Nigerian Research Journal of Engineering and Environmental Sciences 11(1) 2026 pp. 179-194
p ISSN: 2635-3342; e ISSN: 2635-3350

Nigerian Research Journal of Engineering and Environmental Sciences
Journal homepage: www.rjees.com

RJEES

Original Research Article

Physicochemical and Geotechnical Properties of Bioremediated Oil Sludge-Contaminated Soil

Alhassan, M.K.

Department of Civil Engineering, Faculty of Engineering, Nasarawa State University, Keffi, PMB 1007, Keffi, Nigeria.
alhassanmusa@nsuk.edu

http://doi.org/10.5281/zenodo.21047568

ARTICLE INFORMATION

Article history:
Received 03 May 2026
Revised 30 May 2026
Accepted 06 Jun. 2026
Available online 30 Jun. 2026

Keywords:
Bioremediation
Biostimulation
Geotechnical properties
Physicochemical properties
Waste containment systems

ABSTRACT

Oil sludge contamination leads to profound geoenvironmental challenges by changing the physicochemical and geotechnical properties of soil. Thus, cheap and sustainable remediation techniques are required to reclaim the capacity of contaminated soil. This study assessed the potential of using a biostimulant to: (i) activate indigenous microorganisms for decontamination and (ii) evaluate the suitability of the bioremediated soil for civil engineering applications. The study was carried out in two stages. Stage 1 included mixing contaminated soil with liquid chicken manure (CM), which was obtained from 0, 2.5, 5, 7.5, and 10% CM by dry weight of soil, and keeping it in microcosms for 30 days. Stage 2 investigated the physical, chemical, bacteriological, and geotechnical properties of the bioremediated soil. Oil degradation was determined using total petroleum hydrocarbons (TPH) concentration. Parameters evaluated included carbon, nitrogen, phosphorus, temperature, pH, optimum moisture content (OMC), maximum dry density (MDD), and unconfined compressive strength (UCS) at curing periods of 7, 14, and 28 days. Results showed that Bacilli species, Rhodococcus, Arthrobacter, Acinetobacter, and Pseudomonas species were the dominant microorganisms in the treatments. At 10% CM treatment, the TPH concentration, organic carbon, and OMC decreased from 12.41%, 78 g/kg, and 18.38%, to 5.4%, 40 g/kg, and 12.6%, respectively. Nitrogen and phosphorus increased to 0.87 and 0.063%, whereas pH attained 7.65 at 7.5% CM treatment. Temperature, MDD, and UCS value increased to 32°C, 1.46 Mg/cm^3, and 208 kN/m^2, respectively. These demonstrate the effectiveness of chicken manure in the remediation of oil sludge for civil engineering applications.

1. INTRODUCTION

Oil sludge contamination has caused tremendous environmental degradation, especially in oil-producing countries, where it changes physical, chemical, biological, and geotechnical properties of soil (Haghsheno and Arabani, 2022). The depletion of nutrients, damage to microorganisms, and high hydrocarbon concentrations are caused by oil sludge contamination, which directly influences the physicochemical properties of soil through the interactions of chemicals that may lead to a drop in cohesion (Khazaal and Ismail, 2021). Oil sludge contamination negatively affects geotechnical properties of oil soil by decreasing friction between soil particles as a result of lubrication. The presence of oil sludge in the pore spaces interferes with permeability, and the settlement of load under contaminated soil tends to be high due to compressible nature of such soil (Osinubi and Nwaiwu, 2005; Devatha et al., 2019; Hassan et al., 2024). Rondom-Afanador et al. (2023), defined oil sludge as a sediment developed from petroleum industry activities that contains a mixture of sand, water, metals, and a high content of hydrocarbons. It is an earth material that has been deteriorated by the buildup of sediment due to the accumulation of hydrocarbons and toxic substances, which adversely affect soil quality and ecosystem health (Matilda and Samuel, 2024).

Several techniques for the remediation of oil sludge contaminated exist, such as vapour extraction, electrokinetics, thermal desorption, and soil washing to immobilize, solidify, and remove hydrocarbons (Zeng et al., 2023). The limitation of these methods, due to cost and environmental effects, led to the use of biological means to remediate oil sludge contaminated soil. Bioremediation has been described as the best option for oil contaminated soil remediation, utilizing microorganisms such as bacteria and fungi; it is an environmentally friendly and cost-effective method (Stepanova et al., 2022; Saeed et al., 2025).

Bio-augmentation, bio-stimulation and natural attenuation are the three strategies used in achieving the goals of bioremediation (Dai et al., 2025). Bioaugmentation refers to the introduction of suitable microbes into for the environment for the purpose of enhancing the specificity of the substrate or improving degradation. In the bioaugmentation process, microorganisms that are not native to the soil environment are added to accelerate the process of bioremediation. This strategy has its own drawbacks in terms of the environmental impact of introducing huge volumes of allochthonous microbes. Among the microbes that have been identified as petroleum hydrocarbons degraders include *Baillus sp., Acinetobacter sp*., *Pseudomonas sp*., *Micrococcus sp*. The following fungal isolates were also utilized in hydrocarbons removal: *Penicillium sp., Aspergillus sp., Candida sp., Fusarium sp., Mucor sp.* (Suyartmana and Setiawati, 2022). However, there is little comparative study of the efficacy of biostimulation strategy on the physicochemical and geotechnical properties. The use of biostimulation helps in the restoration of the soil without negatively affecting the environment, and reduce cost of construction in an area challenged with oil contamination problem.

Biostimulation is the addition of nutrients and suitable conditions for the indigenous microorganisms to thrive by improving the microbial activity that exists in the soil as well as significant enhancement of the process of remediation (Goswami et al., 2018). Dehnavi and Ebrahimipour (2022) reported a 75-90% hydrocarbon removal efficiency through biostimulation and concluded that biostimulation has higher sustainability compared to bioaugmentation. Similarly, Nong et al. (2023), reported a result of 99.84, 71.63, and 9.84% for biostimulation, bioaugmentation, and natural attenuation strategies for degradation of petroleum-contaminated soil. Popoola et al. (2022), investigated the influence of biostimulation and bioaugmentation on the effectiveness of biodegradation of crude oil contaminated soil. They explained that nutrients such as nitrogen and phosphorus played a significant role in the degradation of total petroleum hydrocarbons (TPH). Behera et al. (2022) studied the potential of combining extract of poultry litter and bacterial consortium in remediation of sludge from petroleum refinery.

In the past, studies have been conducted on remediation of oil contaminated soil using different types of amendment materials to improve the degradability of microorganisms in degrading hydrocarbons. Atai et al. (2023) evaluated the potential of wheat straw biochar, rice husk biochar, and spent mushroom compost at 2.5 and 5% concentrations for 120 days at temperature of 20°C. They reported that the addition of bio-stimulants greatly influenced total petroleum hydrocarbons degradation by 67%. Douglas et al. (2025) assessed the potential of cow dung (CD) and chicken manure (CM) for bioremediation of oil contaminated soil. The study revealed that CM reduced speciated total petroleum hydrocarbons by 36% as against 23% and 1% recorded by CD and natural attenuation.

Previous researchers have investigated the effect of oil contamination on either the physiochemical or geotechnical properties of soil using different types of bio-stimulants. Polyak et al. (2018) have studied the effect of oil contamination using various remediation strategies such as bioaugmentation, biostimulation, and natural attenuation on physicochemical and biological indicators of podzolic soil and they reported that oil was responsible in alteration of the microbe metabolism and concluded that biostimulation performed better than other strategies for that soil. Study by Haghshemo and Arabani (2022) demonstrated that oil contamination greatly changes the geotechnical properties of both cohesive and non-cohesive soils such as Atterberg limits, particle size distribution, unconfined compressive strength compaction characteristics, consolidation behaviour, hydraulic conductivity. They reported that the changes in geotechnical properties was influenced by the type of soil. According to Salimnezhad et al. (2021), bioremediation decreased the UCS, MDD and increased porosity, OMC due to production of fibrous like texture in clayey soil. Soil contamination has adverse effects in the foundation of structures due to decrease in soil bearing capacity (Awarri and West, 2025). Mekkiyah et al. (2023) investigated the effects of oil contamination on different types These are sources of great concern for geoenvironmental engineers because engineering properties of soil determine the suitability of the soil in any project.

In this study, CM was used as a source of nitrogen and phosphorus to study the effects of biostimulation on physicochemical and geotechnical properties of soil for application in civil engineering works. The study showed that CM addition to the contaminated soil significantly reduced the total petroleum hydrocarbons concentrations and impacted positively to the improvement of the physicochemical properties of soil for use in civil engineering works.

2. MATERIALS AND METHODS

2.1. Material Collection and Sample Preparation

Soil sample for this study was collected from Kaduna Refinery, Kaduna, within 10° 27’16.85’’ N; 7° 24’46.58’’E, at a depth of 50 cm in accordance with BS 1377 (1990) as shown in Figure 1. The organic manure (chicken manure) was collected from a poultry farm and dried under the shade to avoid denaturing of the manure (FAO, 2001; Li et al., 2020).

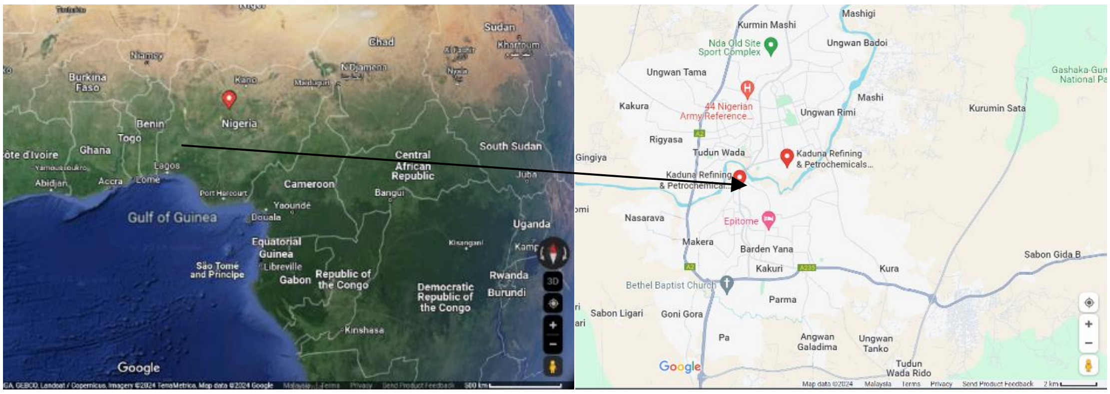

Figure 1: Location of soil sampling at Kaduna Refinery and Petrochemical Cooperation (KPRC), Kaduna State, Nigeria

2.2. Methods

2.2.1. Nutrient extraction from chicken manure

The CM at varying contents (0, 2.5, 5, 7.5, and 10 % dry weight of soil sample) was ground using a mortar and pestle to obtain a powder form. The ground CM was dissolved in water (1:10) to allow nutrient extraction particularly nitrogen and phosphorus, as described by Sushkova et al. (2021). The slurry was then filtered to collect the liquid nutrient for use in bioremediation.

2.2.2. Bioremediation process

The oil sludge contaminated soil was hydrated with the liquid nutrient extracted and kept in microcosms (plastic container) for 30- day period of the study. To ensure adequate moisture for bioremediation in the microcosm, water was added by sprinkling at interval of 2 days. Moisture meter was deployed to monitor and ensure that moisture conditions for bioremediation were maintained.

2.2.3. Organic carbon content determination

Soil sample was collected from the microcosms on a weekly bases for the organic carbon determination which was determined using Walkley-Black method based on ASTM D7572-09. The procedures started by taken 10 g of the soil sample and ground. It was then allowed to pass through 0.5mm sieve. 05g of the ground soil was transferred to 250 ml flask and added 10ml of dichromate solution ($K_2Cr_2O_7$) to disperse the soil. 20ml of concentrated H_2SO_4 was also used and the mixture was turned gently and allowed to stand for 30 minutes. 3 to 4 drops of diphenylamine indicator were added, titrated with 0.5 N ferrous ammonium sulfate. The blank titration was also carried out (i.e., without soil). Carbon content was calculated using the following expression:

$$\%Organic\ Carbon = \frac{(B-S)\times N\times 0.003\times 100\times 1.33}{W} \quad (1)$$

Where B = volume (ml) of $FeSO_4$ used in the blank, S = volume (ml) of $FeSO_4$ used in the sample, N = Normality of $FeSO_4$, 0.003= equivalent weight of carbon in /ml of 1 N dichromate, W = weight of the soil sample in gram.

2.2.4. Percentage nitrogen determination

Soil samples collected from the microcosms was used in nitrogen content determination using Kjeldahl method in accordance with AOAC (2005). Nitrogen content was calculated using the following expression:

$$Nitrogen\,\% = \frac{(V1-V2)\times N\times 14.01}{W}\times 100 \quad (2)$$

Where V_1 = volume of acid used for the sample (ml), V_2 = volume of acid used for blank (ml),

N= normality of acid, W= weight of soil sample (g), 14.01= atomic weight of nitrogen

2.2.5. Phosphorus determination

Bray-1 method was used in determination of the phosphorus content for the untreated soil because the pH value was low while that of the treated sample was determined using Olsen method based on the result of the pH test carried out on the treated soil as described by Lumbanraja et al. (2017).

The result of the phosphorus content was calculated using the following equation:

$$Available\ P = \frac{C\times Ve\times DF}{W} \quad (3)$$

Where C= concentration of phosphorus, Ve = volume of extractant used, W= weight of soil sample, DF = dilution factor.

2.2.6. TPH extraction from contaminated soil

A 10 g of soil was taken from the microcosms, air-dried in the laboratory for 3 days. 5 g of the air-dried sample was placed in a beaker containing 150 ml of toluene (solvent). The mixture was stirred before filtering and then the filtrate was oven-dried at 50°C. The TPH was determined gravimetrically in accordance with ASTM D 5765-16 (2016). Equation (4) was used in calculating the TPH

$$\text{TPH (g/kg)} = \frac{\text{Weight of contaminated soil before remediation} - \text{weight of remediated soil}}{\text{Weight of contaminated soil before remediation}} \times 100 \quad (4)$$

2.2.7. Temperature measurement

A soil thermometer was used to monitor the soil temperature of the microcosms by inserting the probe into the soil in accordance with BS 1377 (1990). The measurements were taken on a daily basis, and the average readings of the week was used in the analysis.

2.2.8. pH measurement

The ATC pH meter (model 132E- made in India) was used to monitor the pH changes in the microcosms. Readings were observed on a weekly basis in accordance with BS 1377 (1990).

2.2.9. Microorganism isolation and enumeration

Samples were taken from each microcosm on a weekly basis to observe the bacterial population. The serial dilution spread plate method was used for the isolation and enumeration of the bacteria involved in the bioremediation process in accordance with APHA Standards (2017).

2.2.10. Compaction test

Compaction was carried on both treated and untreated samples using three energy levels, namely: Standard Proctor test (BSL), WAS, and modified Proctor (BSH) following the procedures outlined in BS 1377 (1990).

2.2.11. Unconfined compressive strength test

This test was carried out on both treated and untreated samples in accordance with [BS 1377 (1990), using cylindrical core samplers with a diameter of 38 mm diameter and a height of 76 mm, which were inserted into the compacted soil. The specimens were then extruded for the UCS test. The three cylindrical specimens were used for curing at 7, 14, and 28 days, respectively. The UCS of the cured specimen were determined on the elapsed day of curing by placing the specimen centrally on the lower platen of the compression testing machine and applied compressive force to the specimen and readings were taken accordingly.

3. RESULTS AND DISCUSSION

3.1. Index Properties

The oil sludge contaminated soil considered for this study was categorized as A-5 (4) in accordance with American Association of State Highway Officials classification system (AASHTO, 1986) and SM group under Unified Soil Classification System (USCS). Table 1 shows the summary of the physical properties of the soil.

Table 1: Physical properties of the oil sludge contaminated soil.

Parameter	Quantity
Percentage passing BS sieve No. 200	38.9
Natural moisture content (%)	6.8
Liquid limit (%)	48.4
Plastic limit (%)	43.6
Plasticity index (%)	4.8
Specific gravity	2.7
AASHTO	A5(4)
USCS	SM
Colour	Dark
pH	6.9

3.2. Organic Carbon Analysis

The carbon, nitrogen, and phosphorus utilized by the bacterial species during the bioremediation process are shown in Figure 2-4. For carbon to be utilized by bacteria during metabolic activities, it has to be converted to carbon (iv) oxide and bacteria take up nutrients in a ratio of C:N:P (100:10:1), bioremediation process (Ou et a., 2024). The plot of organic carbon against CM is shown in Figure 2. It shows that the organic carbon content in 0 % CM was 12. 14%. For samples treated with 2.5, 5, 7.5, and 10% CM, the carbon content decreased to 8.2, 8.7, 6.9, and 5. 4%, respectively, for the 30-day period of bioremediation. The result of organic carbon content in the untreated sample may be as a result of the presence of oil contaminants and the inability of the bacterial species to utilize it, due to an imbalance in nutrient ratio. However, the application of the CM led to depletion or decrease in organic carbon. This shows that bacterial activities took place by utilization of nutrients for cellular build-up, leading to the reduction in TPH. This is in agreement with a study conducted by Oje et al. (2015), who reported on the effects of oil contamination on nutrients.

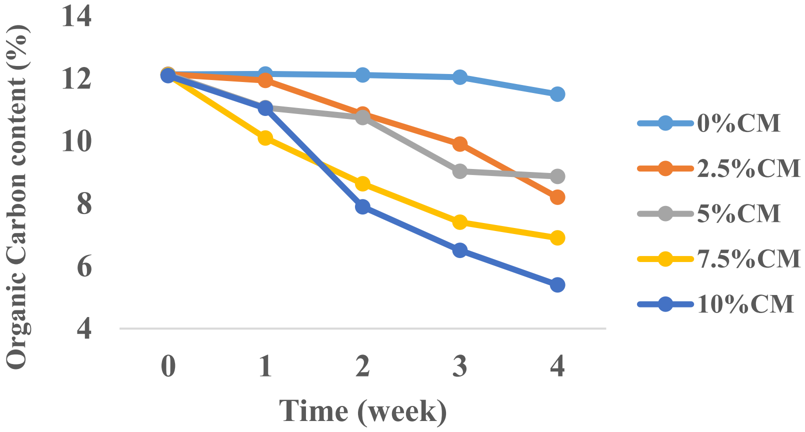

Figure 2: Carbon concentrations in control and bioremediated soil

3.3. Nitrogen Content

Figure 3 shows the variations of percentage nitrogen with CM. Nitrogen is an important nutrient used as protein by the bacteria for metabolic activities during degradation of oil petroleum hydrocarbon (Li and Li, 2025). The nitrogen decreased from 0.06 to 0.052% for the untreated sample. It was observed that the addition of CM enhances the TPH reduction. At first week of the study, the nitrogen percentage for samples treated with 2.5, 5, 7.5, and 10% CM, increased to 0.074, 0.099, 0.119, and 0.123%, respectively which initiated the bioremediation process. Further increase in nitrogen was observed by the second week of the study. However, nitrogen content declined at 3rd week to 0.055, 0.07, 0.079,0.082, and 0.087 for 0, 2.5, 5, 7.5, and 10% CM, respectively. The 4th week showed decrease in nitrogen to 0.068,0.07, 0.073, and 0.079% for 2.5, 5, 7.5, and 10% CM, respectively. The low nitrogen contents observed in the untreated sample may be attributed to the low biomass that led to decrease in microbial activity. Nitrogen is usually loss through ammonia volatilization induced by heterotrophic bacteria such as pseudomonas species which has the genes capable of fixing nitrogen (Liu, et al., 2024). The probable reason for the surge of nitrogen at 2nd week may be due to the nitrogen become readily available. It can be seen that as the time of remediation progressed, the nutrient decreased due to utilization by the bacteria species. This is because microorganisms depend on these nutrients for microbial activities. This is consistent with the findings of Ou et al. (2024) who reported that nutrients improve the efficiency of hydrocarbon degrading bacteria by increasing the amount of nutrients required.

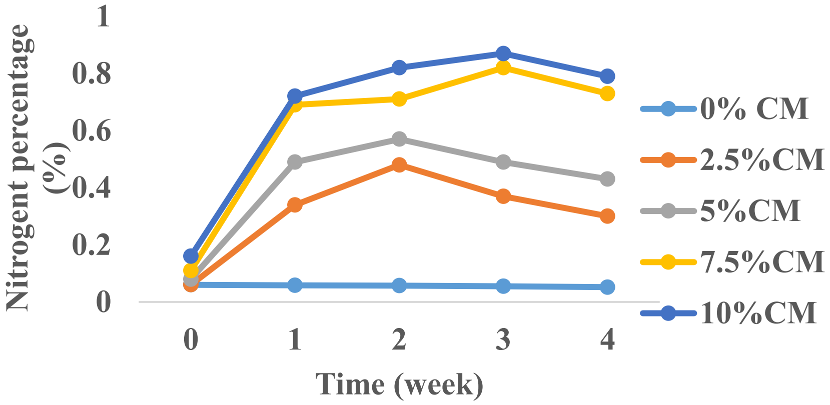

Figure 3: Nitrogen concentrations in control and bioremediated soil

3.4. Phosphorus Concentrations

Figure 4 shows the variation of phosphorus with CM over the period of bioremediation. Phosphorus is essentially needed by the microorganisms during bioremediation for energy transfer. Generally, it was observed that the phosphorus increased with increase in CM content. The 0% CM had initial phosphorus content of 0.02% and increased to 0.029% during the period of bioremediation process whereas for samples treated with 2.5% CM, the peak value of 0.057% of phosphorus content was obtained at the 3rd week of the remediation exercise. However, the 5% CM treatment, yielded the highest phosphorus content of 0.059% at the 2nd week. Similarly, the 7.5% CM produced the highest values of phosphorus content of 0.065% at the 2nd week of the experiment. While the 10% CM resulted to the production of 0.063% phosphorus. It can be seen that the phosphorus content was not enough to bring about high TPH concentrations reduction during the period of bioremediation (Wang et al., 2025). However, Ou et al. (2024), opined that addition of phosphorus in low dose facilitates hydrocarbon degradation as long as the C/P ration is maintained.

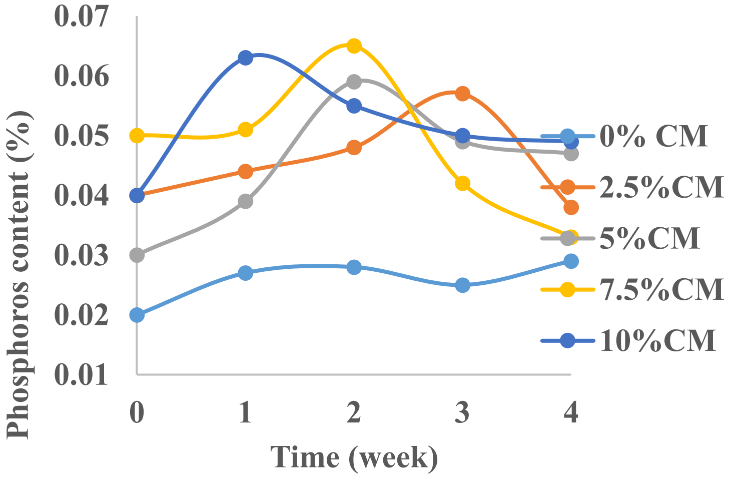

Figure 4: Phosphorus content in control and bioremediated soil

3.5. Temperature Changes

The effect of temperature on the bioremediation of the oil sludge contaminated was monitored with regard to time of remediation at varying CM content. This temperature changes served as stimulant for microbial activities that led to oil degradation. Mesophilic microorganism requires temperature within the range of 20-28°C for their growth against the thermophilic microorganism that perform best within the temperature range of 40-60°C. It was observed that the temperature range for 0 % CM was 25-28°C. For 2.5, 5, 7.5, and 10% CM, the temperature ranges from 25.9-32°C as shown in Figure 5. The average temperature for 0, 2.5, 5, 7.5, and 10% CM was found to be 26.84, 26.42, 28.8, 29, and 29.4°C. Temperatures was higher in all the treatments at 1st week and then declined at 2nd and 3rd week of remediation period. There was upsurge of temperature by the 4th week which led to TPH reduction. However, the average temperature values obtained were lower than the optimum temperature for all the microorganisms involved in the bioremediation. Hydrocarbon utilizing bacteria perform best under their optimum temperature (Zeng et al., 2023).

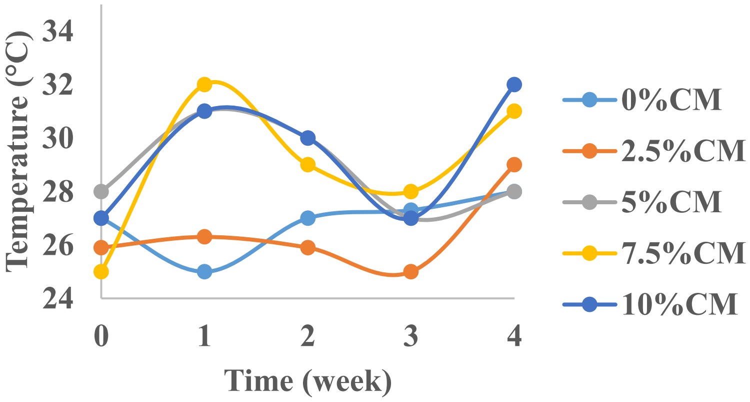

Figure 5: Temperature distribution in control and bioremediated soil

3.6. pH Changes During the Bioremediation Process

During the bioremediation study, the pH of the soil was serving a significant role in the bioremediation process as presented in Figure 6. As indicated in Figure 6, the pH of the control (0% CM) was in a slightly acidic state ranged between 6.79 to 6.9 throughout the period of the study. However, the introduction of CM raised the pH level. For 2.5, 5, 7.5, and 10% CM, the pH was raised to 7. 55, 7.6,7.61, and 7.65, respectively, during the 1st week of the study whereas the pH decreased to 7.27,7.32, 7.41, and 7.44 accordingly, by the 4th week. The increase in pH may be due to presence of ammonium and cations in the CM while the probable reason for the decrease may be due to oxidation of the ammonium by the microbes (Al-Zoubi et al., 2024).

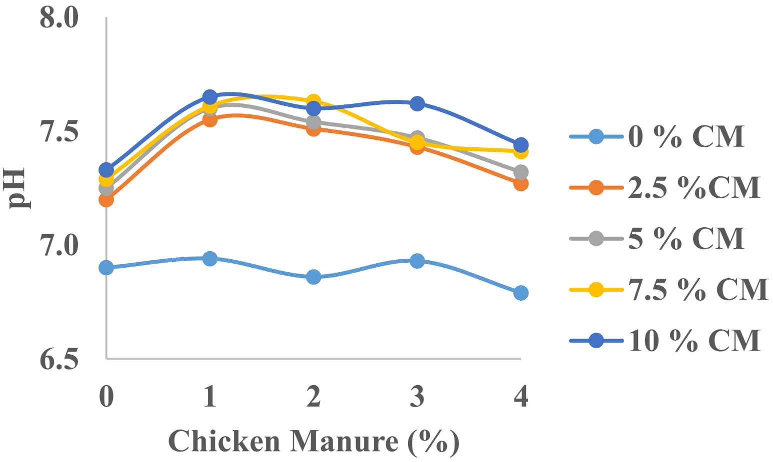

Figure 6: pH levels in control and bioremediated soil

3.7. Microbial Activities

Figure 7 shows the microbes isolated in control and treated soil. The results showed the dominant microbes in 0, 2.5, 5, 7.5, and 10% CM were *Bacilli specie, Rhodococcus, Arthrobacter, Acinetobacter, and Pseudomonas sp*., respectively. Polyak et al. (2018) reported that presence of hydrocarbons changes metabolic activity of microorganisms in oil contaminated soil. It was observed that *Pseudomonas sp.* had higher degrading ability compared to other microorganisms. The addition of CM may have been responsible for harboring the microorganisms in the treated samples since they were noticeably absence in the control. The probable reason for performance of *Pseudomonas sp*. could be attributed to higher nutrient supplied to microorganisms as evidently shown in Figure 3-4. This agrees with finding made by Sahu et al. (2020) who reported on the ability of the microbe to degrade oil when stimulated.

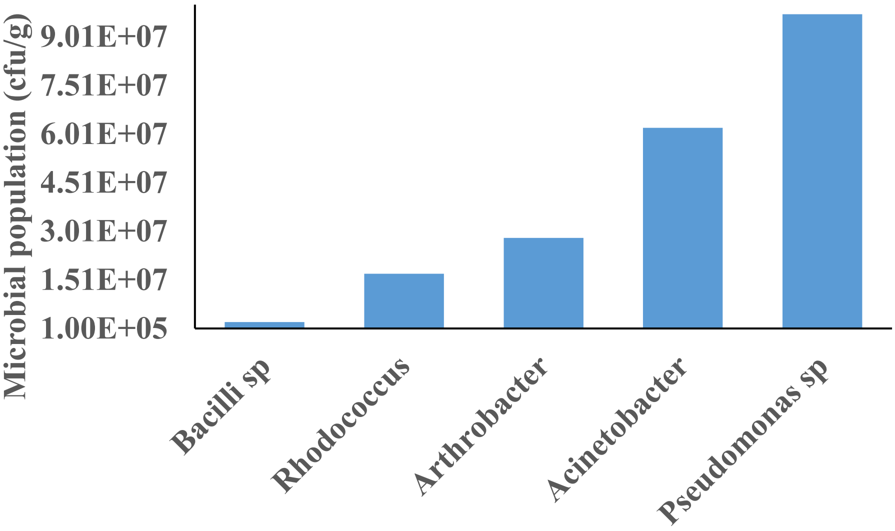

Figure 7: Microorganisms isolated from the microcosms treated with chicken manure dosages

3.8. Bioremediation of Oil Sludge

The bioremediation of oil sludge contaminated soil in the microcosms was assessed in relation to the time at various CM dosage. The bioremediation was evaluated by determination of TPH concentrations which was used as a parameter of remediation. Figure 8 shows the analysis for 0% CM (control) and the treated samples. The TPH was found out to decreased from the initial 78 to 70 g/kg at the end of the study. For 2.5, 5, 7.5, and 10% CM, the TPH concentrations reduced to 62, 59, 51, and 40 g/kg, respectively, from the initial 78 mg/kg before the experiment. CM greatly improved TPH degradation by supplying the nutrients. The removal efficiency for 0, 2.5, 5, 7.5, and 10% CM was 10.26, 20.51, 24.36, 34.62, and 48.72%, respectively. The peak TPH removal of 38 mg/kg was recorded at 10% CM treatment. This shows that more nutrients yield greater microbial activity for higher TPH removal. Similarly, the rate of degradation is shown in Figure 9. It was observed that the rate of degradation increased with an increase in time at varying CM content. The lowest rate of degradation of 8.93 mg/h was found in the control sample while the peak rate of degradation was recorded in 10% CM. The reduction of the TPH concentrations may be due to degradation of the hydrocarbons the microbes (Muthukumar et al., 2023).

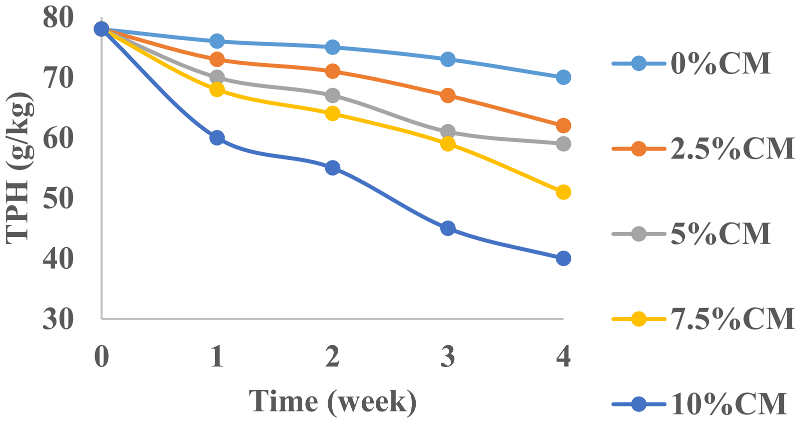

Figure 8: THP concentrations in control and bioremediated soil

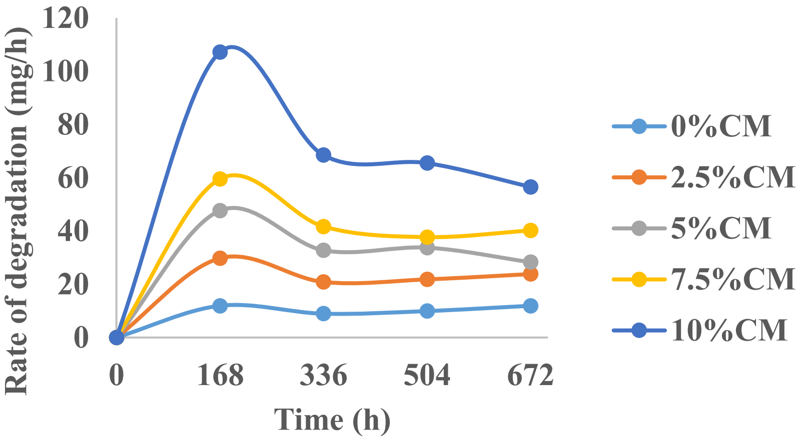

Figure 9: Rate of degradation of the oil sludge contaminant

3.9. Optimum Moisture Content

Moisture in soil serves as lubricant; thus, it dictates the behaviour of soil by making it possible to compress when it is sufficient. Figure 10 shows the optimum moisture contents (OMC) obtained for varying CM contents. It was observed that the OMC values for 0% CM content obtained at BSL, WAS, and BSH compaction energy were 25, 19.5, and 18.38%, respectively, whereas the OMC values for samples treated with 2.5, 5, 7,5, and 10% CM, compacted at BSL compaction energy were 22.8, 21.32, 19.56, and 14.93% as shown in Figure 10. Similar patterns of OMC values were observed at WAS and BSH compaction energy. The high OMC in the control (0% CM), which required a higher amount of water for the hydration of the soil, may be attributed to the presence contaminant. An increase in CM resulted in a corresponding decrease in OMC. In this current study, the presence of oil in the soil added a different dimension, as the oil occupied the voids, thereby preventing soil-moisture interactions. This may be the probable reason for higher water moulding content in the untreated samples, and as the oil content reduces in the treated samples, the OMC values decrease as a result of TPH degradation by the microbes stimulated by the CM addition. This is in agreement with the findings made by Haghsheno and Arabani (2022), who explained how hydrocarbons changes compaction characteristics.

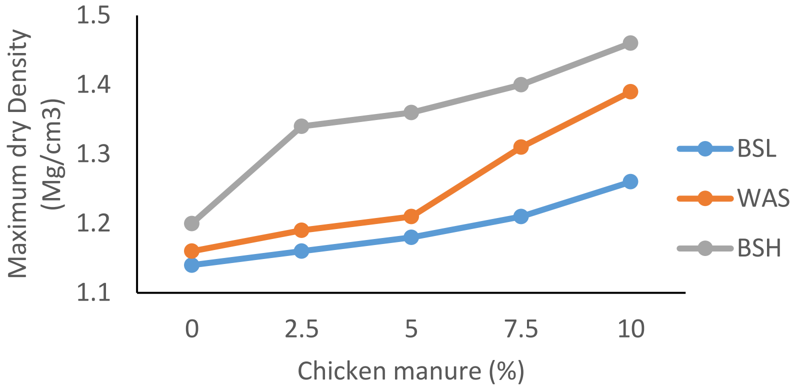

Figure 10: Molding water content in control and bioremediated soil

3.10. Maximum Dry Density

Compaction energy has a profound influence on maximum dry density, thus, the effect of biostimulation was considered in relation to compaction energy. In this study, the maximum dry density of the treated and untreated oil sludge contaminated soil is shown in Figure 11. The results show that the MDD slightly increases with an increase in the stepped concentration of CM. The MDD values for 0% CM were 1.14, 1.16, and 1.2 Mg/cm^3 compacted at BSL, WAS, and BSH compaction energy, respectively. For samples treated with 2.5% CM, the MDD values were 1.16, 1.19, and 1.34 Mg/cm^3 at BSL, WAS, and BSH compaction energy, respectively. When the CM content was increased to 5%, the MDD values increased to 1.18, 1.21, and 1.36 Mg/cm^3, compacted at BSL, WAS, and BSH energy levels. This trend of increase in MDD values was observed up to 10% CM. The probable reason for the observed increase in MDD of the treated sample may be attributed to remediation of oil contaminants that facilitated the binding together of the soil particles, making them denser with compaction. This finding is consistent with that of (Zahermand et al., 2020).

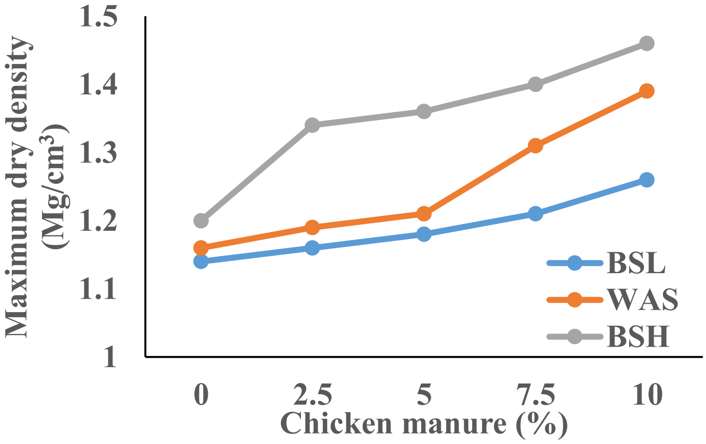

Figure 11: Maximum dry density in control and bioremediated soil

3.11. Unconfined Compressive Strength

Soil strength goes higher when certain amount of compaction energy is applied on the soil. In this study, compaction energy, curing period, and the effects of biostimulation using CM on UCS were investigated. Figure 12 shows the UCS values of the oil sludge contaminated soil treated with different dosages of CM, compacted at BSL energy level, and cured at 7, 14, and 28 days. The results showed that for samples treated with 0, 2.5, 5, 7.5, and 10% and cured at 7 days, the UCS values obtained were 56, 61, 69, 85, and 99 kN/m^2 , respectively. Similarly, the UCS values for the 14 days curing period were 63, 69, 77, 93, and 104 kN/m^2 while the 28 days curing period produced UCS values of 71, 77, 85, 101, and 112 kN/m^2. It was observed that the UCS values progressively increase with increase in CM contents. However, for 0% CM, it can be seen that the UCS values for all the curing period were lower, this may be attributed to the oil content that clogged the pore spaces between the soil particles. The probable reason for the increase in the biostimulated compacted specimens may be due to strength gained as a result of the removal of oil sludge contaminant soil which may significantly changes the strength chracteristics. Similar trends were reported by Liang et al. (2025), who showed that TPH reduction enhances the UCS of remediated soil.

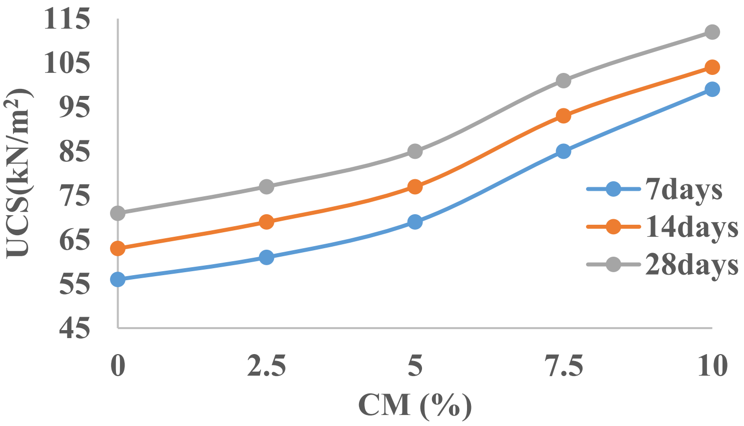

Figure 12: UCS of control and bioremediated soil at BSL energy level

For an intermediary compaction energy (WAS), the UCS is slightly higher than UCS and lower than modified Proctor Standard (BSH). Figure 13 shows the results of UCS of the oil sludge contaminated soil treated with CM and compacted using WAS compaction energy. The 0% CM had lower UCS values of 64, 72, and 85 kN/m^2 for 7, 14, and 28- days curing period, respectively. The peak values of UCS were obtained at 10 % CM treatment. The lower values of UCS obtained at 0% treatment may be attributed to the presence of oil contaminant. The oil contaminated soil-water relationship is hydrophobic in nature making it difficult for the 0% CM to develop strong bonding in the soil. This is because soil is naturally a non-polar substance thus attraction of the electrically charged ions become difficult. This finding is consistent with the one reported by Azam et al. (2022).

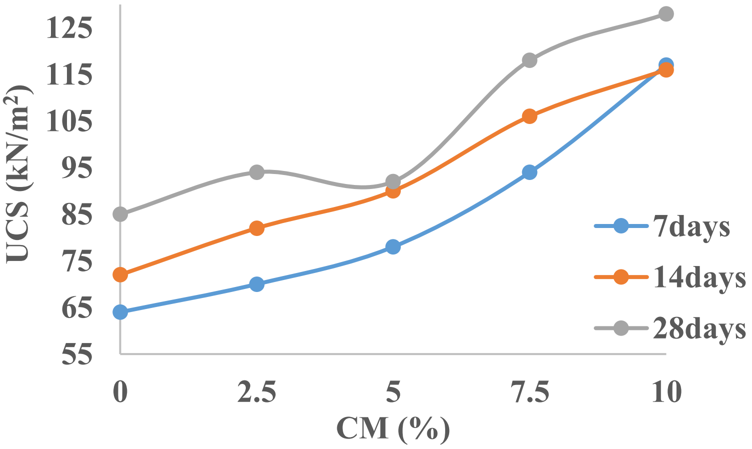

Figure 13: UCS of control and bioremediated soil at WAS energy level

The effects of CM on UCS compacted at BSH energy level is shown in Figure 14. The results indicated that the UCS values obtained for 0% CM were 80, 105, and 123 kN/m^2 cured at 7, 14, and 28-days curing period, respectively. Additionally, the UCS values for 2.5, 5, 7.5, and 10% CM cured at 7 days were 86, 94, 110, and 138 KN/m^2, respectively. It has been generally observed that the UCS values increased with increase in CM content for all the 3 days curing period. The peak UCS values of 138, 158, and 208 KN/m^2 were obtained at 10% CM for 7,14, and 28-days curing period. The TPH reduction in 0% CM was low. Therefore, the probable reason for the low UCS values for the untreated oil sludge contaminated soil may be attributed to the oil content that coated the soil particles thereby inhibiting the soil from binding together which resulted to lack of strength. Similarly, the increased in the UCS values may be due to the reduction in hydrocarbons leading to formation of compact and strong binding in the treated samples. This finding is in agreement to that of Vijayan et al. (2024) and Alhassan et al. (2023) who reported that UCS decreases in oil contaminated soil and microbial activities leads to oil degradation.

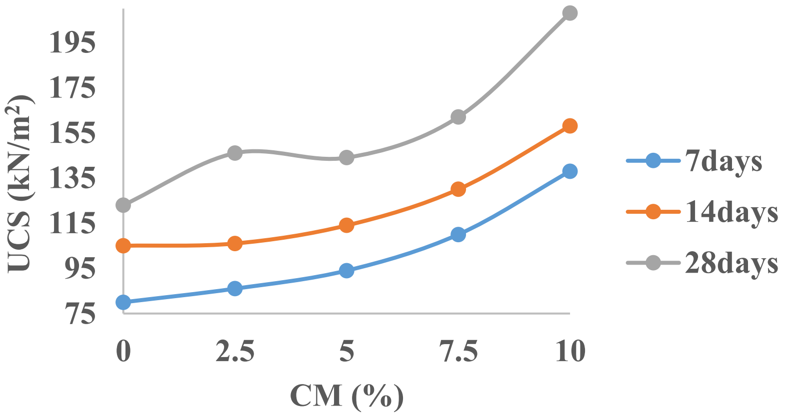

Figure 14: UCS of control and bioremediated soil at BSH energy level

4. CONCLUSION

The purpose of the study was to investigate the effect of oil sludge contamination and bioremediation on the physical, chemical, biological, and geotechnical properties of oil sludge contaminated soil. Results recorded show that the oil sludge contaminated soil classifies as A-5 (4) soil based on the AASHTO classification system or belongs to SM group under the Unified Soil Classification System, containing a liquid limit, plastic limit, and plasticity index of 48.4, 43.6, and 4.8%, respectively. Bio-stimulation using chicken manure degraded the oil content to about 48.72% in 30 days. The addition of chicken manure to oil sludge contaminated soil decreased carbon to 5.4%, while nitrogen and phosphorus increased to 0.87 and 0.063%, respectively. The temperature and pH of the microcosms ranged between 25 to 32°C and 6.9 to 7.65, respectively. The introduction of CM led to the decrease of OMC to 12.5% from 25% of the control due to a higher water requirement for hydration owing to the oil contamination. The MDD and UCS increased with an increase in CM content to 1.46 Mg/cm^3 and 208 kN/m^2 from 1.14 Mg/cm^3 and 123 kN/m^2, respectively, due to formation of a stronger bonding and oil degradation. The UCS of 208 kN/m^2 met the permissible limit requirement for soil material to be used as liner in waste containment systems. However, other important parameters such as hydraulic conductivity and volumetric shrinkage strain were not evaluated. The study showed that bio-stimulation strategy using chicken manure has the ability to restore oil sludge contaminated soil, and the significance of the study includes environmental control and management of oil pollution.

5. ACKNOWLEDGMENT

The author expresses their thanks to Engr. Habibu Abubabakar and Mallam Rabiu of NNPCL Kaduna for assisting in sample collection for this research work.

6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

REFERENCES

AASHTO (1986). Standard Specifications for Transport Materials and Methods of Sampling and Testing.14th Edition, Washington, D.C. American Association of State Highway and Transport Officials.

Al-Zoubi, A. I., Alkhamis, T. M. and Al-Zoubi, H. A. (2024). *Optimized biogas production from poultry manure with respect to pH, C/N, and temperature. Results in Engineering,* 22-102040. Available electronically at https://doi.org/10.1016/j.rineng.2024.102040 Accessed on April, 2025.

Alhassan, M. K., N. N. Nok Daud and S. Celik. (2023). Strength behaviour of treated oil contaminated soil: The role of indigenous microbes. Paper presented at 11th International Symposium on Applied Engineering and Sciences, 20th- 21st November, 2023, Malaysia. 306-307.

American Public Health Association (2017). *Standard Methods for the Examination Water and Wastewater* (23rd ed). American Public Health Association, Washington, DC.

AOAC International. (2005). Official Methods 978.04: Nitrogen in fertilizers-Kheldah method. In *Official Methods of Analysis of AOAC AOAC International* (18th ed.). Gaithersburg, MD, USA: AOAC International.

ASTM International. (2009). ASTM D7572-09: *Standard guide for recovery of aqueous cyanides by extraction from mine rock and soil after remediation of process releases.* ASTM International. West Conshohocken, PA. available electronically at https://doi.org/10.1520/D7572-09 Accessed on March, 2019.

ASTM D5765-16 (2016). *Standard Practice for Solvent Extraction of Petroleum Hydrocarbons from Soils and Sediments Using Closed Microwave Heating*, ASTM International, West Conshohocken, PA.

Azam, M. S., Xiao, Z. and Mia, M. R., (2022). Effects of oil contamination on the geotechnical properties of clayey soil. *Journal of ICT, Design, Engineering and Technological Science,* 6(2), pp. 8-14.

Atai E., Jumbo, R. B. and Cowley, T. (2023). *Efficacy of bioamendments in reducing the influence of salinity on the bioremediation of oil contaminated soil. Science of the Total Environment,* 892-164720.Available electronically at https://doi.org/10.1016/j.scitotenv.2023 Accessed on October, 2025.

Awarri, A. W. and West, A. R. (2025). Geotechnical Characterization of Fuel Contaminated Soil. *Journal of Advances in Geotechnical Engineering,*8(1), pp. 31-40.

Behera, I. D., Manoranjan, N. and Mishra, A. (2022). *Strategic implementation of integrated bioaugmentation and biostimulation for efficient mitigation of petroleum hydrocarbon pollutants from terrestrial and aquatic environment. Marine Pollution Bulletin*, 177-113492. Available electronically at https://doi.org/10.1016/j.marpolbul.2022.113492 Accessed on June 2025.

BS 1377 (1990). Methods of testing soils for civil engineering purposes. British Standard Institute, London, England. (BS).

Dai, Y., Cai, X., Wang, S., Zhao, C. (2025*). Synergistic effects of surfactant biostimulation and indigenous fungal bioaugmentation for enhanced bioremediation of PAH-contaminated soils. Environmental Pollution,* 375-126304. Available electronically at https://doi.org/10.1016/j.envpol.2025.126304 Accessed on May 2025.

Dehnavi, S. M. and Ebrahimipour, G. (2022). Comparative remediation rate of biostimulation, bioaugmentation, and phytoremediation in hydrocarbon contaminants. *International Journal of Environmental Science and Technology*, 19 (11), pp. 11561-11586.

Devatha, C. P.,Vishal, A. V., Puma, J. and Rao, C. (2019). Investigation of physical and chemical characteristics on soil due to crude oil contamination and its remediation. *Applied Water Science*, 9 (4), pp. 89-95.

Doughlas, R. K., Araka, P. P. and Fou, A. (2025). Evaluation of the potential of agricultural wastes-cattle manure and poultry manure for bioremediation of crude oil-contaminated soil. *Bioremediation Journal,* 29(1), pp.96-103. https://doi.org/10.1080/10889868.2024.2322471

Food and Agricultural Organization of the United Nations (FAO). (2001). *Guide to efficient plant nutrient management.* FAO. Rome, Italy.

Goswami, M., Chakraborty, P. and Mukherjee, K. (2018). Bioaugmentation and biostimulation: a potential strategy for environmental remediation. *Journal of Microbiology Experiment*, 6(5), pp. 223-231.

Hassan, A. M. A., Kamal, R. S., Farag, R. K. and Abdei-Raof, M. E. (2024). Petroleum sludge formation and its treatment methodologies: a review. *Environmental Science and Pollution* Research, 31(6), pp. 8369-8386.

Haghsheno, H. and Arabani, M. (2022). Geotechnical properties of oil polluted soil: a review. *Environmental Science and Pollution Research*, 29, pp. 3260-32701.

Khazaal, R. M. and Ismail, Z. Z. (2021). Bioremediation and Detoxication of Real Refinery Oily Sludge using Mixed Bacterial Cell. *Petroleum Research*, 6, pp. 303-308.

Li, X., Li, B., and Tong, Q. (2020). *The effect of drying temperature on nitrogen loss and pathogen removal in laying hen manure*. *Sustainability,*12 (1), pp. 403.

Li, J. and Li, G. (2025). Nitrogen Addition on the Physicochemical Properties and Microbial Diversity of Spring Wheat Soil in the Loess Plateau. *Agronomy,* 15(2584, pp. 1-18. https://creativecommons.org/licenses/by/4.0/

Liang, J., Zheng, X., and Wang, L. (2025). *Studying the properties of solidified oil-contaminated soil by magnesium oxychloride cement*. *Scientific Reports*, 15-19846. Available at https://doi.org/10.1038/s41598-025-05031

Liu, X., Yang, R., Zhao, J. and Xiao, D. (2024). Effects of biological nitrogen fixation and nitrogen deposition on soil microbial communities. *Microorganisms,*12 (12), pp. 24-29.

Lumbanraja, J., Mulyani, S. and Utomo, M. (2017). Phosphorus Extraction from Soil Constituents Using Bray P-1 Mehlich-1 and Olsen Solutions. *Journal of Tropical Soils*, 22(2), pp. 68-76.

Matilda, M. I., and Samuel, H. S. (2024). *Bioremediation of oil Spill: concepts, methods and applications*. *Discovery Chemistry*, 1(1), pp. 42. Available electronically at https://doi.org/10.1007//s44371-024-00038-2

Mekkiyah, H. M., Al-Hamadani, Y. A. J. and Abdulhameed, A. S (2023). *Effects of crude oil on geotechnical properties of various soils and the developed remediation methods*. *Applied science*, 13-9103. https://doi.org/10.3390/app13169103

Muthukumar, B.Surya, S., Sivakumar, K. and Al-Salhi, M. S. (2023). Influence of bioaugmentation in crude oil contaminated soil by Pseudomonas species on the removal of total petroleum hydrocarbon. *Chemosphere,* 310-136826. Available at https://doi.org/10.1061/j.chemosphere.2022.136826 Access on January 2025.

Nong, J., Peng, P., Pan, J. and Shen, T. (2023). Effect of bioaugmentation and biostimulation on hydrocarbon degradation and bacterial community composition in different petroleum-contaminated soil layers. *Water, Air, and Pollution*, 234-561. Available electronically at https://doi.org/10.1007/s11270/s11270-023-06161-7 Access on September 2025.

Oje, O. A., Ubani, C. S. and Onwurah, I. N. E. (2015). Variation in Carbon (C), Phosphorus (P) and Nitrogen (N) Utilization during the Biodegradation of Crude Oil in Soil. *Petroleum and Environmental Biotechnology,* 6(2), pp.1-7.

Osinubi, K. J. and Nwaiwu, C. M. O. (2005). Hydrocarbon contamination effects on geotechnical properties of fined-grained soils. *Nigerian Journal of Soil Science*, 131 (8), pp.1034-1041.

Ou,Y., Wu, M., Yu, Y. and Liu, Z. (2024). Low dose phosphorus supplementation is conducive to remediation of heavily petroleum-contaminated soil- From the perspective of hydrocarbon removal and ecotoxicity risk control. *Science of the Total Environment*, 929-172478. https://doi.org/10.1016/j.scitotenv.2024.172478

Polyak, Y. M., Bakina, L. G., Chugunova, M. V. and Mayachkina, N. T. (2018). Effect of remediation strategies on biological activity of oil-contaminated soil -A field study. *International Biodeterioration and Biodegradation*, 126, pp.57-68.

Popoola, L. T., Yusuff, A. S., Adeyi, A. A. (2022). Bioaugmentation and biostimulation of crude oil contaminated soil: Process parameters influence. *South African Journal of Chemical Engineering,* 39(1), pp.12-18.

Rondom-Afanador, C., Pinilla-Miza, G., Casalla-Cuevro, F. C. (2023). Bioremediation of heavy of heavy oily sludge: a microcosm study. Biodegradation 34, pp.1-20. https://doi.org/10.1007/s10532-022-10006.

Saeed, H., Nalbantoglu, Z. and Uygar, E. (2025). A Comprehensive Review of Hydrocarbon Contaminated Soil Behavior, Geotechnical Properties and Potential Remediation. *Soil and Sediment Contamination Journal*, 34(6), pp.1023-1067.

Salimnezhad, A. soltani-jigheh, H. and Sorki, A. A. (2020). Effects of oil contamination and bioremediation on geotechnical properties of highly plasticity clayey soil. *Journal of Rock Mechanics and Geotechnical Engineering*, 13, pp. 653-67.

Sahu, M., Kumar, D. and Kumar, S. (2020). Bioremediation of crude oil contaminated soil by hydrocarbon degrading bacteria. *International Journal of Advanced Research*, 8(10),866-873.

Suyartmana, P. and Setiawati, M. R. (2022). The Petroleum Hydrocarbon Bioremediation Performance by Inoculating Consortium Petrophylic and the Chicken Manure Amendment. Journal of Agriculture, Environment and Bioresearch, 7(4), pp.60-71.

Stepanova,Y. A., Gladkov, E. A., Osipova, E. S. and Gladkova, O. V. (2022). Bioremediation of soil from petroleum contamination. *Process*, 10 (6), pp.12-24.

Sushkova, S., (2021). Subcritical water extraction of organic acids from chicken manure. *Journal of the Science and Food and Agriculture*, 101(4), pp. 1523-1529.

Vijayan, A., Subash, S. and Athulya, V. P. (2024). Evaluation of geotechnical properties of oil contaminated laterite soil. *International Journal of Engineering Research and Technology (IJERT),* 13(5), pp.1-5.

Wang, X., Du, Z., Li, Z. and Liu, M. (2025). Enhanced biodegradation of crude oil by phosphate-solubilizing bacteria Bacillus subtilis PSB-1: Overcoming soluble phosphorus deficiency. *Journal of Environmental Managemen*t, 391-126426. https://doi.org/10.1016/j.jenvman.2025.126426

Zahermand, S., Vafaeian, M. and Bazyar, M.H. (2020). Analysis of the physical and chemical properties of soil contaminated with oil (petroleum) hydrocarbons. *Earth Science Research Journal*, 24(2), pp.163-168.

Zeng, J., Wu, R., Peng, T. and Li, Q. (2023). Low-thermally enhanced bioremediation of polycyclic aromatic hydrocarbon-contaminated soil: Effects on fate, toxicity and bacterial communities. *Environmental Pollution,* 335, 122247.