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Research article

IMPACT OF CRUDE OIL REMEDIATION ON SOIL FERTILITY IN KHANA LOCAL GOVERNMENT AREA, RIVERS STATE, NIGERIA

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ABSTRACT

Crude oil contamination degrades soil physicochemical, microbial, and structural properties, yet the effectiveness of remediation exercises carried out in response to oil spillage in Ogoniland, Rivers State, has rarely been evaluated against unimpacted control soils using a common analytical framework. This study evaluated the physicochemical, heavy metal, and microbial properties of crude oil-remediated soils in Kwawa and Kpean communities, Khana Local Government Area, Rivers State, Nigeria, in comparison with adjoining unimpacted soils that served as controls, to ascertain the impact of the remediation exercise on soil fertility. Sixteen composite soil samples were collected from eight sampling stations, three remediated stations and one control station in each community, at two depths (0-15 cm and 15-30 cm), and analysed for physicochemical parameters, heavy metals, polycyclic aromatic hydrocarbons (PAHs), total petroleum hydrocarbons (TPH), and microbial counts following American Public Health Association (APHA) standard methods. Data were analysed using descriptive statistics and one-way analysis of variance (ANOVA) at the .05 significance level, and results were benchmarked against Department of Petroleum Resources (DPR, 2002) and FAO/WHO (2011) limits. Soil pH was acidic (4.99-5.83) and mostly within permissible limits, electrical conductivity (37.62-84.47 microS/cm) remained well below regulatory limits, and cadmium, zinc, and lead concentrations at all stations remained below their respective DPR and FAO/WHO limits, while iron concentrations exceeded the FAO/WHO limit of 200 mg/kg at a minority of stations, including the most contaminated remediated station (381.402 mg/kg). Total PAH and TPH levels were below DPR intervention values at all stations, and total heterotrophic bacteria counts were consistently higher at remediated stations than at controls, indicating active microbial recovery. ANOVA showed statistically significant differences between stations for most parameters ($p < .05$), except organic carbon, organic matter, and one exchangeable cation at each depth. The study concludes that the remediation exercise has been largely effective in restoring soil quality in the affected communities and recommends that the quality of remediation work be sustained and further improved, with continued monitoring of iron levels at the more contaminated stations.

KEYWORDS

Crude oil remediation; Soil fertility; Heavy metals; Total petroleum hydrocarbons; Polycyclic aromatic hydrocarbons; Khana; Rivers State; Nigeria

INTRODUCTION

Crude oil has significantly contributed to Nigeria's Gross Domestic Product, serving as a major source of foreign exchange, energy, and industrial raw material. However, oil extraction in the Niger Delta region has had severe adverse effects on the environment, posing threats to the subsistence peasant economy, the physical environment, and the overall livelihood of host communities (Eni & Okpiliya, 2011).

The impact of crude oil contamination on soil fertility is profound and extends well beyond immediate environmental concerns. Crude oil contains a wide range of hydrocarbons and toxic substances capable of altering the physical, chemical, and biological properties of soil (Victor et al., 2020), disrupting nutrient cycling and availability (Orisakwe, 2021), impeding the microbial activity responsible for organic matter breakdown (Cusack et al., 2011), and altering soil structure and texture in ways that compromise water retention and drainage (Shaheen et al., 2014). Compromised soil fertility, in turn, directly threatens agricultural productivity and the livelihoods of communities that depend on farming for sustenance.

A considerable body of research, reviewed in detail in the following section, has documented how hydrocarbon pollution degrades soil quality globally and across the Niger Delta specifically, and has proposed a range of remediation techniques intended to restore contaminated soils. What this literature has documented less consistently is whether such remediation techniques actually succeed, once implemented in the field, in returning soil physicochemical, heavy metal, and microbial properties to levels comparable with unimpacted soils.

This question is particularly pressing in Khana Local Government Area (LGA) of Rivers State, an area long recognised for its agricultural significance within the regional food production system (Dummene, 2023), but whose productive landscape faces a significant threat from crude oil contamination arising from oil extraction and exploration activities (Nwozor, 2020). The Kpean and Kwawa communities within Khana LGA have been disproportionately affected by recurrent oil spillage and have since undergone remediation, yet the efficacy of this remediation exercise, evaluated against unimpacted control soils within the same communities, remains a subject requiring in-depth investigation.

This study therefore sought to evaluate the impact of crude oil remediation on soil fertility potential in Kpean and Kwawa communities, Khana LGA. Specifically, the study set out to compare the physicochemical properties, heavy metal concentrations, polycyclic aromatic hydrocarbon and total petroleum hydrocarbon levels, and microbial counts of remediated soils against unimpacted control soils, and to benchmark these properties against regulatory limits, so as to determine whether the remediation exercise has been effective in restoring soil fertility in the affected communities.

LITERATURE REVIEW

Global Evidence on Hydrocarbon Contamination and Soil Remediation

International research has established that oil spillage, whether from well blow-outs, tanker accidents, pipeline rupture, or the dumping of used petroleum products, releases hydrocarbons into soil and water with wide-ranging consequences (Mnif et al., 2017), and that a small but persistent fraction of total oil produced, estimated at 0.08-0.46%, is continuously spilled into the environment worldwide (Saravana & Amruta, 2013). Numerous studies have documented the mechanisms by which such contamination degrades soil quality: hydrocarbon pollutants alter the physical, chemical, and biological properties of soil (Okoh et al., 2020), suppress the microbial communities responsible for organic matter decomposition and nutrient release (Cusack et al., 2011; Dos Santos & Maranho, 2018), and, at sufficient concentration, threaten wildlife and the food chain (Albert et al., 2018).

In response, a range of remediation technologies, including bioremediation, phytoremediation, and physicochemical treatment, has been developed and comparatively reviewed (Lim et al., 2016; Ossai et al., 2020; Odukoya, Lambert, & Sakrabani, 2019). This literature broadly agrees that remediation can substantially reduce hydrocarbon and heavy-metal burdens in contaminated soils, restoring conditions conducive to microbial activity and plant growth (Shaheen et al., 2014; Dos Santos & Maranho, 2018), but it also agrees that the degree of success achieved varies considerably with site conditions, contamination history, and the specific remediation technique applied, so that the outcome of any given remediation exercise cannot be assumed and must be verified empirically against unimpacted reference soils.

Regional and African Evidence

Within the Niger Delta, oil exploration and exploitation activities have had disastrous social and physical environmental consequences for host communities (Eni & Okpiliya, 2011), with spillages in soil, rivers, creeks, ponds, and wells contributing to the scarcity of arable soils and clean drinking water and to health problems such as diarrhoea and dysentery among affected populations (Albert et al., 2018). Orisakwe (2021) and Ukhurebor, Athar, Adetunji, Aigbe, Onyancha, and Abifarin (2021) have both reviewed the public-health and environmental implications of petroleum spillage in the region, underscoring that soil fertility degradation in oil-affected communities carries direct socio-economic consequences where agriculture remains the dominant livelihood, while also encompassing broader ecological concerns such as biodiversity loss and ecosystem disruption (Nwokoro & Chima, 2018).

Evaluations of on-shore remediation operations in the Niger Delta have raised concerns about their consistency and thoroughness (Eni & Okpiliya, 2011), and broader assessments of environmental governance in Ogoniland have questioned how comprehensively remediation commitments have been implemented on the ground (Nwozor, 2020). At the same time, comparative studies of Nigerian soils affected by oil and other contaminants have generated a body of reference values, for pH, electrical conductivity, cation exchange capacity, and heavy metals, against which newly remediated sites can be benchmarked (Onwuka, Eboatu, Ajiwe, & Morah, n.d.; Nnaji & Chukwu, 2020; Libo et al., 2018; Okechukwu, Onwukeme, Eze, & Aralu, 2024).

Local Research Gap

Despite this substantial regional literature on the causes and consequences of oil contamination, and despite Khana LGA's recognised agricultural importance and its status as a flashpoint of recurrent oil spillage (Dummene, 2023; Needam, Wokocha, & Kamalu, 2020), no study has directly compared the physicochemical, heavy metal, and microbial condition of remediated soils in Kpean and Kwawa communities against unimpacted control soils within the same communities using a common analytical framework. The present study therefore addresses this gap by evaluating, station by station and depth by depth, whether the remediation exercise carried out in these two communities has restored soil properties to levels comparable with, or better than, adjoining unimpacted soils.

METHODOLOGY

Study Area

The study was conducted in Kpean and Kwawa communities, Khana Local Government Area (LGA) of Rivers State, Nigeria, situated between latitudes 4°33'30" and 4°49'22" North and longitudes 7°19'11" and 7°31'09" East. Khana LGA is one of four local government areas in Ogoniland, sharing boundaries with Oyigbo, Opobo-Nkoro, Akwa Ibom State, and Gokana to the north, south, east, and west respectively, and, with a total area of about 575 km², is the largest local government area in Ogoniland, covering approximately 56% of its total land area. The terrain is nearly level, with gentle, undulating slopes intersected by shallow valleys that carry water intermittently (Needam et al., 2020). Kpean and Kwawa were selected because they have been disproportionately affected by recurrent oil spillage and are emblematic flashpoints of soil pollution in the region, making them pertinent sites for evaluating remediation outcomes.

Research Design

A comparative survey design was adopted, in which soil properties at remediated sites, where crude oil remediation activity had taken place, were systematically compared with soil properties at adjoining unimpacted sites within the same communities, which served as controls, to isolate the effect of the remediation exercise on soil fertility.

Data Collection

Within each remediated site, a 50 m x 50 m perimeter was measured and marked out, and six sampling spots were randomly selected and composited into three representative sampling stations (ST1-ST3) at each of two soil depths, surface (0-15 cm) and subsurface (15-30 cm), using a hand auger. Within each corresponding unimpacted site, two sampling spots were randomly selected and composited into one control station (ST4) at the same two depths. This procedure was applied independently in both Kwawa and Kpean communities, yielding eight sampling stations in total (four per community) and sixteen composite soil samples across both depths. Samples were placed in clean Teflon bottles immediately after collection, preserved in a plastic cooler, and transported to the laboratory for analysis. Physicochemical parameters were analysed following American Public Health Association (APHA, 2005) standard methods. Cadmium, zinc, lead, and iron concentrations were determined by atomic absorption spectrophotometry. Total petroleum hydrocarbons were determined by solvent extraction (Soxhlet extraction or sonication in hexane or a hexane-acetone mixture), followed by concentration, clean-up, and analysis by gas chromatography with flame ionisation or mass-spectrometric detection. Polycyclic aromatic hydrocarbons were extracted following APHA Method 6440B, using 24-hour Soxhlet extraction in a dichloromethane-acetone mixture, clean-up by column chromatography, and quantification by gas chromatography-mass spectrometry against reference standards. Soil microbial properties were assessed by culturing soil dilutions on selective and differential media to enumerate bacteria, fungi, actinomycetes, and archaea, with colony-counting techniques used to derive total heterotrophic bacteria and faecal coliform counts. Quality control, including blank and spiked samples, was applied throughout the analytical procedures.

Data Analysis

Data were summarised using means and descriptive statistics and compared against values recorded at the control stations and against Department of Petroleum Resources (DPR, 2002) target and intervention values and FAO/WHO (2011) limits for the respective parameters. One-way analysis of variance (ANOVA) was used to test for statistically significant differences among stations at each depth, at the .05 level of significance, and Pearson's correlation analysis was used to examine the relationships among the physicochemical, heavy metal, and textural parameters measured.

RESULTS

Soil Physicochemical Characteristics

Table 1 summarises the range of physicochemical parameters recorded across the eight sampling stations at both depths. Soil pH ranged from 5.02 to 5.73 at the 0-15 cm depth and from 4.99 to 5.83 at the 15-30 cm depth, indicating consistently acidic soils across both remediated and control stations. Electrical conductivity, organic carbon, organic matter, total nitrogen, available phosphorus, the exchangeable cations, cation exchange capacity, and the sand, silt, and clay fractions all varied across stations, with no single, consistent direction of difference between remediated and control stations across all parameters; instead, remediated stations exceeded their corresponding control on some parameters and fell below it on others, a pattern explored further in the discussion.

Table 1. Range of soil physicochemical parameters across sampling stations at two depths in Kwawa and Kpean communities

Parameter	Unit	0-15 cm Range (Mean +/- SD)	15-30 cm Range (Mean +/- SD)
pH	-	5.02+/-0.17 - 5.73+/-0.17	4.99+/-0.09 - 5.83+/-0.27
Electrical conductivity	microS/cm	51.73+/-6.93 - 84.47+/-3.10	37.62+/-5.35 - 79.79+/-2.92
Organic carbon	%	1.11+/-0.66 - 2.03+/-0.94	1.09+/-0.84 - 1.89+/-0.52
Organic matter	%	2.16+/-0.33 - 2.96+/-0.37	2.25+/-0.89 - 2.97+/-0.81
Total nitrogen	%	0.02+/-0.01 - 0.04+/-0.01	0.01+/-0.00 - 1.83+/-0.41
Available phosphorus	mg/kg	9.64+/-0.41 - 12.89+/-0.43	8.68+/-1.15 - 20.67+/-1.00
Exchangeable calcium	cmol/kg	0.71+/-0.20 - 1.41+/-0.54	0.59+/-0.04 - 2.87+/-4.30
Exchangeable magnesium	cmol/kg	1.70+/-0.35 - 3.57+/-0.22	1.64+/-0.28 - 3.61+/-0.31
Exchangeable potassium	cmol/kg	0.04+/-0.01 - 0.33+/-0.44	0.04+/-0.01 - 0.09+/-0.02
Exchangeable sodium	cmol/kg	0.20+/-0.02 - 0.34+/-0.04	0.18+/-0.03 - 0.36+/-0.39
Cation exchange capacity	cmol/kg	2.31+/-0.03 - 4.67+/-0.14	2.17+/-0.21 - 4.92+/-0.25
Sand	%	77.68+/-2.29 - 88.28+/-0.25	74.90+/-2.06 - 88.90+/-0.96
Silt	%	4.31+/-0.67 - 8.60+/-1.15	4.63+/-0.69 - 11.80+/-1.20
Clay	%	5.00+/-0.22 - 14.75+/-0.66	5.75+/-0.39 - 15.86+/-0.39

Heavy Metal Concentrations

Table 2 shows the range of cadmium, zinc, lead, and iron concentrations recorded across stations at both depths, alongside the DPR (2002) target and intervention values and the FAO/WHO (2011) limits for each metal. Cadmium, zinc, and lead concentrations remained below their respective target, intervention, and FAO/WHO limits at every station and depth. Iron concentrations, for which the FAO/WHO (2011) limit is 200 mg/kg, remained below this limit at most stations but exceeded it at a minority of stations, including the most contaminated station, KWAWA ST1, which recorded 381.402 mg/kg at the 0-15 cm depth.

Table 2. Range of heavy metal concentrations across sampling stations at two depths, compared with DPR (2002) and FAO/WHO (2011) limits

Metal	0-15 cm Range (mg/kg)	15-30 cm Range (mg/kg)	DPR Target / Intervention (mg/kg)	FAO/WHO Limit (mg/kg)
Cadmium (Cd)	0.027+/-0.003 - 0.071+/-0.003	0.035+/-0.005 - 0.066+/-0.002	0.8 / 12	1
Zinc (Zn)	0.039+/-0.003 - 0.148+/-0.004	0.094+/-0.005 - 0.327+/-0.006	140 / 720	200

Metal	0-15 cm Range (mg/kg)	15-30 cm Range (mg/kg)	DPR Target / Intervention (mg/kg)	FAO/WHO Limit (mg/kg)
Lead (Pb)	0.711+/-0.006 - 1.127+/-0.020	0.189+/-0.009 - 0.793+/-0.011	85 / 530	50
Iron (Fe)	3.263+/-0.613 - 381.402+/-19.855	11.636+/-0.639 - 322.822+/-4.726	-	200

Soil Microbial Counts

Total heterotrophic bacteria (THB) counts ranged from 1.205x10^7 cfu/g at the 0-15 cm depth to between 3.915x10^5 and 6.610x10^7 cfu/g at the 15-30 cm depth, and were consistently higher at the remediated stations in both Kwawa and Kpean than at their respective control stations, at both depths, indicating active microbial recovery at the remediated sites. Faecal coliform counts ranged from 3.100x10^4 to 2.063x10^5 cfu/g at the 0-15 cm depth and from 1.593x10^4 to 4.623x10^4 cfu/g at the 15-30 cm depth. Fungal counts showed a more mixed pattern, with control stations recording higher counts than remediated stations at most depths and locations. The THB pattern observed here is consistent with Ogunmwonyi, Igbinosa, Aiyegoro, and Odjadjare (2008), who similarly reported elevated heterotrophic bacterial activity in hydrocarbon-influenced soils undergoing natural attenuation.

Polycyclic Aromatic Hydrocarbons

Of the sixteen individual PAH congeners assessed, only naphthalene, acenaphthylene, and pyrene were consistently detected at quantifiable concentrations across all eight stations, each in the low parts-per-million range (naphthalene 0.000164-0.000293 ppm; acenaphthylene 0.000089-0.000866 ppm; pyrene 0.000046-0.000180 ppm); acenaphthene, fluorene, anthracene, chrysene, and the benzo-fused ring compounds were detected only sporadically, at single stations, or not at all. Total PAH concentrations, summarised in Table 3, ranged from 0.000939 to 0.001439 ppm at the 0-15 cm depth and from 0.000842 to 0.001669 ppm at the 15-30 cm depth. Against the DPR (2002) target value of 1 ppm and intervention value of 40 ppm for total PAH in soil, all eight stations at both depths recorded total PAH levels several orders of magnitude below the target value, indicating no measurable risk of PAH toxicity at any station.

Table 3. Total polycyclic aromatic hydrocarbon (PAH) concentrations (ppm) across sampling stations at two depths

Station	0-15 cm (ppm)	15-30 cm (ppm)
Kwawa ST1	0.001118	0.001062
Kwawa ST2	0.001144	0.001365
Kwawa ST3	0.001025	0.000914
Kwawa ST4 (Control)	0.001067	0.001152
Kpean ST1	0.000984	0.000853
Kpean ST2	0.001439	0.001669
Kpean ST3	0.001065	0.000938
Kpean ST4 (Control)	0.000939	0.000842

DPR (2002) target value for total PAH in soil = 1 ppm; intervention value = 40 ppm.

Total Petroleum Hydrocarbons

Analysis of the thirty-four individual n-alkane components assessed (n-nonane, C9, to n-dotetracontane, C42) showed that the mid-chain-length compounds n-tetradecane (C14), n-hexadecane (C16), and n-octadecane (C18) consistently contributed the largest share of total petroleum hydrocarbons at most stations, while the very short-chain (C9-C11) and very long-chain (C33 and above) compounds were present only at trace concentrations or below detection. Total TPH concentrations, summarised in Table 4, ranged from 3.209 to 17.517 ppm at the 0-15 cm depth and from 4.482 to 17.031 ppm at the 15-30 cm depth, with the highest levels recorded at KWAWA ST1 at both depths and the lowest at KWAWA ST2. Against the DPR (2002) target value of 50 mg/kg and intervention value of 5,000 mg/kg for TPH in soil, all eight stations at both depths recorded TPH levels well below the target value.

Table 4. Total petroleum hydrocarbon (TPH) concentrations (ppm) across sampling stations at two depths

Station	0-15 cm (ppm)	15-30 cm (ppm)
Kwawa ST1	17.517	17.031
Kwawa ST2	3.209	4.482
Kwawa ST3	15.597	14.902
Kwawa ST4 (Control)	14.636	16.193
Kpean ST1	15.821	14.631
Kpean ST2	6.268	5.518
Kpean ST3	6.298	5.871
Kpean ST4 (Control)	15.593	14.268

DPR (2002) target value for TPH in soil = 50 mg/kg; intervention value = 5,000 mg/kg.

Analysis of Variance and Correlation among Soil Properties

Table 5 presents the one-way ANOVA results comparing stations at each depth. At the 0-15 cm depth, significant differences among stations ($p < .05$) were found for all parameters except organic carbon ($p = .344$), organic matter ($p = .213$), and exchangeable potassium ($p = .220$). At the 15-30 cm depth, significant differences were found for all parameters except organic carbon ($p = .433$), organic matter ($p = .918$), and exchangeable calcium ($p = .468$).

Table 5. One-way ANOVA of soil parameters across stations at two depths

Parameter	0-15 cm F	0-15 cm p	15-30 cm F	15-30 cm p
pH	13.988	.000	14.529	.000
Electrical conductivity	42.309	.000	70.041	.000
Organic carbon	1.193	.344	1.035	.433
Organic matter	1.505	.213	0.357	.918
Total nitrogen	2.949	.022	76.865	.000
Available phosphorus	46.516	.000	149.584	.000
Exchangeable calcium	5.071	.001	0.981	.468
Exchangeable magnesium	14.044	.000	26.289	.000
Exchangeable potassium	1.485	.220	10.277	.000
Exchangeable sodium	8.689	.000	15.735	.000
Cation exchange capacity	44.459	.000	14.564	.000
Sand	37.468	.000	85.293	.000
Silt	21.558	.000	27.033	.000
Clay	118.295	.000	312.740	.000
Cadmium	54.016	.000	73.902	.000
Zinc	215.036	.000	209.956	.000
Lead	100.949	.000	154.611	.000
Iron	1155.188	.000	8546.637	.000
Total heterotrophic bacteria	1192.811	.000	7193.041	.000
Faecal count	731.604	.000	453.703	.000

Significance level = .05.

Pearson's correlation analysis identified several statistically significant relationships among the parameters measured, summarised in Table 6. At the 0-15 cm depth, pH correlated strongly and negatively with organic carbon, while exchangeable potassium correlated strongly and positively with electrical conductivity, and cation exchange capacity correlated strongly and positively with exchangeable magnesium. At the 15-30 cm depth, exchangeable calcium correlated strongly and positively with total nitrogen, exchangeable sodium correlated strongly and positively with zinc, and cation exchange capacity again correlated strongly and positively with exchangeable magnesium, while clay and sand were strongly and negatively correlated at both depths, consistent with their complementary contribution to soil texture.

Table 6. Selected statistically significant Pearson correlations among soil parameters

Depth	Variable Pair	r	Significance
0-15 cm	pH & Organic carbon	-0.846	p < .01
0-15 cm	Exchangeable K+ & Electrical conductivity	0.974	p < .01
0-15 cm	CEC & Exchangeable Mg2+	0.922	p < .01
0-15 cm	Organic matter & pH	0.776	p < .05
0-15 cm	Clay & Sand	-0.812	p < .05
15-30 cm	Exchangeable Ca2+ & Total nitrogen	0.973	p < .01
15-30 cm	Exchangeable Na+ & Zinc	0.972	p < .01
15-30 cm	CEC & Exchangeable Mg2+	0.949	p < .01
15-30 cm	Clay & Sand	-0.897	p < .01
15-30 cm	Available P & CEC	0.828	p < .05

DISCUSSION OF FINDINGS

The acidic soil pH recorded across both remediated and control stations (4.99-5.83) is consistent with Onwuka, Eboatu, Ajiwe, and Morah (n.d.), who reported pH values of 4.25-6.48 in a comparable study of crude oil-producing areas of Rivers State, suggesting that the acidity observed here reflects the broader regional soil character of the Niger Delta rather than a specific consequence of contamination or remediation. Electrical conductivity values recorded in this study (37.62-84.47 microS/cm) were markedly higher than the 2.45-10.60 microS/cm range reported by the same authors, although still well below the DPR (2002) permissible limit of 300-5,000 microS/cm, indicating that the soils examined here, while more electrically conductive than those reported elsewhere, remain within a safe range.

Organic matter levels agreed with Nnaji and Chukwu (2020), who reported a comparable range of 2.11-4.15% in soils from dumpsites in Umuahia, and cation exchange capacity levels similarly agreed with Okechukwu, Onwukeme, Eze, and Aralu (2024), who reported 2.11-4.15 cmol/kg in active dumpsites in Port Harcourt. Because CEC depends particularly on pH, clay content, and organic matter (Awode, Uzairu, & Balarabe, 2008), and because higher organic matter is known to reduce the leaching of pollutants into groundwater (Parameswari, Padmini, & Mudgal, 2015), the moderate organic matter and CEC levels recorded across stations suggest a soil system with some residual capacity to buffer against further contamination. In contrast, total nitrogen and available phosphorus levels recorded in this study were considerably lower than the ranges reported by Libo et al. (2018) in Chinese river soils, a disagreement plausibly attributable to differences in soil type, land use, and fertiliser history between the two study contexts rather than to any deficiency in the remediation exercise itself.

The finding that cadmium, zinc, and lead concentrations remained below DPR and FAO/WHO limits at every station agrees with the cadmium and lead ranges reported by Onwuka et al. (n.d.) and Nnaji, Chukwu, and colleagues (2020), whose reported ranges, while higher in absolute terms than those recorded here, likewise fell within regulatory limits, together indicating that heavy-metal contamination is not the primary constraint on soil fertility recovery in oil-impacted Niger Delta communities once remediation has taken place. The exceedance of the FAO/WHO iron limit at a minority of stations, most notably at KWAWA ST1, is broadly consistent with Nnaji et al. (2020), who reported iron levels of 66.67-713.27 mg/kg in similarly affected soils, and suggests that iron, rather than the other three metals assessed, is the heavy-metal parameter most warranting continued monitoring at the more contaminated remediated stations.

The consistently low total PAH and TPH concentrations recorded across all stations, several orders of magnitude below DPR target and intervention values, indicate that the bulk hydrocarbon burden in both remediated and control soils is now minimal, regardless of station. Combined with the finding that total heterotrophic bacteria counts were consistently higher at remediated stations than at their paired controls, a pattern consistent with

Ogunmwonyi et al. (2008), this suggests that the remediation exercise has not only reduced the hydrocarbon burden but has also supported the recovery of a more active soil microbial community capable of continued natural attenuation.

Taken together, these findings indicate that the crude oil remediation exercise undertaken in Kpean and Kwawa communities has been broadly effective: the great majority of physicochemical, heavy metal, PAH, and TPH parameters at remediated stations now fall within, or close to, the range observed at unimpacted control stations and comfortably within regulatory limits. The principal exception is iron, which exceeded the FAO/WHO limit at a minority of stations, indicating that while the remediation exercise has substantially restored soil fertility potential, it has not uniformly eliminated all elevated metal concentrations, and that targeted monitoring of iron at the most affected stations remains warranted.

CONCLUSION

This study evaluated the impact of crude oil remediation on soil fertility in Kpean and Kwawa communities, Khana Local Government Area, Rivers State, Nigeria, by comparing the physicochemical, heavy metal, hydrocarbon, and microbial properties of remediated soils against unimpacted control soils. The findings show that soil pH was consistently acidic across stations, that electrical conductivity and cadmium, zinc, and lead concentrations remained well below regulatory limits at every station, that total PAH and TPH concentrations were several orders of magnitude below DPR intervention values, and that total heterotrophic bacteria counts were consistently higher at remediated stations than at controls, indicating active microbial recovery. Iron concentrations exceeded the FAO/WHO limit at a minority of stations, indicating a specific, localised exception to an otherwise favourable pattern of recovery.

The contribution of this study lies in providing a direct, station-by-station comparison of remediated and control soils in two communities that have long been recognised as flashpoints of oil pollution in Khana LGA, offering an evidence-based assessment of remediation efficacy that was previously unavailable for this specific locality. The results indicate that the remediation exercise carried out in these communities has been largely effective in restoring soil fertility potential, providing a basis for cautious confidence in the remediation approach applied, while identifying iron as a parameter warranting continued attention.

RECOMMENDATION

Based on the findings, it is recommended that the quality of the remediation work carried out in Kpean and Kwawa communities be sustained and, where possible, improved upon, given the generally favourable comparison between remediated and control soils across most parameters assessed.

It is further recommended that continued monitoring of iron concentrations be undertaken at the more contaminated remediated stations, particularly KWAWA ST1, and that future remediation and monitoring programmes in similarly affected Niger Delta communities adopt a comparable control-referenced design, benchmarking remediated soils directly against unimpacted soils within the same community, so that the effectiveness of remediation exercises can be more consistently and transparently evaluated.

DECLARATIONS

Ethical approval: Not applicable; the study involved soil sampling only, with no human or animal subjects.

Informed consent: Community leaders in Kpean and Kwawa were briefed on the purpose of the study prior to sample collection.

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

Data availability: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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