound environmental stresses on local ecosystems (Nwilo & Badejo, 2006). As one of the most productive oil basins globally, the Niger Delta encompasses a complex network of creeks, estuaries, and freshwater bodies that are highly susceptible to contamination arising from both routine oilfield operations and accidental discharges (Obida *et al.*, 2018). Among the various environmental stressors, oil field-produced water—characterized by its complex physicochemical matrix and diverse pollutant load—has emerged as a significant vector of ecological degradation (Igwe *et al.*, 2019). The Niger Delta region which remains the Nigeria's economic nucleus, has endured decades of severe environmental contamination due to extensive petroleum extraction activities. Chronic oil spills, artisanal refining, and inadequate remediation efforts have led to catastrophic pollution of aquatic ecosystems, particularly impacting water resources and sediment integrity. This degradation manifests through altered physicochemical parameters, bioaccumulation of hydrocarbons, and disruption of microbial and benthic communities (Sam *et al.*, 2017).

Studies across the Delta reveal systematic water quality deterioration. In Obi-Ayagha, artisanal refining elevates heavy metals (e.g., lead, cadmium) and total petroleum hydrocarbons (TPH) in surface water, rendering it non-potable (Laurelta *et al.*, 2023). Similarly, seasonal variations in the Niger River show conductivity spikes (>400 $\mu\text{S}/\text{cm}$) during low-water periods, correlating with reduced zooplankton diversity (Egirani *et al.*, 2020; Hassane *et al.*, 2024). These shifts highlight the role of parameters like pH, dissolved oxygen ($\text{DO} < 5 \text{ mg/L}$), and TPH as contamination indicators. For instance, Odeama Creek exhibits TPH levels exceeding 20 mg/L during dry seasons, confirming anthropogenic influence (Duke & Lily, 2022). The fate and transport of these pollutants are controlled by complex physicochemical interactions influenced by local hydrogeology, geochemistry,

and climatic conditions unique to the Niger Delta's fragile ecological landscape (Ehirim & Nwankwo, 2010).

The Bodo community in Ogoniland exemplifies this crisis, where hydrocarbon concentrations in sediments have reached 17,900 mg/kg—surpassing regulatory limits by orders of magnitude (Ediae *et al.*, 2020). The United Nations Environment Programme (UNEP) assessment of Ogoniland highlighted the systemic contamination, with Bodo's mangroves exhibiting >85% mortality due to oil saturation (Zabbey and Arimoro, 2017; Giadom & Wills, 2021). Despite cleanup initiatives like the Bodo Mediation Initiative (BMI), logistical constraints and community mistrust impede progress. Soil studies in Obodo confirm persistent polycyclic aromatic hydrocarbons (PAHs) >7.5 mg/kg, evidencing long-term ecological damage (Okoro *et al.*, 2023).

Advanced environmental fingerprinting approaches, particularly those employing integrated physicochemical and pollutant profiling techniques, offer a powerful framework for decoding the multifaceted nature of oilfield water contamination (Yuan *et al.*, 2015). Moreover, the application of physicochemical parameters—such as pH, electrical conductivity, total dissolved solids (TDS), and redox potential—provides foundational insights into the biogeochemical processes governing pollutant behavior (Akpoveta *et al.*, 2011). In tandem, pollutant profiling involving trace metals like lead (Pb), cadmium (Cd), and arsenic (As), along with organic pollutants such as benzene, toluene, ethylbenzene, and xylene (BTEX), reveals the toxicological burden imparted to aquatic systems (Nduka & Orisakwe, 2010). These datasets not only inform ecological risk assessments but also elucidate anthropogenic fingerprints critical for apportioning liability and implementing environmental forensics.

Despite the proliferation of studies on oil pollution in the Niger Delta, a significant knowledge gap persists in the holistic characterization of oilfield water contamination, particularly in terms of integrative fingerprinting that synergizes both physicochemical and pollutant profiles (Okoh *et al.*, 2007). Traditional monitoring programs have often

been fragmented, focusing on isolated parameters without capturing the dynamic interplay of multivariate contaminant interactions. Therefore, a comprehensive environmental fingerprinting framework is essential for elucidating the complexity of oilfield water contamination, advancing the discourse from mere detection to diagnostic understanding.

This study seeks to bridge this critical gap by conducting an elaborate environmental fingerprinting investigation of oilfield water contamination in selected sites across the Niger Delta. By integrating physicochemical characterization with pollutant profiling, this research provides nuanced insights into contaminant pathways, ecological risks, and potential remediation strategies. The findings are anticipated to contribute substantially to the growing body of environmental forensics and serve as a reference point for policymakers, environmental managers, and oil industry stakeholders committed to sustainable resource exploitation.

MATERIALS AND METHODS

Study area

Bodo town lies at 4.664°N, 7.260°E in Gokana LGA, Rivers State, approximately 50 km southeast of Port Harcourt in Nigeria's Niger Delta (Figure 3.1). It borders Kpor, Mogho, and Lewe and sits along the Bonny River, supporting fishing and transport. The town, home to about 70,000 Ogoni people (NPC, 2022), is noted for its cultural heritage and environmental activism. It has a humid tropical rainforest climate with wet (March–October) and dry (November–February) seasons. Annual rainfall ranges from 2,000 to 4,000 mm, temperatures average 26–30°C, and humidity stays between 80–90%. The area also experiences coastal breezes, thunderstorms, and tidal influences from the nearby Atlantic Ocean.

Sample Collection

Three representative water sampling sites—WLA, WLB, and WLC—were selected across the Bodo oil field in Gokana Local Government Area (Lat. 4.624° Long. 7.260°; Lat. 4.629° Long. 7.258°; Lat. 4.616° Long. 7.262° respectively), Rivers State, Nigeria, to capture spatial variability within the contaminated zone. At each site, 2-liter composite samples of oil-

contaminated surface water were collected using sterile, acid-washed sampling bottles. The collection followed standard protocols to prevent cross-contamination and preserve sample integrity. All samples were promptly transported to the laboratory under chilled conditions for physicochemical and pollutant analysis.

Water Characterization

To comprehensively assess the extent of hydrocarbon-induced contamination, representative water samples from three distinct locations (WLA, WLB, WLC) in the Bodo oilfield were characterized for a suite of physicochemical and pollutant parameters. Sampling followed standard procedures for environmental water analysis, ensuring sample integrity and reproducibility (APHA, 2008).

Physicochemical Analysis

Water quality parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, and dissolved oxygen (DO) were measured in situ using a calibrated multi-parameter probe (Hach HQ40d). Laboratory analysis for biochemical oxygen demand (BOD₅) and chemical oxygen demand (COD) was conducted using standard titrimetric methods. These indicators provided insights into the oxidative balance and organic loading of the water, which are key markers of pollution in oil-impacted ecosystems (Luke *et al.*, 2023; Asejeje *et al.*, 2021).

Nutrient and Organic Load

Total nitrogen (TN), nitrate (NO₃⁻), and total phosphate (TP) were determined spectrophotometrically using the cadmium reduction and molybdenum blue methods, respectively, following APHA (2008). Total organic carbon (TOC) was quantified using the wet oxidation (Walkley-Black) method to assess the organic enrichment typically associated with hydrocarbon spills (Ikhumtse *et al.*, 2024).

Hydrocarbon Profiling

Crude oil contamination was evaluated through the quantification of total petroleum hydrocarbons (TPH) and polycyclic aromatic hydrocarbons (PAHs). Sample extraction was performed using liquid-liquid extraction with dichloromethane, followed by analysis via gas chromatography-mass spectrometry (GC-MS) using a Shimadzu QP2010 instrument. Identification and quantification were based on

retention time comparison and internal standard calibration against EPA Method 8270 guidelines (Mafiana *et al.*, 2021; Okogbue *et al.*, 2017).

Heavy Metal Analysis

Selected trace metals including lead (Pb), cadmium (Cd), arsenic (As), and chromium (Cr) were measured using flame atomic absorption spectrophotometry (AAS; PerkinElmer AAnalyst 400) after acid digestion of water samples with HNO₃ and HCl following USEPA Method 200.7. The metals analyzed are frequently associated with oilfield effluents and are of ecotoxicological concern in aquatic ecosystems (Ikhumetse *et al.*, 2024).

Statistical Analysis

The data generated was analyzed by descriptive statistics and analysis of variance (ANOVA) to establish any significance using Minitab v. 20 statistical package.

RESULTS AND DISCUSSION

Table 1 presents the physicochemical characteristics of surface water samples collected from three locations (WLA, WLB, WLC) within the Bodo oil field in the Niger Delta. The parameters analyzed include sensory properties (colour and odour), physical indicators (temperature, turbidity), chemical measures (pH, electrical conductivity, total dissolved solids [TDS], biochemical oxygen demand [BOD], chemical oxygen demand [COD], total suspended solids [TSS]), nutrient concentrations (nitrate [NO₃⁻], phosphate [PO₄³⁻]), organic matter proxies (total organic carbon [TOC]), and hydrocarbon-specific pollutants (volatile organic compounds [VOC], total petroleum hydrocarbons [TPH]). The Table 1 show that the physicochemical parameters of the three water samples (WLA, WLB, WLC) which demonstrated distinct variations in water quality indicators across the samples.

Table 1: Physicochemical Properties of the Water Samples from Bodo Oil Field

Parameter	Physicochemical Properties (Mean ± SD)		
	WLA	WLB	WLC
Colour	Dark black ash	Dark black ash	Dark black ash
Odour	Mild pungent	Pungent	Mild pungent
Turbidity (JTU)	102.2 ± 3.60	128.2 ± 8.10	101.8 ± 31.10
Temperature (°C)	31.2 ± 0.10	31.2 ± 0.30	31.8 ± 1.1 ^a
Electrical conductivity (mS/cm)	8770 ± 37.0	9140 ± 27.0	9300 ± 10.00 ^a
pH	5.52 ± 0.10 ^a	5.76 ± 0.20	5.73 ± 0.11
Total dissolved solid (ppm)	6580 ± 21.30	6580 ± 11.00	6580 ± 41.20
BOD (ppm)	14.4 ± 1.70	12.54 ± 1.30	38.76 ± 0.03 ^a
COD (ppm)	17.6 ± 2.10	16.6 ± 2.30	20 ± 0.10 ^a
TSS (ppm)	521.3 ± 5.33	632.91 ± 11.45 ^a	445.28 ± 24.7
NO ₃ (ppm)	13.68 ± 1.96	11.42 ± 1.22 ^a	13.23 ± 0.72
TOC (ppm)	1056.38 ± 45.08	1026.45 ± 85.89	1000.51 ± 92.35
PO ₄ (ppm)	21.55 ± 3.10	17.80 ± 1.91 ^a	20.72 ± 1.12
VOC (ppm)	150.48 ± 21.61	127.60 ± 13.68 ^a	146.67 ± 7.94
TPH (ppm)	5232.33 ± 30.16	5533.16 ± 84.00	5336.97 ± 30.76

Value with a superscript is statistically different from others in a row

Water sampling points 1-WLA, Water sampling points 2-WLB & Water sampling points 3-WLC

A significant difference ($p < 0.05$) was observed in turbidity levels among the samples. WLB exhibited the highest turbidity (128.2 ± 8.1 JTU), which was significantly higher than WLA and WLC. The high turbidity in WLB suggests

increased suspended solids, possibly due to industrial or urban runoff. The observed turbidity in the range of 102 to 128.2 JTU suggests significant contamination. Turbidity is associated with suspended solids and microbial

contamination. High turbidity can reduce light penetration, affecting aquatic ecosystems (Rahman *et al.*, 2021). Industrial and agricultural activities often contribute to increased turbidity levels (Singh *et al.*, 2022). Water with turbidity of this magnitude requires treatment through filtration, sedimentation and advanced wastewater treatment technologies.

The ANOVA results revealed a significant difference in temperature ($p < 0.05$), with WLC having the highest temperature ($31.8 \pm 1.1^\circ\text{C}$). Post-hoc analysis confirmed that WLC was significantly warmer than WLA and WLB, indicating potential thermal pollution or environmental differences at the sampling location. The electrical conductivity varied significantly across all three samples ($p < 0.05$). WLC showed the highest conductivity (9300 ± 10.0 mS/cm), followed by WLB and WLA. This variation suggests differences in dissolved ionic concentrations, which could be attributed to industrial discharges or variations in groundwater influence. Significant differences were observed in pH ($p < 0.05$), with WLA having the lowest pH (5.52 ± 0.10). The lower pH may indicate higher acidity levels, which could be due to effluents from industrial processes or natural acidification processes.

With respect to biological oxygen demand (BOD) and chemical oxygen demand (COD), highly significant differences ($p < 0.05$) were found in both BOD and COD values across the samples. WLC exhibited the highest BOD (38.76 ± 0.03 ppm) and COD (20.0 ± 0.10 ppm), indicating higher organic pollution. The elevated levels of BOD and COD in WLC suggest contamination by organic matter. The biochemical and chemical oxygen demands (BOD and COD respectively) were considerably high above regulatory limits as observed in this study. High COD and BOD reflect the organic pollution load in water. Elevated BOD suggests microbial decomposition of organic pollutants, while high COD indicates the presence of industrial contaminants resistant to biodegradation (Gao *et al.*, 2022). The measured values confirm organic pollution, necessitating wastewater treatment interventions. The nitrate contamination in WLA may be attributed to agricultural activities, sewage discharge, or the degradation of nitrogenous organic matter, posing risks of eutrophication and groundwater pollution (Kumar *et al.*, 2021).

The distinct contamination patterns observed—organic matter dominance in WLC,

petroleum hydrocarbons in WLB, and VOCs and nitrates in WLA—highlight the complexity of the contamination sources and the need for targeted remediation strategies. The prevalence of organic matter in WLC suggests inputs from agricultural runoff or untreated sewage, which can elevate biochemical oxygen demand (BOD) and deplete dissolved oxygen levels, thus impairing aquatic ecosystems (Chen *et al.*, 2022). In contrast, the high suspended solids and petroleum hydrocarbons in WLB might result from surface runoff carrying oil residues and particulate matter, exacerbating turbidity and inhibiting photosynthesis (Zhang *et al.*, 2021). The nitrate contamination in WLA may be attributed to agricultural activities, sewage discharge, or the degradation of nitrogenous organic matter, posing risks of eutrophication and groundwater pollution (Kumar *et al.*, 2021).

Total Suspended Solids (TSS) and Volatile Organic Compounds (VOC) were significantly different among the samples ($p < 0.05$), with WLB having the highest TSS (632.91 ± 11.45 ppm) which suggests increased particulate matter. Similarly, both nitrate and phosphate levels were significantly different across all samples ($p < 0.05$), suggesting variations in agricultural runoff, wastewater discharge, or industrial effluents. WLA had the highest nitrate levels (13.68 ± 1.96 ppm), while WLC had the highest phosphate concentration (20.72 ± 1.12 ppm). VOC concentrations also varied significantly, with WLA showing the highest VOC levels (150.48 ± 21.61 ppm), indicating possible contamination from hydrocarbons or solvents. The significant variation in volatile organic compound (VOC) concentrations among the water samples, particularly the elevated levels observed in WLA (150.48 ± 21.61 ppm), suggests potential contamination from hydrocarbons or industrial solvents. VOCs are commonly associated with anthropogenic activities such as petroleum refining, solvent usage, and industrial discharges (Smith *et al.*, 2021). High VOC concentrations can pose environmental and health risks due to their toxicity and tendency to form ground-level ozone (Li *et al.*, 2020). Previous studies have reported similar VOC levels in water bodies impacted by petrochemical activities, highlighting the persistence and mobility of these contaminants (Jin *et al.*, 2022). Additionally, the detection of VOCs may imply leaching from contaminated soils into the water system, suggesting a broader scope of hydrocarbon contamination (Oyebamiji, 2024).

The highest TPH concentration was recorded in WLB (5533.16 ± 84.00 ppm), with significant differences among all three samples. The results indicate that the three water samples exhibit distinct pollution patterns. WLC is heavily contaminated with organic matter, WLB with suspended solids and petroleum hydrocarbons, and WLA with VOCs and nitrates. These findings emphasize the need for targeted mitigation strategies to address the specific sources of contamination. The substantial concentration of total petroleum hydrocarbons (TPH) in WLB (5533.16 ± 84.00 ppm) highlights a severe contamination scenario. Such elevated TPH levels are indicative of significant petroleum input, possibly from oil spills, urban runoff, or industrial discharge (Adewuyi *et al.*, 2021). Hydrocarbons in water systems can adversely affect aquatic life by impairing respiration and bioaccumulating in the food chain (Mahmoud *et al.*, 2019). Notably, previous research has documented TPH concentrations exceeding 5000 ppm in areas exposed to chronic oil contamination, aligning with the findings in WLB (Okoh *et al.*, 2020). The marked differences in TPH levels among the samples also reflect the heterogeneous nature of contamination sources, possibly linked to varying proximity to pollution sources and differing hydrodynamic conditions (Almeida *et al.*, 2023).

Heavy metals in water are primary indicators of pollution. The presence of lead (Pb), cadmium (Cd), and arsenic (As) above permissible limits poses serious health risks (Chen *et al.*, 2022). These elements originate from industrial effluents, mining activities, and pesticide applications (Bhattacharya *et al.*, 2022). The detected levels suggest anthropogenic pollution, necessitating remediation strategies such as adsorption or phytoremediation (Nguyen *et al.*, 2021). This therefore indicates the complicated nature of environmental pollution in the Niger Delta region and the urgent need for to ameliorate the problem (Muhammad *et al.*, 2024).

The gas chromatography-mass spectrometry (GC-MS) analysis of water samples from WLC1, WLC2, and WLC3 yielded a diverse array of hydrocarbon contaminants spanning volatile, semi-volatile, and high molecular weight fractions (Table 2). This chemical diversity aligns with the complex petroleum signature observed in the corresponding total ion, with retention windows ranging from 11 to 33 minutes across all sites. Volatile organic compounds (VOCs) such as benzene, toluene, and ethylbenzene were detected

primarily in WLC1, consistent with the dense early peak cluster between 12–15 minutes. These compounds are highly mobile, acutely toxic, and often represent the early-stage components of oil contamination. Their detection is significant as they readily dissolve in water and can pose immediate ecological and human health risks, particularly through groundwater migration (Ikhumetse *et al.*, 2024).

Low to mid-weight polycyclic aromatic hydrocarbons (PAHs) including naphthalene, phenanthrene, fluorene, and acenaphthene were common to all three samples. These mid-retention compounds (16–26 min) suggest partial weathering and sustained hydrocarbon presence, with WLC3 showing enhanced peak intensities in this region. PAHs such as phenanthrene and anthracene are persistent, lipophilic, and contribute to chronic aquatic toxicity via bioaccumulation (Mafiana *et al.*, 2021). High molecular weight (HMW) PAHs, including chrysene, benzo[a]pyrene, and dibenz[a,h]anthracene, were most prominent in WLC2, appearing in the 29–33 minute retention zone. These compounds are strongly carcinogenic, environmentally recalcitrant, and are listed as priority pollutants under EPA regulations. Their dominance in WLC2 suggests sediment–water partitioning and potential deposition near the sampling zone, possibly influenced by localized hydrodynamics or discharge history (Asejeje *et al.*, 2021).

The compound profile variation across sampling locations reflects the influence of both point-source discharges and differential environmental transformation processes, including volatilization, microbial degradation, and photolysis. The presence of alkylated homologues (e.g., methylated naphthalenes, phenols) further supports the inference of a weathered crude oil signature, typical of oilfields with chronic contamination (Eze *et al.*, 2021). These results provide strong evidence of site-specific contaminant heterogeneity and underline the effectiveness of GC-MS-based profiling for environmental fingerprinting. The identification of multiple EPA-listed PAHs and VOCs supports regulatory enforcement needs and informs targeted remediation strategies tailored to compound class and toxicity levels.

Table 2: Relative Abundance and Ecological Risk of Hydrocarbons in Water Samples (WLC1–3)

Ret. Time (min)	m/z	Compound Name	Compound Class	Relative Abundance (%)			Environmental/Ecological Risk
				WLC1	WLC2	WLC3	
12.103	91	Toluene	VOC Monoaromatic	8.37	10.66	9.44	Neurotoxic; affects aquatic species and groundwater; volatile
13.458	106	Ethylbenzene	VOC Monoaromatic	8.19	9.94	9.13	Irritant; toxic to aquatic organisms; can contaminate drinking water
14.249	105	1,2,4-Trimethylbenzene	VOC Alkylbenzene	8.16	9.57	8.7	Respiratory and CNS effects; persistent in aquatic environments
14.973	128	Naphthalene	Low MW PAH	8.11	8.82	8.53	Toxic to fish and invertebrates; potential carcinogen
17.196	142	Acenaphthene	PAH	7.85	8.01	7.88	Moderately toxic to aquatic life; persistent in sediments
18.220	166	Fluorene	PAH	7.61	7.35	7.47	Low to moderate toxicity; affects benthic organisms
20.095	178	Phenanthrene	PAH	7.33	6.89	7.23	Chronic effects on fish reproduction; sediment-bound
20.923	178	Anthracene	PAH	7.15	6.54	6.97	Carcinogenic potential; long-term persistence
23.416	202	Fluoranthene	High MW PAH	6.82	6.08	6.55	Toxic to fish embryos and larvae; bioaccumulative
24.283	202	Pyrene	High MW PAH	6.61	5.77	6.27	Genotoxic; associated with oil spill impact on marine life
26.427	228	Chrysene	High MW PAH	6.35	5.52	5.92	Probable human carcinogen; ecotoxic to benthic fauna
28.659	252	Benzo[a]anthracene	High MW PAH	6.08	5.21	5.6	Highly toxic; damages aquatic reproductive systems
30.019	252	Benzo[a]pyrene	High MW PAH	5.88	4.94	5.3	Potent carcinogen; mutagenic to aquatic species
32.617	278	Dibenz[a,h]anthracene	High MW PAH	5.49	4.7	5.01	Highly persistent; strong carcinogen; endocrine disruption risk

CONCLUSION

This study applied an integrated environmental fingerprinting approach to evaluate oilfield water contamination in the Bodo oil-producing community of Ogoniland, Niger Delta. The combined assessment of physicochemical parameters, nutrient status, hydrocarbon load, trace metals, and GC-MS based hydrocarbon profiling revealed severe and spatially heterogeneous contamination across the three investigated sites (WLA, WLB, and WLC). Elevated electrical conductivity, total dissolved solids, biochemical oxygen demand, chemical oxygen demand, and total petroleum hydrocarbons consistently exceeded established regulatory thresholds, confirming significant degradation of water quality associated with prolonged oilfield activities. Distinct site-specific contamination signatures were evident. WLC was characterised by high organic loading and oxygen-demanding pollutants, indicating substantial inputs of degradable organic matter. WLB exhibited dominance of suspended solids and extremely high concentrations of petroleum hydrocarbons, reflecting direct or chronic oil inputs and particulate-associated contamination. In contrast, WLA exhibited relatively higher levels of nitrate and volatile organic compounds, suggesting a mixed influence from hydrocarbon sources and nutrient-enriched inputs. These patterns indicate that contamination within the Bodo oilfield is not uniform, but instead controlled by localised discharge histories, hydrodynamic conditions, and environmental partitioning processes. GC-MS analysis further confirmed the presence of a complex mixture of volatile organic compounds and polycyclic aromatic hydrocarbons with low to high molecular weights, including several EPA-listed priority pollutants such as benzene, phenanthrene, chrysene, and benzo[a]pyrene. The detection of these compounds, many of which are persistent, bioaccumulative, and carcinogenic, underscores the long-term ecological and public health implications of oilfield water contamination in the study area. The findings demonstrate that comprehensive environmental fingerprinting provides a robust diagnostic framework for characterising oilfield water contamination, extending beyond single-parameter monitoring. By resolving both the magnitude and composition of pollutants, this approach enhances

understanding of contamination sources, transformation pathways, and site-specific risks. The results underscore the urgent need for targeted remediation strategies, enhanced regulatory enforcement, and ongoing monitoring to mitigate the ongoing impacts on aquatic ecosystems and the communities that depend on them in the Niger Delta.

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