IJMAAS International Journal of Microbiology and Applied Sciences
ISSN 1115-4004 Volume 5 issue 3 Sept, 2026 Research Article

Physicochemical Properties and Microbial Population of Crude Oil Polluted Forest Soil Ecosystem of Ogbogu and Unpolluted Soil of Ahiahu in Rivers State, Nigeria

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ABSTRACT

Crude oil contamination of soil is known to affect soil quality and productivity. This study assessed selected physicochemical properties, particle-size distribution and microbial populations in polluted forest soil ecosystem of Ogbogu (OG) and Ahiahu (AH)'s unpolluted forest soil which served as control. Ogbogu and Ahiahu are located in Ogba/Egbema/Ndoni Local Government Area, Rivers State, Nigeria. Soil samples were collected at 0–15 cm and 15–30 cm depths and analyzed using standard methods. Results obtained were analysed using descriptive statistics and significance testing at the 5% level. Total organic carbon (TOC) ranged from 5.42 ± 0.04% to 9.85 ± 0.44%, with the highest value at OG 0–15 cm and the lowest at AH 15–30 cm. Total organic nitrogen (TON) ranged from 0.22 ± 0.02% to 0.42 ± 0.02%, available phosphorus from 8.49 ± 0.79 to 16.67 ± 0.95 mg/kg, and potassium from 63.45 ± 4.16 to 102.56 ± 5.11 mg/kg. Soil pH ranged from 5.28 ± 0.08 to 5.92 ± 0.09, indicating moderately acidic conditions, while electrical conductivity (EC) ranged from 585.44 ± 25.65 to 932.05 ± 35.78 µS/cm. Moisture content ranged from 13.85 ± 0.57% to 20.48 ± 0.79%, and bulk density ranged from about 1.38 to 1.65 g/cm^3. TOC, phosphorus, potassium, EC and moisture content differed significantly ($P < 0.05$), whereas pH, TON and bulk density did not. Particle-size analysis showed a silt-dominated soil, with silt ranging from 62.50 ± 1.29% to 72.50 ± 1.29%, sand from 14.75 ± 0.96% to 20.75 ± 0.96%, and clay from 12.75 ± 0.50% to 16.75 ± 0.50%. Total heterotrophic bacterial counts ranged from 75.38 ± 23.92 to 92.88 ± 29.39, while reported bacterial densities ranged from 1.64×10^3 to 7.54×10^5 CFU/g. The highest mean count occurred at AH 0–15 cm (92.88 ± 29.39), whereas the highest reported bacterial density occurred at OG 15–30 cm (7.54×10^5 CFU/g). These findings indicate substantial depth- and site-related variation in soil conditions and microbial abundance in the polluted forest environment. Nickel and cobalt were identified as important heavy-metal concerns. Therefore, continued hydrocarbon assessment and evidence-based bioremediation are recommended.

Keywords: Polluted Forest Soil, Physicochemical Properties, Ogbogu, Heavy Metals, Bacteria, Hydrocarbon Degradation.

Introduction

The soil ecosystem is fundamental in sustaining the forest productivity, biodiversity and ecological equilibrium especially in the tropical areas like the Niger Delta where forest ecosystems are very sensitive to anthropogenic disturbances (Wokocha and Khana 2026; Akpan, et al., 2025; Agbogidi, and Ilondu, 2021).

Soil is a key component of forest ecosystems because it supports plant growth, nutrient cycling, microbial activity and the physical processes that sustain terrestrial biodiversity.

Rivers State in the Niger Delta has experienced severe environmental degradation over the past few decades and these soil ecosystem functions are increasingly threatened by petroleum exploration, oil spills, artisanal refining operations, pipeline vandalism, industrial discharges, and other anthropogenic activities (Amadi, and Nwankwoala, 2026; Izah, and Angaye, 2025).

Edori et al. (2025) noted that there are considerable differences in heavy metal levels among various soil settings throughout the Rivers State, which means that there is an ongoing anthropogenic contribution to the soil and environmental pressures.

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Likewise, Nwodiogbu (2024 indicated that the contamination of soils cause by the hydrocarbons was high, which demonstrated the continuation of heavy metals of crude oil origin in the environment and their possible effects on nature. Microbial communities in soil are also important indicators of soil health since they are the catalysts of nutrient cycling and decomposition of organic matter.

Physicochemical properties such as pH, total organic carbon, total organic nitrogen, phosphorus, potassium, electrical conductivity, and moisture and bulk density provide additional evidence of changes in soil quality. The study document emphasizes that these variables interact with microbial abundance and contaminant behaviour. Similar relationships have been reported in studies of polluted soils in the Niger Delta (Abdullahi, 2024; Osarokaka et al., 2021; Olukaejire and Ayuba, 2025).

Microorganisms are particularly useful indicators of soil condition because they participate in decomposition and nutrient cycling. Petroleum contamination can change the structure and activity of microbial communities, while prolonged contamination may select for microorganisms capable of using hydrocarbons as carbon and energy sources. The source document therefore links the occurrence of hydrocarbon-utilizing microorganisms with the possibility of natural attenuation and bioremediation (Denmodei, 2026; Muhammad, 2024; Evans, 2024).

Nevertheless, oil pollution has a major impact on the composition of microbes, and the microbial activity, especially the total population of heterotrophic bacteria and fungi (Denmodei, 2026). Hydrocarbon-using microorganisms tend to grow more numerous in the contaminated soils of the Niger Delta as they become adapted to petroleum-contaminated habitats, and vulnerable microbial communities die off (Muhammad, 2024). This change is an ecological imbalance that is brought about by stress of pollution. The bioremediation researches in the area have proven that under favorable conditions, microorganisms may degrade petroleum hydrocarbons, but its performance is influenced by environmental factors, including pH, nutrients and toxicity of heavy metals (Evans, 2024). Physicochemical properties of soil such as pH, total organic carbon (TOC), total organic nitrogen (TON), potassium, phosphorus and cation exchange capacity (CEC) are very important indicators of both soil fertility and soil pollution status. In contaminated areas, such parameters are usually distorted, and the soil productivity decreases (Abdullahi, 2024). Consequently, the interplay between the microbial communities, the physicochemical properties of soils and heavy metal contamination is important in determining the ecological soundness of the polluted forest soils like that in Ogbogu Community, Rivers State (Osarokaka et al., 2021).

Despite the environmental importance of the Niger Delta, the supplied document notes that site-specific information for polluted forest soils in Ogbogu and Ahiahu is limited. This aim of this present study was to assess selected physicochemical properties, particle-size distribution and microbial populations in polluted forest soil ecosystem of Ogbogu and Ahiahu's unpolluted forest soil which served as control. The present study therefore synthesizes the reported results for these communities, emphasizing the measured soil properties, particle-size distribution and microbial counts.

Materials and Methods

Study Area Description and Sources of Soil Samples

Ogbogu Community forest is located in Ogba Egbma Ndoni Local Government Area of Rivers State within the Niger Delta region of Nigeria; an area characterized by tropical rainforest vegetation and extensive oil exploration activities. The region experiences high rainfall and humidity, which influence soil formation, nutrient cycling, and microbial activity. The community is predominantly engaged in agriculture, fishing, and small-scale trading, with livelihoods heavily dependent on the surrounding natural environment. However, ongoing oil-related activities have contributed to environmental degradation, particularly soil and water contamination.

Soil sample for this study was obtained from selected forest locations within Ogbogu Community that was impacted by crude oil pollution. Sampling sites was chosen based on visible signs of contamination such as oil stains, vegetation stress, and proximity to human activities.

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Control sample was collected from Ahiahu relatively undisturbed forest areas close to Ogbogu community to provide comparative baseline data. This allows for proper evaluation of pollution impact on soil quality and microbial composition (She et al., 2023).

Sample Collection Procedures

Soil samples were collected using a sterilized soil auger at depths of 0–15cm and 15-30cm which represents the topsoil layer where microbial activity is most active.

At each sampling point, multiple sub-samples were collected and mixed to form a composite sample (Ononugbo *et al.,* 2011).

Collected samples were placed in sterile polyethylene bags, labeled appropriately, and transported to the laboratory in an ice-packed cooler to preserve microbial integrity and prevent contamination before analysis.

The Map of Ogbogu Community is presented in Figure 1 below.

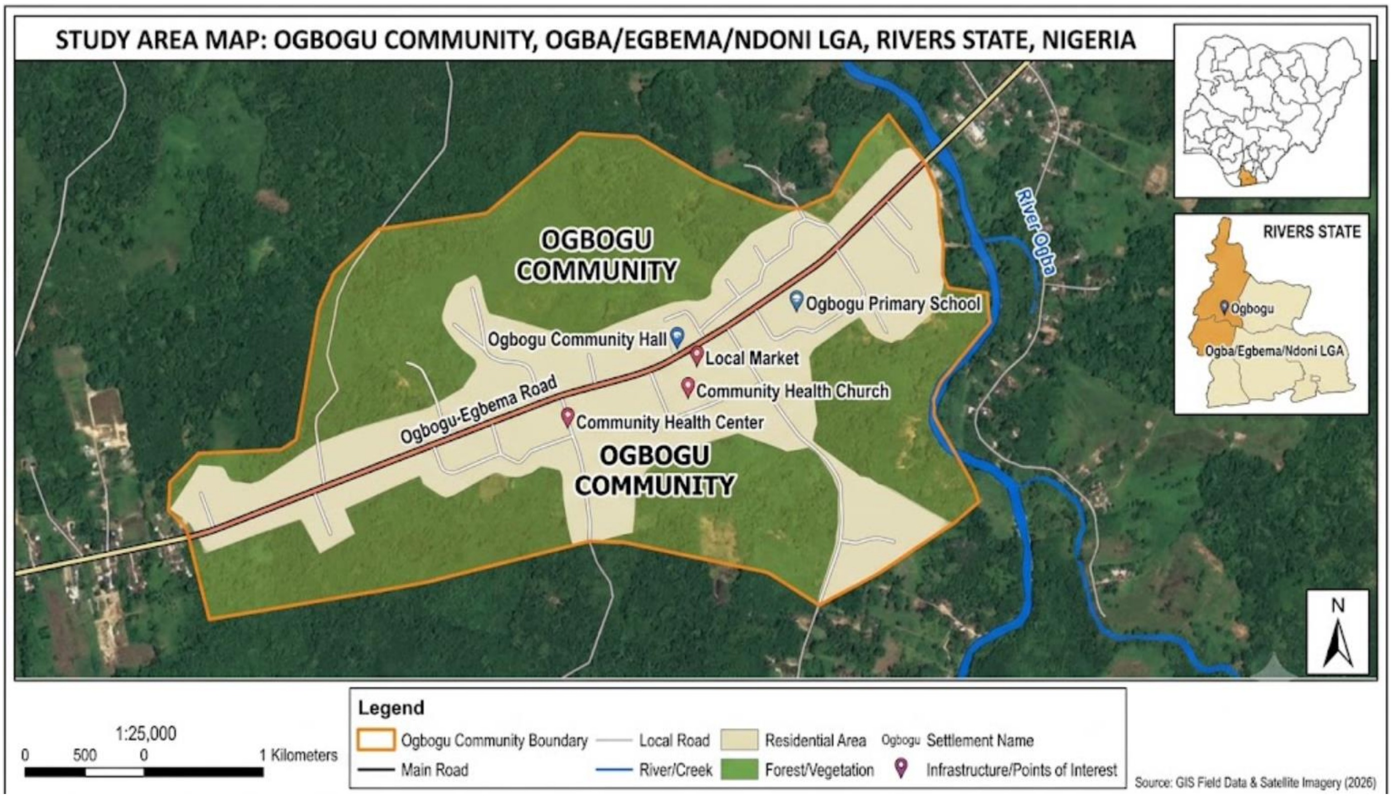

Fig. 1: Map of Ogbogu Community in Ogba/Egbema/Ndoni LGA of Rivers State (Ononugbo, *et al.,* 2011).

Determination of Physicochemical Parameters (pH, TON, TOC, P, K, CEC)

Soil pH was determined using a calibrated pH meter in a soil-water suspension. Total organic carbon (TOC) was measured using the Walkley-Black method 1934, while total organic nitrogen (TON) was determined using the Kjeldahl digestion method. Phosphorus (P) and potassium (K) were analyzed using spectrophotometric and flame photometric methods respectively.

Cation exchange capacity (CEC) was determined using ammonium acetate saturation techniques to assess soil nutrient-holding capacity **(**Ross and Ketterings, 2011).

Cultivation and Enumeration of Total Heterotrophic Bacteria and Fungi

Total heterotrophic bacteria were enumerated using the serial dilution and pour plate technique on nutrient agar medium **(**Aneja, 2018).

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Plates was incubated at 37°C for 24-48 hours, after which colonies were counted and expressed as colony-forming units per gram of soil. Fungal populations were determined using potato dextrose agar (PDA) medium and incubated at room temperature for 3-5 days, colony counts were recorded to estimate fungal abundance in the soil samples (Cappuccino and Welsh, 2019; Pepper et al., 2015).

Experimental Design and Statistical Analysis

Data obtained from laboratory analysis were subjected to statistical analysis using descriptive statistics such as mean, standard deviation, and percentage composition. Inferential statistics such as ANOVA analysis was used to determine significant differences and relationships between variables at a 0.05 level of significance (Chukunda et al., 2019)

Results

Results of the Physicochemical Parameters of crude oil Polluted and unpolluted Forest Soils are presented in Table 1.

Table 1: Physicochemical parameters of Polluted Forest Soil in Ogbogu and Ahiahu (Unpolluted site) in Ogba Egbema Ndoni Rivers State

Physico-Chemical Parameter	Unpolluted Forest Soil (Control - Ahiahu)		Crude Oil Polluted Forest Soil (Ogbogu)	
	0-15 cm	15-30 cm	0-15 cm	15-30 cm
Total organic carbon (TOC)	8.57±0.34[b]	5.42±0.04[a]	9.85±0.44	6.21±0.45
Total organic nitrogen (TON)	0.37±0.02 [a]	0.22±0.02 [a]	0.42±0.02 [a]	0.26±0.02 [a]
Phosphorus (P)	14.32±0.80 [b]	8.49±0.79 [a]	16.67±0.95 [b]	10.40±0.82 [a]
Potassium (K)	94.14±3.88 [ab]	63.45±4.16 [a]	102.56±5.11 [b]	71.2±4.42 [a]
pH	5.52±0.08 [a]	5.92±0.09 [a]	5.28±0.08 [a]	5.73±0.09 [a]
Electrical conductivity (µS/cm)	813.84±27.19 [a]	585.44±25.65 [b]	932.05±35.78 [b]	672.59±28.70 [a]
Moisture content (MC)	15.00±0.65 [b]	20.48±0.79 [a]	13.85±0.57 [b]	18.83±0.87 [a]
Bulk Density (g/cm³)	1.55±0.03 [a]	1.3825 [a]	1.65±0.08 [a]	1.46±0.03 [a]

Mean ± Standard Deviation values across columns with a p-value ≤ 0.05 is considered statistically significant using Duncan Multiple Range Test.

Table 1 shows that, the Total Organic Carbon (TOC) readings ranged from 5.42 ± 0.04% to 9.85 ± 0.44% with a mean value of about 7.51% for both locations and depths. The maximum TOC was recorded in OG (0–15 cm) (9.85 ± 0.44 %) and minimum in AH (15–30 cm) (5.42 ± 0.04 %). The TON values ranged from 0.22 ± 0.02% to 0.42 ± 0.02% with an overall mean of ~0.32%. The maximum concentration of nitrogen was in the surface soil of OG (0.42%), the lowest in the subsurface of AH (0.22%). Available phosphorus content varied from 8.49 ± 0.79 mg/kg to 16.67 ± 0.95 mg/kg with a mean of around 12.47 mg/kg. Phosphorus in surface soils was higher than in deeper soils at both sites. Potassium concentrations were found between 63.45±4.16 mg/kg and 102.56±5.11 mg/kg with an overall mean of around 82.84 mg/kg. The largest concentration was detected in OG surface soil and the lowest in AH subsurface.

The pH of the soil ranged from 5.28 ± 0.08 to 5.92 ± 0.09, with a mean of about 5.61. Both locations were moderately acidic. OG surface soil was the most acidic (pH 5.28). Electrical conductivity ranged from 585.44 ± 25.65 µS/cm to 932.05 ± 35.78 µS/cm with a mean of about 751 µS/cm. Moisture content ranged from 13.85±0.57% to 20.48±0.79% with an average of about 17.04%. AH subsoil had the highest moisture content (20.48 %) and OG surface soil the lowest (13.85 %). Bulk density ranged from 1.38 ± 0.03 to 1.65 ± 0.08 g/cm³ with an average value of about 1.51 g/cm³. The top 0–15 cm layer of surface soils consistently had higher organic carbon, nutrients, electrical conductivity and heavy metals compared to the 15–30 cm layer. Moreover, the TOC ranged from 5.42% in AH (15–30 cm) to 9.85% in OG (0–15 cm) with a mean value of 7.51%. TON values ranged from 0.22–0.42 % (mean 0.32 %).

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Phosphorus ranged from 8.49–16.67 mg/kg (mean 12.47 mg/kg). Surface soils contained more available phosphorus than subsoils. Potassium ranged from 63.45–102.56 mg/kg (mean 82.84 mg/kg), indicating moderate potassium availability. pH ranged from 5.28–5.92 (mean 5.61), showing that the soils are moderately acidic. Electrical conductivity ranged from 585.44–932.05 µS/cm (mean 751 µS/cm).

The higher values in surface soils indicate greater accumulation of dissolved ions from pollution sources. Moisture content ranged from 13.85–20.48% (mean 17.04%). Bulk density ranged from 1.38–1.65 g/cm³ (mean 1.51 g/cm³), indicating moderate soil compaction, especially in OG surface soil. However, There was significant difference in (P<0.05) in the TOC, phosphorus, potassium, EC and moisture content while pH, TON, and bulk density showed no statistical significant difference (P>0.05) in the study.

Particulate size of soil in polluted forest soil in Ogbogu and Ahiahu in Ogba Egbema Ndoni Rivers State are as presented in Table 2. The particle size study revealed that Silt was 62.5-72.5% (Mean = 67.5%). Sand varied from 14.75–20.75% (Mean = 17.75%). Clay (12.75–16.75%) (Mean = 14.75%) Silt-loam soils were prominent and silt has the largest share. The high silt content helps hold moisture but may make it more susceptible to erosion if vegetative cover is lost. There was significant difference (P<0.05) in the particulate sizes of forest soil across various depths of the sampling locations of the study.

Table 2: Particulate Size of Unpolluted and in Crude oil Polluted Forest Soils in Ahiahu and Ogbogu

Soil Particle	Soil Particle Size of Forest Soils			
	Unpolluted (Control - Ahiahu)		Crude Oil Polluted (Ogbogu)	
	0-15 cm	15-30 cm	0-15 cm	15-30 cm
Silt (%)	66.5±1.29[ab]	62.5±1.29[a]	72.5±1.29[ab]	68.5±1.29[a]
Sand (%)	18.75±0.96[a]	20.75±0.96[a]	14.75±0.96[a]	16.75±0.96[a]
Clay (%)	14.75±0.50[a]	16.75±0.50[b]	12.75±0.50[a]	14.75±0.50[ab]

Note: Mean ± Standard Deviation values across columns with a p-value ≤ 0.05 is considered statistically significant using Duncan Multiple Range Test.

The total bacterial counts of the polluted forest soils as shown in Table 3 exhibited significant changes across the two sampling stations (AH and OG) and throughout the two sampling depths (0–15 cm and 15–30 cm), indicating variances in bacterial abundance within the soil profile. The mean average counts of bacteria were between 75.38±23.92 and 92.88±29.39 with the overall mean average count of about 84.27±30.04. The corresponding bacterial population represented as colony forming units (CFU/g) ranged from 1.64×10^3 to 7.54×10^5CFU/g, with an overall mean bacterial density of approximately 2.83×10^5CFU/g.

At AH station, the average bacterial count in the 15–30 cm depth was 80.95 ± 29.15, while in the 0–15 cm depth was 92.88 ± 29.39. The respective bacterial densities ranged from $1.64 \times 10^3 \pm 3.27 \times 10^3$ CFU/g in the surface soil to $2.48 \times 10^4 \pm 4.09 \times 10^4$ CFU/g in the deeper soil. The average bacterial count at OG station was 75.38 ± 23.92 to 87.88 ± 37.71 at 15-30 cm to 0-15 cm soil depth. However, bacterial density was much higher than that of AH, increasing from $3.49 \times 10^5 \pm 2.79 \times 10^5$ CFU/g at the 0–15 cm level to $7.54 \times 10^5 \pm 2.39 \times 10^5$ CFU/g at the 15–30 cm depth.

Table 3: Total Heterotrophic Bacteria Count of Soil in Polluted Forest Soil in Ogbogu and Ahiahu in Ogba Egbema Ndoni Rivers State

Depth (cm)	Ahiahu (AH)		Ogbogu (OG)	
	Average Count	CFU/g	Average Count	CFU/g
0-15	92.88±29.39[ab]	$1.64x10^3±3.27x10^3$	87.88±37.71[b]	$3.49x10^5±2.79x10^5$
15-30	80.95±29.15[a]	$2.48x10^4±4.09x10^4$	75.38±23.92[a]	$7.54x10^5±2.39x10^5$

Note: Mean ± Standard Deviation values across columns with a p-value ≤ 0.05 is considered statistically significant using Duncan Multiple Range Test.

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The 0-15cm sampling depth reported a higher mean average bacterial count of about 90.38 across the sampling depths while the 15-30cm sampling depth had a lower mean of about 78.17. In comparison between the two stations, AH had a significantly higher overall mean average bacterial count (86.92) than OG (81.63).

In general, the data indicate that the polluted forest soils supported large bacterial populations throughout the soil profile. The maximum mean bacterial count was seen in AH (0-15cm), however the maximum bacterial density (7.54×10^5 CFU/g) was in OG (15-30cm). There was a significant difference (P,0.05**)** in the bacteria count across various depth of the sampling points of the study.

Discussion

This study has revealed that, Physicochemical Parameters of forest soil of Ogbogu and Ahiahu in Ogba Egbema Ndoni Rivers State showed clear spatial and depth-related variations in the physicochemical properties of polluted forest soils in Ogbogu Community. Overall, the surface soils (0–15cm) recorded higher concentrations of total organic carbon (TOC), total organic nitrogen (TON), available phosphorus, potassium, and electrical conductivity (EC) than the subsurface soils (15–30 cm), whereas moisture content was generally higher in the deeper soil layer. These findings are consistent with the fact that the topsoil is the primary zone for organic matter accumulation, microbial activity, and pollutant deposition, while nutrients and soluble salts decrease with increasing soil depth **(**Eilers, et al., 2012).**)**

The TOC values ranged from 5.42 ± 0.04% to 9.85 ± 0.44%**,** with the highest concentration recorded at the OG station (0–15cm) and the lowest at AH (15–30 cm). The decline in TOC with depth reflects reduced accumulation of plant residues and microbial biomass in the subsurface. The relatively high TOC observed in both stations may also indicate the contribution of petroleum hydrocarbons and other organic contaminants associated with oil pollution in the Niger Delta.

The marked decline in TOC from 9.85 ± 0.44% in OG surface soil to 5.42 ± 0.04% in AH subsoil indicates a strong depth effect on organic-carbon distribution. Surface soil commonly receives leaf litter, root residues and other organic inputs, while petroleum residues can also contribute to measured carbon in contaminated environments. The pattern reported here is consistent with the interpretation in the source document and with studies cited there, including Wang, et al., 2018; Ojo 2012; Osinbanjo and Kekane (2015**)**

Total organic nitrogen (TON) followed the same general depth pattern, ranging from 0.22 ± 0.02% to 0.42 ± 0.02%. The higher surface values suggest greater organic-matter inputs and biological activity near the soil surface. Phosphorus and potassium were also higher in the surface horizon. Because these nutrients are associated with organic matter, mineral weathering and plant cycling, their distribution can provide useful evidence of differences in soil functioning. The supplied discussion relates these patterns to findings reported by Adeyemi et al. (2008) Nikolava (2015), Okoye et al (2014), Wang et al. (2018), Arias et al. (2005) and Chukwuolobe et al. (2014).

All measured pH values were acidic, ranging from 5.28 ± 0.08 to 5.92 ± 0.09. The lowest pH occurred in OG surface soil. Acidic conditions are common in humid tropical soils, but petroleum contamination and the products of hydrocarbon degradation may further influence soil reaction. The source document compares the result with Khan et al. (2013) and Akpoveta et al. (2010) and Sellami et al (2022).

Electrical conductivity (EC) was significantly higher in the surface soils, reaching 932.05 ± 35.78 µS/cm at OG 0–15 cm. This pattern may indicate greater concentrations of soluble ions and contamination-related inputs near the surface. In contrast, moisture content increased with depth, reaching 20.48 ± 0.79% at AH 15–30 cm. The higher moisture in deeper soil is consistent with reduced evaporation and greater water retention.

Bulk density ranged from approximately 1.38 to 1.65 g/cm³. The highest value was recorded in OG surface soil. Higher bulk density can restrict pore space, water movement and root penetration. The source document relates this observation to petroleum-induced compaction and pore blockage, citing Adelabu, et al (2011) and Utang et al. (2013).

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These findings agree with Wang, et al., (2018), who reported significantly higher Total organic carbon (TOC) concentrations in surface soils of oil-impacted communities in Bayelsa State due to hydrocarbon contamination and surface litter accumulation. Similarly, Ojo (2012) found that contaminated soils in Ogoniland contained elevated organic carbon in the upper soil horizon because hydrocarbons increase the measured carbon content. Likewise, Uzoekwe and Kekane (2015) observed that oil-contaminated forest soils in Rivers State exhibited decreasing TOC with depth owing to reduced organic residue incorporation.

TON ranged from 0.22 ± 0.02% to 0.42 ± 0.02%, with higher values consistently observed in the surface soils than in the deeper layer. The OG station recorded slightly higher nitrogen concentrations than AH, suggesting better retention of organic matter or differences in contamination history. The reduction in nitrogen with increasing depth corroborates the findings of Adeyemi et al. (2008) who reported that nitrogen concentrations decrease with soil depth due to reduced microbial mineralization and lower organic matter inputs. Similarly, Okoro et al. (2022) observed significant declines in total nitrogen from surface to subsurface soils in crude oil-polluted sites in the Niger Delta, attributing the pattern to microbial utilization of nitrogen during hydrocarbon degradation. Available phosphorus varied from 8.49 ± 0.79 mg/kg to 16.67 ± 0.95 mg/kg, with the highest concentration at OG (0–15 cm). The decrease with depth suggests that phosphorus remains largely concentrated in the topsoil because of its limited mobility and strong adsorption to soil particles.

This trend agrees with Iwegbue et al. (2021), who reported greater phosphorus availability in surface soils than subsurface layers in oil-producing communities of southern Nigeria. Similarly, Asamoaha et al. (2021) found that phosphorus concentrations declined significantly with soil depth due to adsorption by iron and aluminium oxides and limited downward movement in acidic tropical soils. Exchangeable potassium ranged from 63.45 ± 4.16 mg/kg to 102.56 ± 5.11 mg/kg, with the highest value occurring at OG (0–15 cm). The higher potassium concentration in surface soils is likely associated with organic matter decomposition, fertilizer residues, and weathering of soil minerals.

Comparable findings were reported by Eze et al. (2022), who observed significantly greater potassium concentrations in surface soils of agricultural and oil-impacted lands in Rivers State. Similarly, Chukwulobe et al. (2014) found that exchangeable potassium decreased significantly with soil depth due to nutrient uptake by vegetation and leaching processes.

The soil pH ranged from 5.28 ± 0.08 to 5.92 ± 0.09, indicating that all soils were moderately acidic. Slightly lower pH values were observed in the surface soils, particularly at OG, while pH increased marginally with depth. The acidic nature of the soil may be attributed to hydrocarbon degradation, organic acid production, and heavy rainfall characteristic of the Niger Delta environment. These findings are consistent with Akpan et al. (2020), who reported acidic soil conditions (pH 5.1–6.0) in petroleum-contaminated sites in Akwa Ibom State. Similarly, Akpoveta et al 2010, and Sellami et al (2022) observed acidic soils in crude oil-polluted environments of Rivers State, explaining that petroleum degradation products and acid rain contribute to reduced soil pH. The measured pH values remain within the range commonly reported for tropical forest soils affected by oil pollution. Electrical conductivity ranged from 585.44 ± 25.65 to 932.05 ± 35.78 µS/cm, with the highest EC recorded at OG (0–15 cm). Surface soils consistently showed higher EC than deeper soils, indicating greater accumulation of soluble salts and dissolved ions near the surface.

The observed pattern agrees with Ekeocha et al. (2017), who reported elevated EC in contaminated soils due to increased concentrations of dissolved ions released during hydrocarbon degradation. Similarly, Adebayo et al. (2017) found significantly higher EC values in polluted soils compared with uncontaminated soils, suggesting that contamination increases ionic strength and soil salinity. Moisture content ranged from 13.85 ± 0.57% to 20.48 ± 0.79%, with higher values consistently observed in the deeper soil layer. This increase is expected because deeper soils experience lower evaporation rates and greater water retention than surface soils. This observation agrees with Adelekan et al (2011) and Chukwu et al (2016), who reported increasing soil moisture with depth in oil-polluted tropical soils due to reduced surface evaporation and greater pore water retention.

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Similarly, Chen et al. (2023) observed that subsurface soils in wetlands of the Niger Delta retained significantly higher moisture than surface soils, particularly during the rainy season.
Bulk density varied from 1.38 to 1.65 g/cm³, with the highest value recorded at OG (0–15 cm). The relatively higher bulk density in contaminated soils may indicate soil compaction resulting from hydrocarbon contamination, reduced biological activity, and clogging of soil pores by petroleum residues. These findings are comparable to those of Lassaad et al. (2020), who reported increased bulk density in crude oil-contaminated soils compared with uncontaminated forest soils. Likewise, Utang et al. (2013) observed that petroleum contamination reduced soil porosity while increasing bulk density, thereby impairing root penetration and water infiltration.

The present study demonstrated that fungal populations were distributed across both sampling stations (AH and OG) and soil depths (0–15 cm and 15–30 cm), although their abundance varied considerably.

In relation to Particle Size and Pollutant Retention, the dominance of silt (62.50–72.50%) gives the soil a strong capacity to retain moisture and fine particulate-associated substances. At the same time, silt-rich surfaces can be vulnerable to erosion when forest vegetation is removed. In a polluted environment, erosion can redistribute contaminated particles beyond the original pollution zone. The significant depth-related differences in particle size therefore have implications for contaminant transport and long-term soil management.

The total heterotrophic bacterial counts demonstrate that substantial microbial activity persists in the polluted soils. The highest mean count, 92.88 ± 29.39, occurred at AH 0–15 cm, whereas OG 15–30 cm had the highest reported density, 7.54×10^5 CFU/g. This difference between average count and reported density should be interpreted carefully because the source document presents these as separate measures and the units/scales are not fully reconciled in the original text. The presence of hydrocarbon-utilizing bacteria and fungi is ecologically important. Petroleum contamination can suppress sensitive microorganisms while selecting for organisms capable of metabolizing hydrocarbons.

Ogbonna et al. (2020) reported that bacteria including P*seudomonas, Bacillus* and *Comamonas* can occur in crude-oil-contaminated soils. Independent literature also supports the role of fungi and bacteria in petroleum-hydrocarbon degradation and bioremediation (Aponte et al., 2020; Azubuike., 2016).

The fungal results reported in the source are similarly suggestive of microbial adaptation. The higher AH surface count and the higher OG subsurface density may reflect differences in oxygen, moisture, organic substrates and contaminant distribution. The overall mean fungal count of 14.16 ± 4.91 (average count) and an overall mean fungal density of approximately 8.48×10^4 CFU/g indicate that the polluted forest soils still supported active fungal communities despite petroleum contamination. This observation suggests that many fungal species inhabiting the study area possess adaptive mechanisms that enable them to tolerate or utilize hydrocarbons as carbon and energy sources. Recent reviews have emphasized that fungi are among the most resilient microorganisms in petroleum-contaminated soils because they produce extracellular oxidative enzymes capable of degrading complex hydrocarbon compounds, thereby allowing them to survive and proliferate under polluted conditions (Aponte et al., 2020; Zhong et al., 2020). Higher fungal count recorded in the surface soil (0–15 cm), particularly at AH (21.75 ± 7.41), agrees with the widely reported trend that fungal abundance is generally greatest in surface horizons where organic matter, oxygen, moisture, and plant litter are more readily available. Surface soils receive continuous deposition of leaf litter and root exudates, providing substrates that stimulate fungal growth and activity. This finding corroborates the observations of Aponte et al. (2020), who reported that hydrocarbon-degrading fungi remain abundant in the upper layers of contaminated soils because these layers provide better aeration and nutrient availability for fungal metabolism. Similarly, Azubuike et al (2016) explained that filamentous fungi colonize surface soils efficiently due to their extensive hyphal networks, enabling them to exploit hydrocarbons and other organic substrates simultaneously. Conversely, the lower fungal count observed at the 15–30 cm depth in AH (6.63 ± 2.81) may be attributed to declining organic matter content, reduced oxygen availability, and limited nutrient diffusion with increasing soil depth.

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Deeper soil layers generally contain fewer readily degradable organic substrates and experience less biological activity than surface soils. Similar reductions in microbial abundance with increasing soil depth have been reported in petroleum-contaminated environments, where microbial growth is constrained by reduced aeration and substrate availability (Li et al., 2020). An interesting finding of the present study is that OG station exhibited higher fungal abundance at the deeper soil layer (15–30 cm) than at the surface. This suggests localized environmental conditions that favour fungal survival below the surface, such as downward migration of hydrocarbons, greater soil moisture retention, or accumulation of degradable organic materials in subsurface horizons. Hydrocarbon contamination often infiltrates deeper soil layers, where specialized fungal communities capable of metabolizing petroleum compounds become established. According to Li et al. (2020), several hydrocarbon-utilizing fungi possess physiological adaptations that enable them to colonize deeper contaminated soils and participate actively in natural attenuation processes. Likewise, Borowik et al. (2017) identified several hydrocarbon-utilizing fungal species from crude oil-contaminated soils in the Niger Delta, demonstrating that fungal populations can remain abundant in contaminated subsurface soils where hydrocarbons persist.

The substantially higher fungal density recorded at OG (3.16×10^5 CFU/g) compared with AH suggests that contamination may have selectively enriched hydrocarbon-degrading fungi rather than suppressing the fungal community entirely. Petroleum hydrocarbons are known to inhibit sensitive fungal species while simultaneously stimulating populations capable of utilizing hydrocarbons as their primary carbon source. This phenomenon has been widely documented in contaminated ecosystems, where fungal diversity may decline but populations of hydrocarbon-degrading species increase (Zhong et al., 2020**)** Recent evidence indicates that filamentous fungi such as *Aspergillus*, *Penicillium*, *Fusarium*, *Trichoderma*, and *Pleurotus* frequently dominate oil-polluted soils because of their efficient hydrocarbon-degrading enzyme systems. Overall, the fungal populations observed in this study suggest that the polluted forest soils retain considerable biological potential for natural biodegradation of petroleum contaminants. Rather than eliminating fungal communities, hydrocarbon pollution appears to have altered community composition by favouring tolerant and hydrocarbon-degrading species. This agrees with recent systematic evidence showing that fungal treatments can reduce petroleum hydrocarbon concentrations by approximately 50–60% in contaminated terrestrial environments, highlighting the ecological significance of indigenous fungi in bioremediation (Zhong et al., 2020).

Conclusion

The findings of this study has revealed that the crude oil polluted forest soils in Ahiahu and the unpolluted Ogbogu forest soil have distinct physicochemical and microbial characteristics that vary with depth and location. Surface soils generally contained more TOC, TON, phosphorus, potassium and EC, while deeper soils contained more moisture. The soils were moderately acidic and predominantly silt textured. Total heterotrophic bacteria remained abundant, and hydrocarbon-utilizing microorganisms were reported, suggesting that indigenous microbial communities persist under petroleum-related environmental stress. These microbial populations may contribute to natural attenuation, although their effectiveness will depend on contaminant concentration, nutrient availability, pH, moisture, oxygen and heavy-metal toxicity.

Recommendations

Based on the findings of this study, the following recommendations are made:

1. Regular environmental monitoring should be carried out by the relevant authorities to assess changes in soil physicochemical properties, heavy metal concentrations, and microbial populations over time, particularly in highly contaminated areas such as station Ogbogu.
2. Comprehensive assessment of petroleum hydrocarbons**,** including Total Petroleum Hydrocarbons (TPH) and Polycyclic Aromatic Hydrocarbons (PAHs), should be undertaken to determine the extent of hydrocarbon pollution and associated ecological risks. Establish regular monitoring of soil physicochemical properties, microbial populations and heavy-metal concentrations at the study sites.

3. Evaluate combined bioremediation and phytoremediation approaches, especially where heavy metals may inhibit microbial degradation.
4. Protect forest vegetation and reduce activities that expose soil to erosion and further contamination.

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