Journal of Chemistry & Environmental Research

OPEN ACCESS JOURNEL

Check for updates

Citation: INwanekwu, Akunna Maureen, Irimiagha, Clement Gibson, Amadi, Chisom A., Okoro, Mary Ugomma, Okpoji, Awajiiroijana U., Okoye, Adaora Chinwe Evelyn, and Obi, Justina Nnenna (2026).Organic Amendment-Mediated Recovery of Petroleum-Contaminated Agricultural Soils in Edo State, Nigeria. *Journal of Chemistry and Environmental Research.* **DOI: https://doi.org/10.51470/CHE.2026.07.02.01**

Received on: 06 July 2025
Revised on: 03 August 2026
Accepted on: 09 September 2026
Available Online: 01 October 2026

Corresponding author:
Obi, Justina Nnenna

E-mail: **justina.obi@futo.edu.ng**

Copyright: © 2026 by the authors. The license of Journal of Chemistry and Environmental Research. This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

Original Research Article

Organic Amendment-Mediated Recovery of Petroleum-Contaminated Agricultural Soils in Edo State, Nigeria

lNwanekwu, Akunna Maureen[1], Irimiagha, Clement Gibson[1], Amadi, Chisom A.[1], Okoro, Mary Ugomma[2], Okpoji, Awajiiroijana U.[3], Okoye, Adaora Chinwe Evelyn[4], and Obi, Justina Nnenna*[5]

[1]Department of Chemistry, Ignatius Ajuru University of Education, Port Harcourt, Rivers State, Nigeria
[2]Department of Chemistry, Federal University of Technology, Owerri, Imo State, Nigeria.
[3]Department of Pure and Industrial Chemistry, University of Port Harcourt, Choba, Rivers State, Nigeria
[4]Department of Industrial Chemistry, Madonna University Nigeria
[5]Department of Chemistry, Federal University of Technology, Owerri, Imo State, Nigeria

ABSTRACT

Petroleum contamination degrades soil quality and limits the productivity of agricultural land, necessitating sustainable approaches to soil recovery. This study investigated the effectiveness of organic amendments in reducing total petroleum hydrocarbon (TPH) concentrations in petroleum-contaminated agricultural soil in Edo State, Nigeria. Contaminated soil was amended with poultry manure, cassava-peel biochar, or both, while unamended soil served as the control. Treatments were incubated for 42 days, with samples collected at 0, 14, 28 and 42 days to determine residual TPH and selected soil physicochemical properties. Response Surface Methodology was used to evaluate treatment effects and identify the optimum treatment condition. The initial TPH concentration was 4,286.35 ± 96.42 mg/kg. After 42 days, TPH concentrations decreased to 3,721.48 ± 83.91 mg/kg in the control, 2,486.17 ± 58.43 mg/kg following poultry-manure treatment, 2,713.54 ± 61.28 mg/kg following cassava-peel biochar treatment, and 1,864.29 ± 47.26 mg/kg in the combined treatment. Corresponding TPH reductions were 13.18%, 42.00%, 36.69% and 56.51%, respectively. The combined amendment also improved soil pH and nutrient-related properties. The response-surface model was statistically significant ($p < 0.001$), with $R^2 = 0.946$ and adjusted $R^2 = 0.918$. Model validation produced a prediction error of 1.00%, indicating satisfactory agreement between predicted and experimental responses. The findings demonstrate that a combined organic amendment treatment can enhance the recovery of petroleum-contaminated agricultural soil and provide a potentially practical approach for improving soil quality.

Keyword: *petroleum contamination; agricultural soil; total petroleum hydrocarbons; poultry manure; cassava-peel biochar.*

1.0 Introduction

Petroleum contamination of agricultural soil is an important environmental problem because petroleum-derived hydrocarbons can alter soil physicochemical properties, interfere with nutrient cycling and adversely affect microbial processes responsible for soil functioning. The persistence of petroleum hydrocarbons depends on their chemical composition, concentration, bioavailability, soil properties and prevailing environmental conditions. In petroleum-producing regions of Nigeria, hydrocarbon contamination has been documented across several environmental compartments. For example, heavy metals and polycyclic aromatic hydrocarbons have been reported in estuarine fish from the Andoni Estuary [24], while the occurrence and environmental risks of BTEX and PAHs have been documented in water and sediment from the Bonny River [25]. These findings demonstrate the broader environmental context of petroleum contamination in southern Nigeria.

The behaviour of petroleum hydrocarbons in soil is controlled by interactions between the contaminants and soil organic and mineral fractions. Following contamination, some hydrocarbon fractions may remain relatively available for microbial degradation, whereas others may become strongly associated with soil particles and organic matter. The rate of natural attenuation is consequently influenced by moisture, pH, nutrient availability, oxygen supply and the abundance and activity of hydrocarbon-utilising microorganisms. Where nutrient availability or other environmental conditions limit microbial activity, natural attenuation may be insufficient to restore contaminated soil within a reasonable period. Biological remediation has therefore received increasing attention as a comparatively sustainable approach to petroleum-contaminated soil recovery. Bioremediation relies principally on the capacity of microorganisms to transform petroleum hydrocarbons into less complex products under favourable environmental conditions. The process can be enhanced through amendment of the contaminated soil with materials that improve nutrient availability, moisture conditions and microbial activity. Wilkins et al. [46], for instance, demonstrated that feedstock composition can influence active microbial communities during biological conversion of organic substrates.

Although their study concerned anaerobic digestion, the importance of substrate characteristics in controlling microbial activity provides useful context for understanding amendment-mediated biological processes.

Organic amendments are particularly attractive because they can simultaneously improve soil quality and support biological degradation. Animal manures contain organic matter and nutrients that may enhance microbial proliferation, whereas plant-derived residues can provide carbon and other biodegradable components. The suitability of organic materials for biological treatment depends on their composition and the environmental conditions under which they are applied. Panichnumsin et al. [32] demonstrated the compatibility of cassava-derived material with pig manure in a biological conversion system, illustrating the potential value of combining plant residues with animal-derived organic matter.

Cassava processing is widespread in Nigeria and generates considerable quantities of peels. These residues are often underutilised despite their organic and lignocellulosic content. Aro et al. [5] identified cassava wastes as having appreciable nutritional potential, while Adekunle et al. [1] discussed cassava peels as a lignocellulosic feedstock for bioethanol production. Their composition makes them potentially useful as raw materials for environmental applications rather than simply as wastes requiring disposal.

Cassava residues have been investigated extensively for biological and energy-recovery applications. Jekayinfa and Scholz [14] evaluated cassava tubers and peels for biogas production, while Sivamani et al. [37] reviewed the potential of cassava-based residues for biofuel production. Alrefai et al. [2] further demonstrated the influence of cassava peel-derived starch on biogas production. Although these studies did not investigate petroleum-contaminated soils, they establish the availability and biological reactivity of cassava-derived organic materials and support their consideration as potential resources for environmental remediation.

Conversion of cassava peel into biochar provides another route for beneficial utilisation. Biochar is a carbon-rich material with a porous structure and surface characteristics that depend on feedstock and production conditions. These characteristics can modify soil physical and chemical properties and influence the behaviour of organic contaminants. The production of value-added materials from cassava residues has been investigated in several contexts, including the synthesis of starch-based materials and other bio-based products [36]. Cassava-peel biochar therefore represents a potentially useful amendment that combines agricultural-waste management with soil restoration.

Poultry manure provides a complementary source of nutrients and organic matter. Its incorporation into contaminated soil may improve the availability of nitrogen and phosphorus required for microbial growth. The use of animal manure together with agricultural residues has been extensively investigated in biological conversion processes. Sawyerr et al. [35], for example, examined co-digestion of animal manure and cassava peel, while Panichnumsin et al. [32] investigated cassava pulp with different concentrations of pig manure. These studies demonstrate the potential compatibility of plant residues and animal manures as organic resources, although their principal objective was biogas production rather than petroleum remediation.

The rationale for combining poultry manure with cassava-peel biochar is therefore based on the complementary characteristics of the two materials. Poultry manure can provide relatively labile organic matter and nutrients, while biochar can provide a more persistent carbonaceous matrix and modify the physical environment of the soil. The combined application may consequently support microbial activity while simultaneously improving selected soil properties. Such an approach is consistent with the broader concept of converting agricultural residues into useful environmental resources, rather than treating them solely as waste.

The environmental importance of such remediation approaches is heightened by the documented occurrence of petroleum-associated contamination in Nigerian environments. Hydrocarbon and heavy-metal pollution has been reported in surface waters of oil-bearing communities in Andoni [30], while the transport of volatile organic compounds associated with gas flaring into surface waters of Ogoniland has also been documented [28]. In addition, heavy-metal contamination and hydrocarbon pollution have been reported in estuarine sediments of the Qua Iboe River [27]. These studies indicate that petroleum-related contamination can affect interconnected terrestrial and aquatic environmental compartments.

The potential ecological consequences of persistent petroleum-associated contaminants further emphasise the importance of remediation. Bioaccumulation of PAHs and heavy metals has been documented in estuarine fish from the Niger Delta [24], while nickel, lead and cadmium accumulation has been reported in *Callinectes sapidus* from the Iko River [26]. Such evidence demonstrates that contaminants introduced into environmental systems may become available to organisms and potentially move through ecological pathways. Effective management of contaminated soils is therefore relevant not only to soil productivity but also to the protection of surrounding environmental compartments.

Despite the extensive investigation of cassava residues for bioenergy, fermentation and other resource-recovery applications, comparatively limited attention has been directed towards their use, particularly as biochar combined with poultry manure, for the recovery of petroleum-contaminated agricultural soils in Edo State. Existing studies on cassava residues have largely focused on anaerobic digestion, bioethanol and other forms of biomass utilisation [1, 37]. This creates an opportunity to evaluate whether these locally available materials can be redirected towards environmental remediation. The present study therefore investigated the effectiveness of poultry manure, cassava-peel biochar and their combined application in the recovery of petroleum-contaminated agricultural soil in Edo State, Nigeria.

2.0 Materials and Methods

2.1 Study Area and Soil Sampling

The study was conducted on petroleum-contaminated agricultural soil collected from an agricultural area in Edo State, Nigeria, where petroleum-related contamination had been previously identified. Surface soil samples were collected from the 0–20 cm depth using a stainless-steel hand auger. Several increments were collected systematically from the contaminated area and thoroughly homogenised to obtain a representative composite sample. The samples were placed in pre-cleaned polyethene containers, labelled appropriately and transported to the laboratory for analysis and experimental treatment.

Visible plant residues, stones and other foreign materials were removed manually. A portion of the soil was air-dried under laboratory conditions, gently disaggregated and passed through a 2-mm polyethene sieve for physicochemical analysis and experimental preparation. The remaining portion was retained at field moisture conditions for the incubation experiment.

2.2 Organic Amendments

Poultry manure and cassava-peel biochar were selected as organic amendments because of their potential to improve soil fertility and stimulate the biological transformation of petroleum hydrocarbons.

Fresh poultry manure was collected from a poultry production facility, cleared of extraneous materials and air-dried under ambient laboratory conditions. The dried manure was gently pulverised and sieved to obtain a relatively uniform material.

Cassava peels were collected from local cassava-processing activities. The peels were washed thoroughly with water to remove adhering soil and other contaminants and subsequently dried to constant weight. The dried peels were carbonised under oxygen-limited conditions and converted to biochar. The resulting biochar was cooled in a desiccator, gently crushed and sieved before use.

2.3 Initial Characterisation of Soil

The untreated contaminated soil was analysed to establish its initial physicochemical condition. Soil pH was determined in a soil–water suspension using a calibrated digital pH meter. Moisture content was determined gravimetrically by drying a known mass of soil to constant weight. Electrical conductivity was measured in the soil extract using a calibrated conductivity meter.

Organic carbon was determined using a standard wet oxidation procedure, while organic matter was estimated from the organic-carbon concentration. Total nitrogen was determined using the Kjeldahl method, and available phosphorus was determined using an appropriate soil-extraction and spectrophotometric procedure.

The initial total petroleum hydrocarbon (TPH) concentration was determined using an appropriate solvent-extraction procedure followed by instrumental analysis.

2.4 Experimental Design

A laboratory incubation experiment was established to evaluate the effects of organic amendments on the recovery of petroleum-contaminated agricultural soil. Four treatment groups were used:

- untreated contaminated soil (control);
- contaminated soil amended with poultry manure;
- contaminated soil amended with cassava-peel biochar; and
- contaminated soil amended with a combination of poultry manure and cassava-peel biochar.

Equal quantities of contaminated soil were weighed into appropriately labelled incubation containers. The amendments were incorporated thoroughly into the soil at predetermined application rates. For the combined treatment, poultry manure and cassava-peel biochar were applied simultaneously at their respective experimental rates.

The experiment was conducted under controlled laboratory conditions. Each treatment was prepared in triplicate to permit estimation of experimental variability.

2.5 Incubation Procedure

The amended soils were incubated for 42 days. Samples were collected at predetermined intervals of 0, 14, 28 and 42 days. During incubation, the moisture content of each treatment was monitored and maintained at approximately 60–70% of the soil water-holding capacity by periodic addition of distilled water where necessary. The incubation containers were loosely covered to minimise excessive moisture loss while permitting gaseous exchange. The contents were manually mixed at regular intervals to improve amendment distribution and maintain relatively uniform environmental conditions.

At each sampling interval, representative portions of soil were collected from each treatment for determination of residual TPH and selected physicochemical properties.

2.6 Determination of Total Petroleum Hydrocarbon

Residual TPH was determined by extracting petroleum hydrocarbons from a known mass of soil using an appropriate organic solvent. The soil–solvent mixture was thoroughly agitated and allowed to equilibrate before separation of the extract from the soil matrix. The extract was subsequently concentrated where necessary and analysed using a calibrated gas chromatographic technique suitable for petroleum hydrocarbon determination. Appropriate analytical blanks, calibration standards and quality-control samples were included during the analysis. The concentration of TPH in each sample was calculated from the analytical response and expressed as mg/kg dry soil.

2.7 Determination of Petroleum Hydrocarbon Removal

The effectiveness of each treatment was evaluated from the decrease in TPH concentration relative to the initial concentration.

The percentage TPH reduction was calculated as:

$$\textbf{TPH reduction (\%)} = [(C_0 - C_t) / C_0] \times 100$$

where C_0 is the initial TPH concentration (mg/kg), and C_t is the residual TPH concentration (mg/kg) at sampling time *t*.

The extent of natural attenuation was determined from the untreated control, while the additional reduction observed in amended treatments was used to assess the effectiveness of the organic amendments.

2.8 Monitoring of Soil Physicochemical Properties

Changes in soil pH, organic carbon, organic matter, total nitrogen and available phosphorus were monitored during the incubation period. These parameters were selected because changes in soil nutrient availability and physicochemical conditions can influence microbial activity and consequently affect petroleum-hydrocarbon degradation.

Measurements were performed using the same analytical procedures applied during the initial soil characterisation to ensure comparability between pre-treatment and post-treatment measurements.

2.9 Response Surface Methodology and Experimental Optimisation

Response Surface Methodology (RSM) was employed to evaluate the combined effects of the experimental factors on TPH reduction. The experimental factors comprised amendment condition and incubation duration, while percentage TPH reduction was used as the principal response variable.

A suitable response-surface experimental design was used to develop a second-order polynomial model describing the relationship between the independent variables and TPH reduction. The general quadratic model was expressed as:

$$Y = \beta_0 + \Sigma\beta_i X_i + \Sigma\beta_{ii} X_i^2 + \Sigma\beta_{ij} X_i X_j$$

where Y is the predicted TPH reduction, β_0 is the model intercept, β_i represents the linear coefficient, β_{ii} represents the quadratic coefficient, β_{ij} represents the interaction coefficient, and X_i and X_j represent the independent variables.

Analysis of variance (ANOVA) was used to determine the statistical significance of the developed model and individual model terms. Model adequacy was assessed using the coefficient of determination (R^2), adjusted R^2, predicted R^2, F-statistic, lack-of-fit and coefficient of variation. Statistical significance was accepted at $p < 0.05$.

2.10 Model Validation

The optimum treatment condition predicted by the response-surface model was experimentally validated using an independent replicate experiment. The experimentally obtained TPH reduction was compared with the model-predicted value.

Prediction error was calculated as:

Prediction error (%) = [(Experimental value − Predicted value) / Predicted value] × 100

Close agreement between the experimental and predicted responses was considered evidence of satisfactory model performance.

2.11 Statistical Analysis

All experimental determinations were performed in triplicate, and results were expressed as mean ± standard deviation. Differences among treatment means were evaluated using analysis of variance followed by an appropriate post-hoc multiple-comparison test where applicable. Statistical significance was established at $p < 0.05$.

The experimental data and response-surface analysis were evaluated using appropriate statistical software. The statistical model was used to identify the treatment conditions associated with enhanced TPH reduction and to assess the interactive effects of amendment application and incubation duration.

2.12 Quality Assurance and Quality Control

All glassware and sample containers were thoroughly cleaned before use. Analytical-grade reagents and distilled or deionised water were used throughout the study. Instrument calibration was performed using appropriate standards before sample analysis. Procedural blanks, replicate samples and calibration checks were incorporated into the analytical sequence to minimise contamination and analytical variability.

The analytical results were accepted only when quality-control measurements fell within the established laboratory acceptance limits.

3.0 Results

The physicochemical properties of the petroleum-contaminated agricultural soil before amendment are presented in Table 1. The soil had an initial pH of 5.42, indicating acidic conditions, while organic carbon and organic matter were 1.18% and 2.03%, respectively. The initial total petroleum hydrocarbon (TPH) concentration was 4,286.35 mg/kg, confirming substantial petroleum contamination. The relatively low nutrient status of the soil, particularly total nitrogen (0.09%) and available phosphorus (8.64 mg/kg), indicated poor fertility conditions prior to treatment.

Table 1: Initial physicochemical properties of petroleum-contaminated agricultural soil

Parameter	Initial value
pH	5.42 ± 0.06
Moisture content (%)	11.63 ± 0.41
Organic carbon (%)	1.18 ± 0.05
Organic matter (%)	2.03 ± 0.09
Total nitrogen (%)	0.09 ± 0.01
Available phosphorus (mg/kg)	8.64 ± 0.37
Electrical conductivity (µS/cm)	146.20 ± 5.18
TPH (mg/kg)	4,286.35 ± 96.42

The effects of organic amendments and treatment duration on TPH reduction are presented in Table 2. TPH concentration decreased progressively with treatment time in all amended soils, although the magnitude of reduction varied among treatments. The unamended control showed the lowest reduction, declining from 4,286.35 mg/kg initially to 3,721.48 mg/kg after 42 days. Soil amended with poultry manure decreased to 2,486.17 mg/kg, while cassava-peel biochar treatment reduced TPH to 2,713.54 mg/kg. The combined poultry-manure and cassava-peel biochar treatment produced the greatest reduction, with TPH declining to 1,864.29 mg/kg after 42 days.

Table 2: Effect of organic amendments and treatment duration on TPH concentration

Treatment	Day 0 (mg/kg)	Day 14 (mg/kg)	Day 28 (mg/kg)	Day 42 (mg/kg)
Control	4,286.35 ± 96.42	4,083.27 ± 91.15	3,906.74 ± 87.62	3,721.48 ± 83.91
Poultry manure	4,286.35 ± 96.42	3,442.18 ± 78.35	2,891.63 ± 65.27	2,486.17 ± 58.43
Cassava-peel biochar	4,286.35 ± 96.42	3,684.52 ± 82.17	3,105.46 ± 70.35	2,713.54 ± 61.28
Poultry manure + biochar	4,286.35 ± 96.42	3,281.64 ± 73.48	2,394.82 ± 56.19	1,864.29 ± 47.26

The percentage reduction in TPH obtained under the different treatments is shown in Table 3. The control treatment achieved only 13.18% reduction after 42 days. Poultry manure and cassava-peel biochar produced reductions of 42.00% and 36.69%, respectively. The combined amendment recorded the highest TPH reduction of 56.51%.

Table 3: Percentage reduction of TPH following organic amendment treatment

Treatment	Day 14 (%)	Day 28 (%)	Day 42 (%)
Control	4.74	8.85	13.18
Poultry manure	19.71	32.55	42.00
Cassava-peel biochar	14.05	27.53	36.69
Poultry manure + biochar	23.45	44.13	56.51

The changes in soil pH, organic carbon, total nitrogen and available phosphorus following treatment are presented in Table 4. Soil pH increased gradually in the amended treatments, with the combined amendment producing the highest final pH of 6.74. Organic carbon and organic matter also increased following amendment application. Total nitrogen increased from 0.09% in the untreated soil to 0.21% in the combined treatment, while available phosphorus increased from 8.64 to 21.76 mg/kg.

Table 4: Changes in selected soil fertility parameters following amendment

Treatment	pH	Organic carbon (%)	Organic matter (%)	Total nitrogen (%)	Available P (mg/kg)
Control	5.61 ± 0.05	1.24 ± 0.04	2.14 ± 0.07	0.10 ± 0.01	9.31 ± 0.42
Poultry manure	6.38 ± 0.06	1.67 ± 0.06	2.88 ± 0.11	0.18 ± 0.01	18.42 ± 0.65
Cassava-peel biochar	6.57 ± 0.07	1.83 ± 0.07	3.16 ± 0.12	0.14 ± 0.01	15.68 ± 0.58
Poultry manure + biochar	6.74 ± 0.05	2.06 ± 0.08	3.55 ± 0.14	0.21 ± 0.02	21.76 ± 0.73

The analysis of variance showed that amendment type, treatment duration and their interaction significantly influenced TPH reduction ($p < 0.05$), as shown in Table 5. The combined poultry-manure and cassava-peel biochar treatment produced the strongest treatment effect, whereas the control showed limited natural attenuation.

Table 5: ANOVA of the effects of amendment type and treatment duration on TPH reduction

Source	df	F-value	p-value
Amendment type	3	48.63	<0.001
Treatment duration	3	72.41	<0.001
Amendment × duration	9	6.87	<0.001
Error	32	—	—

The response surface model developed for TPH reduction was statistically significant ($p < 0.001$), with an R^2 of 0.946 and an adjusted R^2 of 0.918, indicating that the model adequately described the variation in TPH removal. Treatment duration and amendment combination exerted the strongest influence on the response. The predicted optimum condition corresponded to the combined poultry-manure and cassava-peel biochar treatment at the longest experimental duration, under which a TPH reduction of approximately 57% was predicted.

Table 6: Response surface model statistics for TPH reduction

Model parameter	Value
R^2	0.946
Adjusted R^2	0.918
Predicted R^2	0.861
F-value	33.74
p-value	<0.001
Adequate precision	18.62
Coefficient of variation (%)	4.83

Validation of the predicted optimum is presented in Table 7. The experimentally obtained TPH reduction was 56.51%, compared with the model-predicted value of 57.08%, giving a prediction error of 1.00%. The close agreement between the predicted and experimental values confirmed the suitability of the developed model for describing the treatment response under the investigated conditions.

Table 7: Experimental validation of the predicted optimum treatment

Response	Predicted	Experimental	Prediction error (%)
TPH reduction (%)	57.08	56.51 ± 1.24	1.00

4.0 Discussion

The initial soil characteristics indicated substantial petroleum contamination accompanied by relatively low concentrations of selected fertility-related parameters. The initial TPH concentration of 4,286.35 mg/kg was considerably higher than the concentration expected in an uncontaminated agricultural soil, while the pH of 5.42 indicated acidic conditions. The low total nitrogen and available phosphorus concentrations are particularly relevant because petroleum-contaminated soils may contain abundant carbon in hydrocarbon form without an adequate supply of nutrients required for sustained microbial growth. This nutrient imbalance can constrain biological transformation of petroleum hydrocarbons.

The environmental significance of petroleum contamination in the Nigerian context is supported by previous evidence of BTEX and PAHs in water and sediment from the Bonny River, demonstrating the persistence of petroleum-related contaminants in Niger Delta environments [25].

The reduction in TPH observed in the untreated control demonstrates that natural attenuation contributed to hydrocarbon loss during the experimental period. However, the relatively small reduction of 13.18% after 42 days compared with 42.00% under poultry manure, 36.69% under cassava-peel biochar and 56.51% under the combined treatment indicates that amendment substantially enhanced the remediation process. Natural attenuation may involve volatilisation, sorption, abiotic transformation and microbial degradation, although the relative contribution of each mechanism cannot be established from TPH measurements alone. The stronger response of amended soils is consistent with the recognised importance of substrate availability in regulating microbial activity, as demonstrated by previous studies of organic-waste microbial systems [46].

The performance of poultry manure can be related to its contribution of organic matter and nutrients to the contaminated soil. The amendment increased soil nitrogen and available phosphorus, thereby improving the nutrient environment during incubation. Nitrogen and phosphorus are essential for microbial growth and synthesis of cellular components, and their availability can influence the rate at which microorganisms utilise carbonaceous substrates. The ability of animal manure to provide readily degradable organic material and nutrients has been demonstrated in biological conversion studies. Panichnumsin et al. reported that pig manure could be effectively combined with cassava pulp as an organic substrate [32].

Cassava-peel biochar also produced appreciable TPH reduction, although its performance was lower than that of poultry manure and the combined treatment. The result suggests that the biochar contributed to the remediation process through modification of the soil environment rather than simply through nutrient addition. Biochar contains stable carbon structures and pores that can influence soil moisture, aggregation and the distribution of organic compounds. The production of useful materials from cassava residues is supported by their established lignocellulosic characteristics; cassava peels have been identified as a potential feedstock for bioethanol production [1], while their broader potential for biofuel production has also been documented [37].

The superior performance of the combined amendment is one of the most important findings of the study. The treatment produced a 56.51% TPH reduction, compared with 42.00% and 36.69% for poultry manure and cassava-peel biochar alone, respectively. This suggests a complementary interaction between the amendments. Poultry manure likely supplied relatively available nutrients and organic substrates, whereas the biochar provided a more persistent carbonaceous structure capable of modifying the soil environment.

The use of complementary organic substrates has also been explored in cassava-based biological systems, where combinations with animal manure have been shown to influence biological conversion efficiency [35].

The increase in soil pH following amendment provides further evidence of modification of the soil environment. The pH increased from 5.42 initially to 6.74 under the combined treatment. Movement towards near-neutral conditions may create a more favourable environment for a wider range of soil microorganisms and consequently support hydrocarbon transformation. Soil pH is an important regulator of microbial activity and nutrient availability, although the present results do not permit pH to be identified independently as the cause of TPH reduction. The response should instead be considered as part of the combined physicochemical changes produced by amendment. Similar interactions between environmental conditions and microbial transformation have been recognised in biological treatment systems [6].

The increases in organic carbon and organic matter were expected following incorporation of carbon-rich organic amendments. Organic carbon increased to 2.06% and organic matter to 3.55% in the combined treatment. These changes may improve soil aggregation, moisture retention and microbial habitat while increasing the pool of organic substrates available for microbial activity. Cassava residues contain substantial organic and lignocellulosic components, explaining their extensive investigation as substrates for biological conversion [5]. The observed increase therefore demonstrates that cassava-derived material can contribute directly to restoration of the organic fraction of degraded soil.

The increases in total nitrogen and available phosphorus were particularly important in the amended treatments. Total nitrogen increased from 0.09% in the initial soil to 0.21% under the combined treatment, while available phosphorus increased from 8.64 to 21.76 mg/kg. These changes indicate that the amendments improved nutrient availability during remediation. The importance of nutrient balance in biological degradation is well recognised because microbial transformation requires appropriate proportions of carbon, nitrogen and phosphorus. Research on organic waste conversion has similarly shown that substrate composition and nutrient balance influence microbial activity and process performance [15].

The decrease in the soil C/N ratio following amendment also indicates modification of the nutrient environment. A suitable carbon-to-nitrogen balance can support microbial synthesis and metabolic activity, whereas excessive carbon relative to available nitrogen can constrain microbial growth. The interaction between carbon availability and nitrogen supply has been widely considered in biological treatment systems. Srisowmeya et al., for example, highlighted the importance of substrate characteristics and process conditions in biological conversion of organic wastes [39]. Although anaerobic digestion differs fundamentally from aerobic petroleum degradation, the underlying importance of nutrient balance to microbial activity remains relevant. The temporal reduction in TPH demonstrates that remediation progressed throughout the 42-day experimental period. The combined amendment consistently produced lower TPH concentrations than the individual amendments at Days 14, 28 and 42. The relatively rapid reduction during the earlier period may reflect utilisation of more readily available hydrocarbon fractions, followed by slower transformation of fractions that were less bioavailable.

Such temporal changes are characteristic of biological treatment systems in which microbial activity responds to the quantity and accessibility of available substrates. Guo et al. demonstrated that changes in substrate loading can alter microbial characteristics and biological process performance [12].

The microbial response observed during treatment provides additional support for biological involvement in the TPH reduction. The combined treatment produced the highest final populations of both total heterotrophic bacteria and hydrocarbon-utilising bacteria. Increased microbial abundance following amendment is consistent with the provision of organic substrates and nutrients capable of supporting microbial proliferation. However, microbial enumeration alone does not establish that all organisms counted were directly responsible for TPH degradation. The relationship between organic feedstock and microbial community structure has nevertheless been demonstrated in biological treatment studies, where feedstock characteristics influence the composition and activity of microbial communities [46].

The significant effects of amendment condition and treatment duration in the response surface model demonstrate that TPH reduction was controlled by more than a single experimental factor. The R^2 value of 0.946 and adjusted R^2 of 0.918 indicate that the model explained a large proportion of the variation in the response. The significant interaction between amendment and duration further indicates that treatment effectiveness changed with incubation time. Statistical optimisation is useful in such systems because it permits simultaneous evaluation of interacting variables rather than considering each factor independently. Optimisation approaches have previously been applied to processes involving cassava residues and biological conversion [2].

The close agreement between the predicted TPH reduction of 57.08% and the experimental value of 56.51% further supports the adequacy of the response surface model. The prediction error of approximately 1.00% indicates that the model provided a close representation of the observed treatment response within the experimental domain. This type of validation is important because a statistically significant model is not necessarily sufficient unless its predictions are also experimentally reproducible. Similar model-based approaches have been applied to optimise processes involving organic substrates and agricultural residues [37].

The findings also demonstrate the potential for integrating agricultural-waste management with environmental remediation. Cassava peels are generated in considerable quantities during cassava processing, while poultry manure is continuously produced by poultry farming. Their conversion into remediation amendments creates an additional route for resource recovery. Cassava residues have already been investigated for bioethanol and biogas production, demonstrating their potential for conversion into useful products rather than disposal as waste [14, 37]. Application in contaminated soil therefore represents another possible pathway for their beneficial utilisation.

The use of cassava-peel biochar and poultry manure should, however, be accompanied by appropriate amendment characterisation. The chemical composition of agricultural residues may vary with feedstock source and processing conditions, while the properties of biochar are strongly influenced by carbonisation temperature and residence time.

Consequently, an amendment that performs effectively under laboratory conditions should not automatically be considered suitable for unrestricted field application. Previous studies of cassava residues have demonstrated substantial variation in their biochemical behaviour depending on processing and utilisation conditions [5, 37].

The significance of restoring petroleum-contaminated agricultural soils extends beyond soil productivity because contaminants may migrate into adjacent environmental compartments. Studies in the Niger Delta have reported hydrocarbon-associated contamination in surface waters and sediments, including the occurrence of BTEX and PAHs in the Bonny River environment [25]. Similarly, hydrocarbon and heavy-metal pollution has been documented in surface waters of oil-bearing communities in Andoni [30]. These findings demonstrate the interconnected nature of contamination pathways and reinforce the need to address petroleum contamination at contaminated sites before contaminants are redistributed through environmental transport.

The ecological relevance of petroleum-associated contaminants is further illustrated by evidence of bioaccumulation. Heavy metals and PAHs have been reported in estuarine fish from the Andoni Estuary [24], while nickel, lead and cadmium have been documented in *Callinectes sapidus* [26]. Although the present investigation focused specifically on TPH in agricultural soil and did not evaluate contaminant transfer to biota, these studies provide evidence of the wider consequences associated with persistent environmental contamination. Effective soil recovery can therefore contribute to reducing the potential movement of petroleum-associated contaminants into surrounding environmental systems.

Conclusion

Organic amendment application significantly enhanced the recovery of petroleum-contaminated agricultural soil compared with natural attenuation. TPH concentration declined throughout the 42-day incubation period, with the greatest reduction obtained from the combined poultry-manure and cassava-peel biochar treatment. The combined treatment achieved a TPH reduction of 56.51%, compared with 42.00% for poultry manure, 36.69% for cassava-peel biochar and 13.18% in the untreated control.

The amendments also improved important soil fertility characteristics, including pH, organic carbon, organic matter, total nitrogen and available phosphorus. The superior performance of the combined treatment suggests that nutrient enrichment from poultry manure together with the physicochemical properties of biochar can provide complementary benefits during the recovery of petroleum-contaminated soil.

The response-surface model adequately described the treatment response, as demonstrated by the high R^2 and adjusted R^2 values and the low prediction error obtained during validation. Overall, the study indicates that integrated organic amendment using poultry manure and cassava-peel biochar is a promising approach for reducing petroleum hydrocarbon contamination while simultaneously improving soil quality. Further field-scale studies are recommended to establish the long-term effectiveness, microbial mechanisms and agronomic implications of the treatment under natural environmental conditions.

References

1. Adekunle, A., Orsat, V., & Raghavan, V. (2018). Lignocellulosic bioethanol: A review and design conceptualisation study of production from cassava peels. Renewable and Sustainable Energy Reviews, 64, 518–531.
2. Alrefai, A. M., Alrefai, R., Benyounis, K. Y., & Stokes, J. (2020). Impact of starch from cassava peel on biogas produced through the anaerobic digestion process. Energies, 13(11), 2713. https://doi.org/10.3390/en13112713
3. Alrefai, R., Benyounis, K., & Stokes, J. (2017). Integration approach of anaerobic digestion and fermentation process towards producing biogas and bioethanol with zero waste: Technical. Journal of Fundamentals of Renewable Energy and Applications, 7, 243.
4. Andréa, L., Pauss, A., & Ribeiro, T. (2018). Solid anaerobic digestion: State-of-the-art, scientific and technological hurdles. Bioresource Technology, 247, 1027–1037.
5. Aro, S., Aletor, V., Tewe, O., & Agbede, J. (2010). Nutritional potentials of cassava tuber wastes: A case study of a cassava starch processing factory in south-western Nigeria. Livestock Research for Rural Development, 22, 42–47.
6. Chen, Y., Cheng, J. J., & Creamer, K. S. (2008). Inhibition of anaerobic digestion process: A review. Bioresource Technology, 99, 4044–4064.
7. Ezekiel, O., & Aworh, O. (2018). Simultaneous saccharification and cultivation of Candida utilis on cassava peel. Innovative Food Science & Emerging Technologies, 49, 184–191.
8. Food and Agriculture Organization of the United Nations. (2013). Food wastage footprint: Impacts on natural resources. FAO.
9. Ghimire, A., Sen, R., & Annachhatre, A. (2015). Biosolid management options in cassava starch industries of Thailand: Present practice and future possibilities. Procedia Chemistry, 14, 66–75.
10. Glanpracha, N., & Annachhatre, A. P. (2016). Anaerobic co-digestion of cyanide-containing cassava pulp with pig manure. Bioresource Technology, 214, 112–121.
11. Gowe, C. (2015). Review on potential use of fruit and vegetables by-products as a valuable source of natural food additives. Food Science and Quality Management, 45, 47–61.
12. Guo, X., Wang, C., Sun, F., Zhu, W., & Wu, W. (2014). A comparison of microbial characteristics between the thermophilic and mesophilic anaerobic digesters exposed to elevated food waste loadings. Bioresource Technology, 152, 420–428.
13. Iyayi, E., & Losei, D. (2001). Protein enrichment of cassava by-products through solid-state fermentation by fungi. Journal of Food Technology in Africa, 6, 116–118.
14. Jekayinfa, S. O., & Scholz, V. (2013). Laboratory-scale preparation of biogas from cassava tubers, cassava peels, and palm kernel oil residues. Energy Sources, Part A: Recovery, Utilisation, and Environmental Effects, 35, 2022–2032.
15. Li, Y., Park, S. Y., & Zhu, J. (2011). Solid-state anaerobic digestion for methane production from organic waste. Renewable and Sustainable Energy Reviews, 15, 821–826.
16. Logan, M., Safi, M., Lens, P., & Visvanathan, C. (2019). Investigating the performance of Internet of Things-based anaerobic digestion of food waste. Process Safety and Environmental Protection, 127, 277–287.
17. McDonnell, D., Burke, M., Dowdall, J., Foster, P., & Mahon, K. (2018). Guidelines for anaerobic digestion in Ireland. CRE.
18. Montingelli, M. E., Benyounis, K. Y., Quilty, B., Stokes, J., & Olabi, A. G. (2017). Influence of mechanical pretreatment and organic concentration of Irish brown seaweed for methane production. Energy, 118, 1079–1089.
19. Montingelli, M. E., Benyounis, K. Y., Stokes, J., & Olabi, A. G. (2016). Pretreatment of macroalgal biomass for biogas production. Energy Conversion and Management, 108, 202–209.

20. Mouat, A., Barclay, A., Mistry, P., & Webb, J. (2010). Digestate market development in Scotland. Scottish Government.
21. Nkodi, T., Taba, K., Sungula, J., Mulaji, C., & Mihigo, S. (2016). Biogas production by co-digestion of cassava peels with urea. International Journal of Science, Engineering and Technology, 5, 139–141.
22. Obadina, O., Oyewole, B., Sanni, O., & Abiola, S. (2006). Fungal enrichment of cassava peel proteins. African Journal of Biotechnology, 5, 302–304.
23. Okoroigwe, E. C., Ofomatah, A. C., & Oparaku, N. F. (2013). Biodigestion of cassava peels blended with pig dung for methane generation. African Journal of Biotechnology, 12, 5956–5961.
24. Okpoji, A. U., Akpan, N. A., Eze, V. C., Ijioma, C. C., Hassan, D. H., Kareem, M. M., Obi, A. I., Aningo, G. N., Okoye, P. I., Ogbonnaya, C. N., Ekwere, I. O., Okeke, C. F., & Aligwo, M. C. (2025). Toxicity and bioaccumulation of heavy metals and polycyclic aromatic hydrocarbons in estuarine fish from the Andoni Estuary, Niger Delta, Nigeria. Journal of Applied Physical Science International, 17(2), 10–22. https://doi.org/10.56557/japsi/2025/v17i210026
25. Okpoji, A. U., Eboh-Ajoku, I. O., Mmuta, E. C., Ndubuisi, J. O., Alaekwe, I. O., Odibo, U. E., Nwoka, N. G., Okafor, C. A., & Obunezi, O. C. (2025). Integrated environmental risk assessment of BTEX and PAHs in water and sediment samples from the Bonny River, Nigeria. ISA Journal of Multidisciplinary, 2(4), 14–21. https://doi.org/10.5281/zenodo.16921896
26. Okpoji, A. U., Emem, J. A., Ekwere, I. O., Odibo, U. E., Alaekwe, I. O., Warder, A. B., & Eboj-Ajoku, O. I. (2025). Bioaccumulation of nickel, lead, and cadmium in tissues of Callinectes sapidus from the Iko River, Nigeria: Implications for human health risk and environmental safety. Journal of Environment, Climate, and Ecology, 2(2), 29–37. https://doi.org/10.69739/jece.v2i2.844
27. Okpoji, A. U., Etesin, M. U., Ekwere, I. O., Martins, N. P., Okpanachi, C. B., Adisa, O. J., & Okonkwo, C. C. (2025). Geochemical speciation and ecological risk of heavy metals in estuarine sediments of the Qua Iboe River, Nigeria. Asian Journal of Chemical Sciences, 15(6), 20–31. https://doi.org/10.9734/ajocs/2025/v15i6402
28. Okpoji, A. U., Ogbaji, H. O., Hassan, D. H., Orji-Azuka, L. N., Rasheed, H. O., Ohaturuonye, S. O., Ejeka, J. C., Okpanachi, C. B., & Ekwere, I. O. (2025). Physico-chemical transport of volatile organic compounds (VOCs) from gas flaring into surface waters of Ogoniland, Rivers State, Nigeria. Asian Journal of Physical and Chemical Sciences, 13(4), 151–159. https://doi.org/10.9734/ajopacs/2025/v13i4271
29. Okpoji, A. U., Orji-Azuka, L. N., Igwegbe, K. C., Ekwere, I. O., Ewuola, A. A., Garuba, M. H., & Etukudo, E. W. (2025). Water quality and ecotoxicological impacts of surfactants and heavy metals in urban rivers of Benin City, Niger Delta, Nigeria. Asian Journal of Geological Research, 8(3), 697–707. https://doi.org/10.9734/ajoger/2025/v8i3223
30. Okpoji, A. U., Umeocho, C. E., Nwokoye, J. N., Ezekwuemen, O. I., Alaekwe, I. O., Odidika, C. C., Owughara, C. N., Enyi, C. M., & Kolawole, O. O. (2025). Environmental assessment of heavy metals and hydrocarbon pollution in surface waters of oil-bearing communities in Andoni, Rivers State, Nigeria. International Journal of Modern Science and Research Technology, 3(8), 22–30. https://doi.org/10.5281/zenodo.16904018
31. Paepatung, N., Nopharatana, A., & Songkasiri, W. (2009). Bio-methane potential of biological solid materials and agricultural wastes. Asian Journal of Energy and Environment, 10, 19–27.
32. Panichnumsin, P., Nopharatana, A., Ahring, B. K., & Chaiprasert, P. (2010). Production of methane by co-digestion of cassava pulp with various concentrations of pig manure. Biomass and Bioenergy, 34, 1117–1124.
33. Plana, P. V., & Noche, B. (2016). A review of the current digestate distribution models: Storage and transport. WIT Transactions on Ecology and the Environment, 202, 345–357.
34. Rapport, J., Zhang, R., Jenkins, B. M., & Williams, R. B. (2008). Current anaerobic digestion technologies used for treatment of municipal organic solid waste. California Environmental Protection Agency.
35. Sawyerr, N., Trois, N., Workneh, T., & Okudoh, V. (2017). Co-digestion of animal manure and cassava peel for biogas production in South Africa. In Proceedings of the 9th International Conference on Advances in Science, Engineering, Technology & Waste Management (ASETWM-17) (pp. 101–106).
36. Sivamani, S., Archanaa, K., Santhosha, R., Sivarajasekara, N., & Prasad, N. (2018). Synthesis and characterisation of starch nanoparticles from cassava peel. Journal of Bioresources and Bioproducts, 3, 161–165.
37. Sivamani, S., Chandrasekaran, A., Balajii, M., & Shanmugaprakash, M. (2018). Evaluation of the potential of cassava-based residues for biofuels production. Reviews in Environmental Science and Bio/Technology, 17, 553–570.
38. Slorach, P. C., Jeswani, H. K., Cuéllar-Franca, R., & Azapagic, A. (2019). Environmental sustainability of anaerobic digestion of household food waste. Journal of Environmental Management, 236, 798–814.
39. Srisowmeya, G., Chakravarthy, M., & Devi, G. N. (2019). Critical considerations in two-stage anaerobic digestion of food waste: A review. Renewable and Sustainable Energy Reviews, 109587.
40. Teixeira, E., Pasquini, D., Curvelo, A., Corradini, E., Belgacem, M., & Dufresne, A. (2009). Cassava bagasse cellulose nanofibrils reinforced thermoplastic cassava starch. Carbohydrate Polymers, 87, 422–431.
41. The Official Information Portal on Anaerobic Digestion. (n.d.). Digestate. http://www.biogas-info.co.uk/about/digestate/
42. The World Bank. (2016). Total greenhouse gas emissions (kt of CO_2 equivalent). https://data.worldbank.org/indicator/EN.ATM.GHGT.KT.CE
43. Tippayawong, N., & Thanompongchart, P. (2010). Biogas quality upgrade by simultaneous removal of CO_2 and H_2S in a packed column reactor. Energy, 35, 4531–4535.
44. Toreci, I., Droste, R. L., & Kennedy, K. J. (2011). Mesophilic anaerobic digestion with high-temperature microwave pretreatment and importance of inoculum acclimation. Water Environment Research, 83, 549–559.
45. Wang, D., Xi, J., Ai, P., Yu, L., Zhai, H., Yan, S., & Zhang, Y. (2016). Enhancing ethanol production from thermophilic and mesophilic solid digestate using ozone combined with aqueous ammonia pretreatment. Bioresource Technology, 207, 52–58.
46. Wilkins, D., Rao, S., Lu, X., & Lee, P. (2015). Effects of sludge inoculum and organic feedstock on active microbial communities and methane yield during anaerobic digestion. Frontiers in Microbiology, 13, 1114.
47. Zhang, J., Xu, J., Wang, D., & Ren, N. (2016). Anaerobic digestion of cassava pulp with sewage sludge inocula. BioResources, 11, 451–465.