Arabian Journal of Chemical and Environmental Research

Vol. 13 Issue 2 (2026) 381–395

Enhanced biodegradation of crude oil–contaminated soil using organic solid waste: Effects on pH, microbial dynamics and residual hydrocarbon concentration

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Received 03 April 2026, Revised 07 May 2026, Accepted 09 May 2026

Cited as: *Ngbodi Anthonia O., Mbah Juliet C., Eyide O., Ejejigbe E.S. and Obahiagbon K.O. (2026) Enhanced biodegradation of crude oil–contaminated soil using organic solid waste: Effects on pH, microbial dynamics and residual hydrocarbon concentration, Arab. J. Chem. Environ. Res. 13(2), 381-395*

ABSTRACT

Crude oil contamination significantly impairs soil quality and poses serious environmental risks in oil-producing regions. This study evaluated the bioremediation of crude oil–polluted soil using organic solid waste as a low-cost biostimulatory amendment. Contaminated soil samples were treated with varying amendment weights (0.4, 0.8, 1.6, 2.4, and 3.2 kg), while an untreated control was included. The remediation process was monitored for eight weeks using pH, microbial count, and residual hydrocarbon concentration as performance indicators. Results showed a progressive increase in pH in all amended samples, suggesting improvement in soil conditions favorable for microbial activity. Microbial count remained relatively stable during the initial two weeks, indicating a lag phase, but increased markedly from the third week, corresponding to the exponential growth phase and active hydrocarbon utilization. Residual hydrocarbon concentration decreased substantially in all treatments, with the 3.2 kg amendment showing the highest degradation efficiency, reducing the concentration from about 5602 mg/L to 18 mg/L by week 8. The combined trends confirm that the amendment enhanced biodegradation by stimulating indigenous hydrocarbon-degrading microorganisms and improving the physicochemical environment of the soil. The study demonstrates that organic solid waste is an effective and sustainable amendment for the remediation of crude oil–polluted soil, with remediation efficiency increasing with amendment dosage.

Keywords: Bioremediation; Crude oil–polluted soil; Organic solid waste; Hydrocarbon degradation; Microbial count; Soil pH.

1.0 Introduction

Environmental pollution resulting from crude oil exploration, transportation, refining, and storage has become a major global concern, particularly in oil-producing regions. Among the various forms of pollution associated with petroleum activities, soil contamination by crude oil is one of the most severe due to its long-term adverse effects on soil quality, agricultural productivity, groundwater safety, and ecosystem stability (Barnes et al., 2023). Crude oil contains a complex mixture of hydrocarbons, including alkanes, cycloalkanes, aromatic hydrocarbons, resins, and asphaltenes, many of which are toxic, persistent, and resistant to natural degradation. When crude oil is released into the environment through spills, leakages, pipeline rupture, sabotage, or improper disposal practices, it infiltrates the soil matrix and alters the physical, chemical, and biological characteristics of the soil (Wu et al., 2017).

In many oil-producing countries, especially developing nations such as Nigeria, crude oil contamination of soil is a recurring environmental issue. The Niger Delta region, which hosts a significant portion of Nigeria's petroleum reserves and oil infrastructure, has experienced thousands of oil spill incidents over the years. These spills have caused extensive damage to farmlands, wetlands, mangrove forests, and residential areas. Crude oil pollution reduces soil aeration, blocks pore spaces, lowers water infiltration, inhibits seed germination, suppresses microbial activity, and decreases the availability of essential plant nutrients. In severe cases, it renders agricultural land unproductive for many years, thereby threatening food security and rural livelihoods (Santos et al., 2025).

Traditional remediation methods such as excavation, incineration, thermal desorption, soil washing, and chemical oxidation have been employed to manage hydrocarbon-contaminated soils (Ayilara et al., 2023). However, many of these methods are expensive, energy-intensive, environmentally disruptive, and often unsuitable for large-scale application in low-resource settings. Mechanical and chemical remediation methods may also transfer contaminants from one environmental medium to another rather than completely eliminating them (Muhammad et al., 2022). Consequently, there has been growing interest in the development of sustainable, cost-effective, and environmentally friendly remediation technologies, among which bioremediation has emerged as one of the most promising (Akartasse et al., 2022; El Hammari et al., 2022; Zaaboul et al., 2055).

Bioremediation is the process of using living organisms, primarily microorganisms such as bacteria and fungi, to degrade, detoxify, transform, or remove pollutants from contaminated environments (Gielnik et al., 2021). In the context of crude oil-polluted soils, bioremediation exploits the metabolic capabilities of indigenous or introduced microorganisms to break down hydrocarbon compounds into less harmful substances such as carbon dioxide, water, and biomass (Nagendran et al., 2006). The efficiency of bioremediation depends on several factors, including the type and concentration of pollutants, soil pH, moisture content, oxygen availability, nutrient levels, temperature, and microbial population density (Obi et al., 2022).

One of the major limitations of natural bioremediation in crude oil-contaminated soils is the insufficient availability of nutrients, particularly nitrogen and phosphorus, which are essential for microbial growth and enzymatic activity (Lin et al., 2022). Crude oil is rich in carbon but deficient in nutrients required by hydrocarbon-degrading microorganisms. This imbalance in the carbon-to-nitrogen-to-phosphorus (C:N:P) ratio often slows down the biodegradation process (Zhang et al., 2024). To overcome this challenge, nutrient amendments are commonly introduced into contaminated soils to stimulate microbial activity, a process known as biostimulation.

In recent years, researchers have explored the use of various organic and inorganic amendments such as poultry manure, cow dung, compost, sawdust, rice husk, agricultural residues, and municipal wastes to enhance the biodegradation of petroleum hydrocarbons in soil (Udume et al., 2023). Among these materials, solid waste dump materials have attracted attention due to their abundance, low cost, and potential to improve both the nutrient status and microbial diversity of contaminated soils (Okoh et al., 2020). A solid waste dump typically consists of decomposed or partially decomposed municipal, household, and organic waste materials that may contain rich populations of microorganisms, organic matter, nitrogen, phosphorus, potassium, and trace elements (Gayathri and Krishnaprema, 2023). These properties make solid waste dump materials a potentially effective amendment for stimulating the biodegradation of crude oil in polluted soils (Muhammad et al., 2022).

The concept of using solid waste dump as a bioremediation agent is based on the principle that decomposed waste materials can serve multiple functions simultaneously. First, they can provide essential nutrients that stimulate the growth of hydrocarbon-utilizing microorganisms (Elshafei and Mansour, 2024). Second, they may introduce or enrich indigenous microbial consortia capable of degrading petroleum hydrocarbons (Bayat et al., 2015). Third, the organic matter in the waste can improve soil structure, aeration, moisture retention, and porosity, thereby creating favorable environmental conditions for microbial metabolism. Fourth, the amendment may buffer pH and enhance enzymatic activity in the soil system. As a result, the application of solid waste dump to crude oil-contaminated soil may accelerate the reduction of total petroleum hydrocarbons (TPH) and promote the recovery of soil quality (Marwa, 2024).

The use of solid waste dump in remediation also aligns with the principles of waste-to-resource management and the circular economy. Rather than viewing municipal solid waste solely as an environmental burden, it can be repurposed as a beneficial amendment for restoring polluted ecosystems (Hazim and Al-Ani, 2019). This dual-purpose approach addresses two environmental problems simultaneously: crude oil contamination and improper solid waste disposal. In many developing countries, poor waste management practices have led to the proliferation of open dumpsites, which themselves pose health and environmental risks (Abarian et al., 2019). Harnessing materials from these dumpsites for environmental remediation can therefore provide an innovative and sustainable solution, provided that such materials are properly characterized and applied under controlled conditions (Ibrahim et al., 2020).

Several studies have demonstrated the effectiveness of organic waste-based amendments in enhancing hydrocarbon degradation in contaminated soils. For instance, composted municipal waste, sewage sludge, animal manure, and food waste residues have been reported to improve microbial respiration, increase hydrocarbon degradation rates, and restore soil fertility. However, the use of solid waste dump materials specifically as a direct amendment remains underexplored in many local contexts, particularly in Nigeria. This creates a need for empirical investigation into how such materials influence the remediation of crude oil-polluted soils under specific environmental conditions (Abarian et al., 2019).

Furthermore, soil remediation in the Nigerian context requires technologies that are accessible, affordable, locally available, and technically feasible. Imported remediation chemicals and advanced mechanical technologies may not be practical for rural communities, small-scale farmers, or local environmental management agencies. By contrast, solid waste dump materials are often readily available around urban and peri-urban settlements and may be obtained at minimal cost. If proven effective, they could serve as a practical alternative for local bioremediation programs, especially in regions where crude oil spills and waste disposal challenges coexist.

Despite the potential benefits, the application of solid waste dump materials in soil remediation also raises important scientific and environmental questions. The composition of dump materials can vary widely depending on the source, age, and type of waste deposited. Some dumps may contain hazardous substances such as heavy metals, plastics, or toxic residues that could introduce secondary contamination if not properly screened (Santos et al., 2025). Therefore, any use of solid waste dump materials in bioremediation must be preceded by adequate characterization to assess their nutrient content, microbial load, pH, moisture content, organic carbon level, and potential contaminants. The balance between remediation benefits and possible risks must be carefully evaluated.

In addition to contaminant reduction, effective remediation should also consider soil quality restoration. A remediated soil is not only one with reduced pollutant concentration but also one that regains its ability to support plant growth, microbial activity, and ecological functions. Thus, the use of solid waste dump materials may offer a broader ecological benefit by enhancing soil fertility, increasing organic matter, and improving soil physicochemical properties after contamination.

This study therefore focuses on the bioremediation of crude oil polluted soil using solid waste dump materials as an amendment. The study seeks to investigate the extent to which solid waste dump can enhance the degradation of petroleum hydrocarbons and improve soil properties over time. By evaluating relevant parameters such as pH, moisture content, total petroleum hydrocarbons, organic carbon, microbial activity, and nutrient availability, the study aims to generate scientific evidence on the suitability of solid waste dump as a low-cost biostimulant for crude oil remediation.

Ultimately, the findings of this study are expected to contribute to the growing body of knowledge on sustainable environmental remediation technologies and provide a practical framework for managing crude oil-contaminated soils in resource-limited settings.

2.0 Experimental

2.1 Collection of soil sample

The soil sample was collected from the back of Chemical Engineering Department in the University of Benin, Ugbowo. The soil samples were placed in polythene bags and conveyed to the research laboratory of University for analysis. The soil samples were bulked together to form a composite, mixed thoroughly, crushed and passed through a 2mm sieve to remove large particles of stone and soil. 50 g of the sieved soil sample was taken for physico-chemical analysis. Figure 2.1 shows a small portion of the soil sample.

Figure 2.1 The soil sample.

2.2 Collection of crude oil

The crude oil was obtained from Warri Refinery, Ekpan Delta State. The oil with a dark brown viscous liquid used to pollute the soil. Figure 2.2 shows a small amount of the crude oil sample.

Figure 2.2 The crude oil sample.

2.3 Collection of organic wastes

The solid wastes used in this study was obtained from Oluku waste dump site in polythene bags and transported to the University Laboratory for analysis. The collection and analysis procedure were according to (ASTM D1586, 2018). The solid waste was then measured using a weighing balance in varying masses and then added to the polluted soil. Figure 2.3 shows the organic waste sample.

Figure 2.3 The organic waste sample.

2.4 Characterization of crude oil, soil sample and organic wastes before Bioremediation process

Some of the physical and chemical characteristics of the three samples were determined. These include. Moisture Content, Density, Viscosity, Total Nitrogen, Phosphorus, Potassium, Lead (Pb), Cadmium (Cd). The characterization was determined by using the standard Association of Official Analytical Chemists (AOAC, 1990) methods.

2.5 Experimental Design and Soil Contamination

A batch experimental setup was employed for the study. 40g of prepared soil were artificially contaminated with crude oil to simulate pollution conditions. The contaminated soil was thoroughly mixed to ensure uniform distribution of hydrocarbons and allowed to equilibrate for 48 hours before amendment application.

The experiment consisted of six treatment setups:

Control (C): Polluted soil without amendment
T_1: Polluted soil + 0.4 kg organic solid waste
T_2: Polluted soil + 0.8 kg organic solid waste
T_3: Polluted soil + 1.6 kg organic solid waste
T_4: Polluted soil + 2.4 kg organic solid waste
T_5: Polluted soil + 3.2 kg organic solid waste

Each treatment was set up in triplicate to ensure reproducibility. The soil–amendment mixtures were thoroughly mixed and maintained under ambient laboratory conditions. A pilot of the process is as seen in Figure 2.4.

2.6 Bioremediation Procedure

The bioremediation study was conducted over a period of eight (8) weeks. The experimental units were periodically mixed (twice weekly) to enhance aeration and microbial activity. Moisture content was maintained at approximately 60% of water holding capacity by periodic addition of distilled water to support microbial metabolism.

No external microbial inoculum was added, allowing the process to rely on indigenous microorganisms and those introduced through the organic solid waste amendment.

2.7 Sampling Schedule

Soil samples were collected at weekly intervals (Week 1 to Week 8) from each treatment setup. Samples were homogenized and analyzed immediately or stored under appropriate conditions prior to analysis.

2.8 Physicochemical Analysis

The samples were allowed in a close environment for 7days to develop microbes before readings were taken. Parameters such as pH, residual hydrocarbon concentration (RHC) and Total Microbial Count (TMC) were monitored over the period of 7week.

Figure 2.4 The mixture of soil sample and crude oil sample

2.8.1 Determination of pH

20g of the soil sample was weighed into a 100ml beaker containing 20ml of distilled water. The mixture was stirred thoroughly and allowed to stand for 30 minutes. A pH meter was used to read the pH of a soil.

Figure 2.5 The pH procedure on the mixed sample

2.8.2 Determination of Residual Hydrocarbon Concentration

5g was weighed into a 100ml bottle containing 25ml of n-hexane. The bottle was stirred for 10 minutes and allowed to stand. The sample was then filtered and the filtrate read at 460nm. The RHC of the sample was determined using;

$$RHC_{\frac{mg}{kg}soil} = \frac{absorbance \times CF \times DF \times EV}{Weight\ of\ the\ soil}$$

$$where\ CF = conversion\ factor\ from\ absorbance\ to\ \frac{mg}{extract}$$

$$DF = dilution\ factor$$

$$EV = extract\ volume\ of\ solvent$$

2.8.3 Determination of Total Microbial Count

Dilution of the soil sample was prepared by washing soil with distilled water and diluted using the diluents already prepared. The colony country chamber was assembled by applying the cover glass. Few drops of methylene blue solution were added to the water sample. The chamber was allowed to sit for 5 minutes and examined under microscope using a 4mm lens to count the bacteria in 50. Figure 2.6 show the count in experiment.

Figure 2.6 The microbial count procedure on the mixed sample

3.0 Results and Discussion

3.1 Physicochemical characterization of crude oil, soil sample and organic wastes before Bioremediation process

Table 3.1 shows some basic composition of the raw materials before bioremediation. The crude oil sample was characterized and found to possess a density of 0.872 g/cm³ and viscosity of 18.6 cP, indicating a medium crude oil with moderate flow properties. Nutrient analysis of the soil showed low total nitrogen (0.18%) and phosphorus (8.6 mg/kg), suggesting nutrient deficiency that could limit indigenous microbial degradation. This result is in line with work done by Udume et al., (2023) reporting values of 0.17% for Nitrogen and phosphorous of 7.8 mg/kg. The organic waste has a total nitrogen of 2.46%, phosphorus of 1.285 mg/kg, potassium of 8,940 mg/kg, and a C/N ratio of 10.1, indicating strong potential for use as a biostimulant in the remediation of crude oil contaminated soil. This work is in line with work done by Gayathri and Krishnaprema, (2023) on the influence of organic waste on bioremediation of oil-contaminated soil. Muhammad et al., (2022) also reported in their study that the percentage of nitrogen in a soil obtained from an oil area was very low (0.92%) compared it to Organic carbon (10.5%), and Phosphorous (19.2mg/kg).

Table 3.1 Physicochemical characterization of crude oil, soil sample and organic wastes before Bioremediation

Parameter	**Unit**	**Crude Oil**	**Soil Sample**	**Organic waste**
Moisture Content	%	1.62	14.8	23.6
Density	g/cm³	0.872	1.39	N/A
Viscosity	cP	18.6	N/A	N/A
Total Nitrogen	%	N/A	0.18	2.46
Phosphorus	mg/kg	N/A	8.6	1.285
Potassium	mg/kg	N/A	92.4	8,940
C/N Ratio	-	N/A	38.4	10.1
Lead (Pb)	mg/kg	N/A	18.6	2.8
Cadmium (Cd)	mg/kg	N/A	1.12	0.21
Zinc (Zn)	mg/kg	N/A	41.8	38.6

3.2 pH Effect with Time

Figure 3.1 shows the values of pH of the different sample over a period of eight weeks. For the first week, it was observed that the sample with the solid waste of 1.6kg had the pH value of 5.39 indicating that the soil is acidic and an unfavorable environment for optimal microbial growth (Elshafei and Mansour, 2024). In the second week, the solid waste was added and a slight increase in the pH was observed in all samples. Over longer weeks, there was a steady increase in pH as a result of the presence of microbes alkaline nature. After the adaption of the microbes in the soil, the highest value of pH (5.67) was recorded in the sample with weight 3.2kg. From the plot, it is observed that pH of the sample increases with time indicating the presence of microorganisms. This work is in accordance with studies done by Bayat et al., (2015) on the biodegradation of spent automobile engine oil in soil microcosms amended with cow dung. Udeme et al. (2023) also reported that the initial pH value of all three soil was 4.7, after bioremediation had values of 6.9, 7.1 and 7.6 respectively for a period of 10 weeks. The highest pH at 3.2 kg implies that the larger quantity of amendment had a stronger buffering effect, likely due to higher ash/mineral content, release of basic cations (Ca^{2+}, Mg^{2+}, K^{+}) and enhanced microbial metabolism.

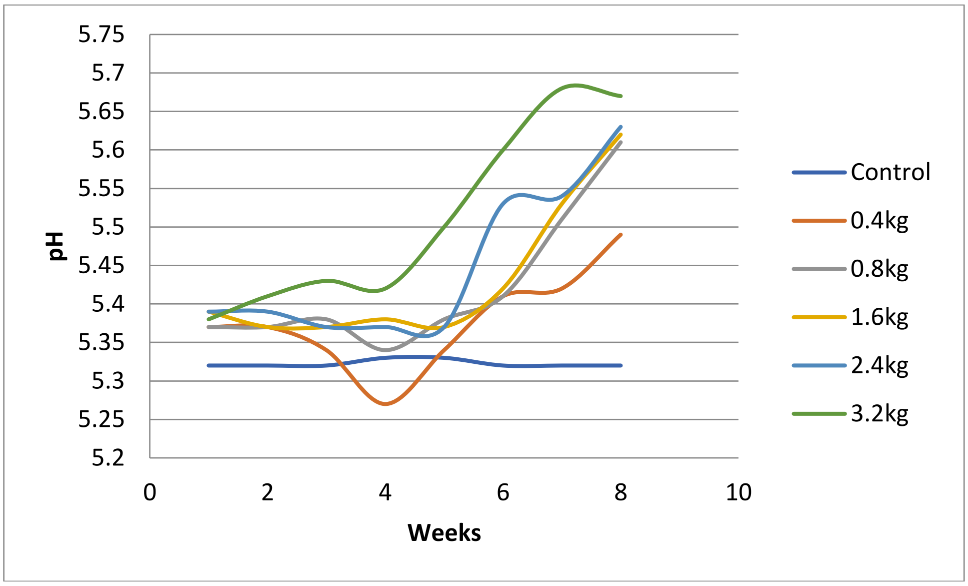

Figure 3.1 Effect of pH with Time

3.3 Effect of Residual hydrocarbon concentration (RHC)

Figure 3.2 shows the amount of Residual hydrocarbon concentration (RHC) over a period of eight weeks. In the first week, the lowest RHC of 5600mg/l was recorded at control while the highest of 5602mg/l was recorded at sample weight 3.2kg when the solid was not added. In the second week a massive decrease of the RHC was observed across the different weights due to biodegradation of the crude oil in process. In the third, fourth, fifth, sixth, seventh and eighth week, increased degradation was observed across all weights with 3.2kg weight sample recording the highest decrease with 18mg/l confirming that the remediation process was sustained rather than temporary, which is a strong indicator of successful biological treatment (Marwa, 2024). Muhammad et al., (2022) also recorded that there was a rapid reduction in the amount of TPH within the first 10days of bioremediation in the amended soils. it can also be seen in work done by Udume et al., (2023) on the study Biostimulation of Petroleum-Contaminated Soil Using Organic and Inorganic Amendments., the results showed that all amendments in this study increased Residual hydrocarbon concentration (RHC) (RHC) biodegradation by 75% within 56 days. The 3.2 kg sample recorded the greatest reduction implying that higher amendment loading improved remediation efficiency, most likely because it more nitrogen, phosphorus, and potassium (NPK), more organic matter, better microbial inoculum, and improved soil aeration and moisture retention (Okoh et al., 2019).

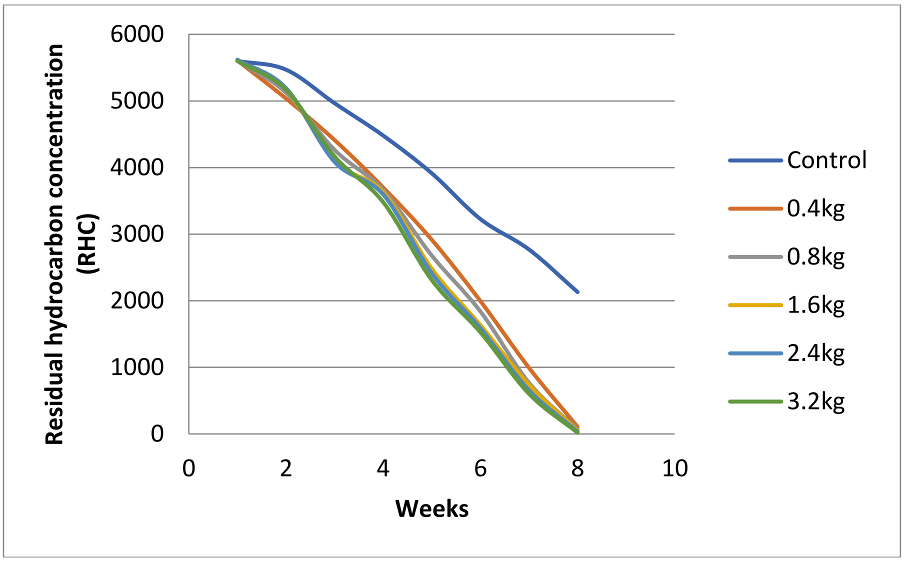

Figure 3.2 Effect of Residual hydrocarbon concentration (RHC) over Time

3.4 Effect of Total Microbial Count

Figure 3.3 shows the values of microbial count for each of the weights over the period of eight weeks. In the first and second week, it is noticed that there was no change in the number of microbial growth as this was the LAG phase where the microbes in the sample where adapting to a new environment. In the third d week, there was a significant increase in each weight. This particular phase or stage is referred to as the LOG phase, where acceleration occurs, where the microorganism feeds on the crude oil and results to multiplication (Okoye et al., 2010). At weeks 7 and 8, a decline in count leading to death stage was observed, this confirms that nutrient availability may have started reducing and microbial competition may have increased (Obi et al., 2022).

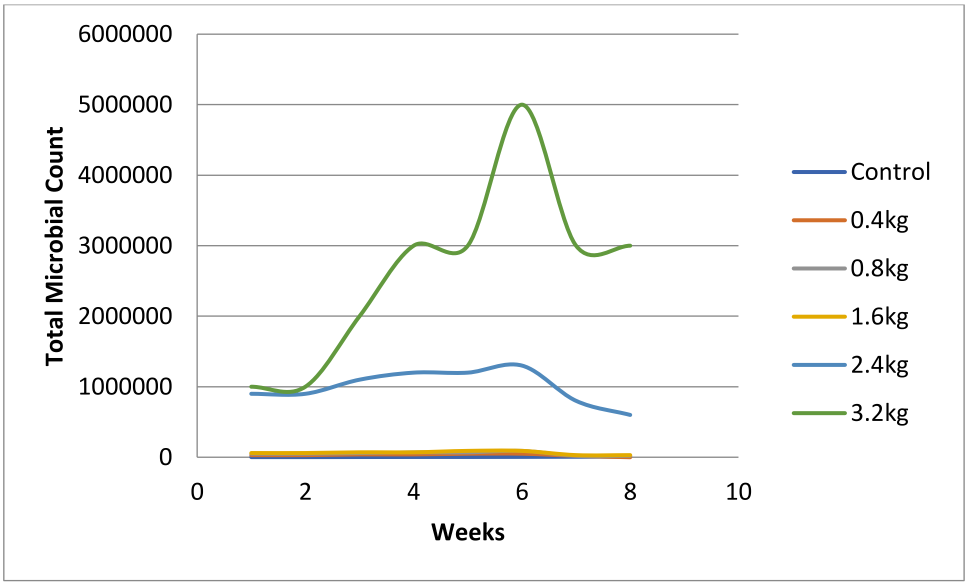

Figure 3.3 Effect of Total Microbial Count over Time

4.0 Conclusion

The results imply that the remediation of crude oil–polluted soil in this study was primarily governed by biologically stimulated degradation rather than natural attenuation alone. The progressive reduction in Residual hydrocarbon concentration (RHC), accompanied by an increase in pH and a corresponding rise in microbial population after the initial lag phase, confirms that the organic solid waste amendment created favorable environmental conditions for hydrocarbon-degrading microorganisms within the period of 8 (eight) weeks. The superior performance of the 3.2 kg treatment further indicates that amendment dosage significantly influences remediation efficiency. Therefore, the study demonstrates that solid waste organic amendment is an effective, low-cost, and sustainable biostimulant for the remediation of crude oil–polluted soil.

Acknowledgements

I wish to acknowledge the, Departments of Chemical and Civil Engineering, University of Benin for their efforts in the availability of the necessary facilities for this work to be done.

Conflicts of Interest

We declare that there is no conflict of interest concerning this publication.

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