

Physicochemical Characterization of Selected Soil Types and Assessment of Moringa and Neem Root Extracts for Total Petroleum Hydrocarbon Reduction in Crude Oil-Contaminated Soils

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DOI: <https://doi.org/10.51584/IJRIAS.2026.11090007>

Received: 18 September 2026; Accepted: 23 September 2026; Published: 29 September 2026

ABSTRACT

Soil physicochemical properties influence the fate, mobility, and biodegradation of petroleum hydrocarbons in contaminated environments. This study characterized four soil types—loamy, silt, clay, and sandy soils—and assessed aqueous and alcoholic extracts prepared from *Moringa oleifera* and *Azadirachta indica* roots as treatment amendments for crude oil-contaminated soils. The soils were characterized before contamination, after contamination, and after treatment, using bulk density, pH, electrical conductivity (EC), moisture content (MC), total organic carbon (TOC), total nitrogen (TN), and phosphorus (P). The experimental design included an untreated contaminated-soil control, while the pre-contamination measurements provided baseline reference values. Each soil was contaminated with 50 mL of crude oil, allowed to stabilize for three days, and treated with 100 mL of the designated root extract for 84 days. Total petroleum hydrocarbon (TPH) reduction and total bacterial count were monitored during the treatment period. Crude oil contamination increased the measured density, EC, MC, TOC, TN, and P values in the investigated soils, while pH generally decreased. After treatment, these properties generally moved toward the pre-treatment soil condition, while TPH reduction increased progressively with time. At day 84, TPH reduction among the reported treatments ranged from 69.03% to 96.14%. For the 600-g soil treatments, first-order kinetic fits gave R^2 values of 0.8671–0.9470, exceeding the corresponding second-order fits. The findings show that soil type, root-extract formulation, and extraction medium are associated with differences in TPH reduction and soil physicochemical response. The study supports further investigation of *Moringa* and *Neem* root extracts as locally available treatment amendments for petroleum-contaminated soils.

Keywords: Bioremediation; Crude oil contamination; *Moringa oleifera*; *Azadirachta indica*; Root extracts; Total petroleum hydrocarbons; Soil physicochemical properties

INTRODUCTION

Soil is a complex and dynamic environmental system whose physical, chemical, and biological properties strongly influence contaminant behaviour and the effectiveness of remediation processes. Soil texture, pH, organic matter content, moisture availability, nutrient concentration, and electrical conductivity can affect the transport, retention, transformation, and biodegradation of petroleum hydrocarbons. These properties also regulate oxygen availability, nutrient cycling, and microbial activity, which are critical factors in the biological degradation of hydrocarbon contaminants. Consequently, understanding changes in soil physicochemical conditions before and after contamination is essential for designing and evaluating effective remediation strategies.

Crude oil contamination remains a major environmental challenge in petroleum-producing regions worldwide and is particularly significant in the Niger Delta region of Nigeria. Petroleum exploration, production,

transportation, refining, and storage activities may result in accidental hydrocarbon releases through pipeline failures, equipment malfunction, operational discharges, and other anthropogenic activities (Ofoegbu et al., 2015; Ogu and Odo, 2015). Once released into the soil environment, petroleum hydrocarbons can alter soil structure and physicochemical properties, reduce nutrient availability, restrict water and air movement, and adversely affect agricultural productivity and ecosystem functioning (Kuppusamy et al., 2016; Wang et al., 2019).

The response of contaminated soil to remediation depends substantially on its inherent physicochemical characteristics. Soil texture, for example, influences hydrocarbon retention, water movement, aeration, and oxygen diffusion. Coarse-textured soils such as sandy soils generally exhibit higher permeability and aeration, which may favour microbial activity and hydrocarbon biodegradation. In contrast, fine-textured soils such as clay and silt may retain water and petroleum hydrocarbons more strongly because of their smaller particle size and larger surface area. As a result, identical remediation treatments may produce different outcomes in soils with contrasting physicochemical and textural characteristics (Youdeowei, 2012; Umeda et al., 2017).

Several physicochemical parameters are commonly used to evaluate the condition and remediation potential of petroleum-contaminated soils. These include pH, electrical conductivity, moisture content, organic carbon, nitrogen, phosphorus, and soil density. Soil pH is particularly important because it influences nutrient availability and the growth and metabolic activity of hydrocarbon-degrading microorganisms. Similarly, moisture content affects microbial proliferation and oxygen transfer within the soil matrix, while electrical conductivity provides information on the concentration of soluble ionic constituents. Organic carbon represents an important component of the soil carbon balance, whereas nitrogen and phosphorus are essential nutrients required for microbial growth and enzymatic processes associated with hydrocarbon degradation.

The availability and balance of carbon, nitrogen, and phosphorus are particularly important during bioremediation because microbial degradation of petroleum hydrocarbons requires adequate nutrient availability in addition to a suitable physical environment. Crude oil may introduce a substantial carbon load into soil while creating nutrient limitations that can restrict microbial growth and biodegradation. Therefore, monitoring total organic carbon, nitrogen, and phosphorus provides useful information on the changing nutritional condition of contaminated soil and its potential influence on biological remediation processes. The combined assessment of these parameters can improve understanding of the relationship between soil conditioning and petroleum hydrocarbon degradation.

Bioremediation is widely recognized as an environmentally sustainable approach for reducing petroleum hydrocarbon contamination through biological transformation and degradation processes. The approach may rely on indigenous microorganisms or involve the addition of organic materials capable of improving the physicochemical and nutritional conditions required for microbial activity (Azubuike et al., 2016). Plant-derived materials and agricultural residues have attracted increasing attention as potential low-cost remediation agents because they are locally available, biodegradable, and may contain organic compounds and nutrients capable of modifying the soil environment and supporting biological activity. Previous studies have demonstrated the potential of organic amendments and plant-based materials to improve conditions favourable for petroleum hydrocarbon degradation (Aghalibe et al., 2017).

Moringa (*Moringa oleifera*) and Neem (*Azadirachta indica*) are widely available plant resources with recognized nutritional, biochemical, and environmental applications. Their different plant parts contain organic compounds, minerals, and other constituents that may influence the physicochemical environment of contaminated soil when introduced as treatment materials. Although various plant-derived materials have been investigated for environmental remediation, relatively limited attention has been given to the physicochemical characterization and comparative application of Moringa and Neem root extracts in crude oil-contaminated soils. In particular, information regarding how these materials interact with soils of contrasting textures remains limited.

The extraction medium may also influence the composition and potential effectiveness of plant-derived treatment materials. Water and alcohol differ in their ability to dissolve and extract plant constituents, resulting in extracts with potentially different chemical compositions. These differences may subsequently influence soil

pH, nutrient availability, organic carbon content, moisture conditions, and other physicochemical factors associated with the remediation environment. Evaluating aqueous and alcoholic extracts of Moringa and Neem roots is therefore important for understanding the relationship between extraction method, plant-derived treatment characteristics, and soil response.

Despite the growing interest in plant-based approaches to petroleum-contaminated soil remediation, several studies have focused primarily on the reduction of total petroleum hydrocarbons without adequately examining the accompanying changes in soil physicochemical conditions. However, the evaluation of remediation performance requires consideration of both contaminant reduction and the restoration or modification of important soil properties. Furthermore, differences in soil texture may substantially influence the interaction between crude oil, treatment materials, nutrients, moisture, and indigenous microbial communities.

Therefore, the present study investigates the physicochemical characteristics of loamy, silt, clay, and sandy soils before crude oil contamination, after contamination, and following treatment with aqueous and alcoholic extracts of Moringa and Neem roots. The root extracts are used as plant-derived treatment amendments rather than as intact plants; consequently, the study concerns extract-assisted soil remediation rather than phytoremediation by living plants. The study evaluates bulk density, pH, electrical conductivity, moisture content, total organic carbon, total nitrogen, phosphorus, total bacterial count, and TPH reduction over an 84-day treatment period. The four soil classes were selected to provide contrasting soil matrices for comparative assessment of treatment response. By examining soil type, root material, extraction medium, and treatment level together, the study seeks to clarify the relationship between soil physicochemical conditions and TPH reduction in crude oil-contaminated soils.

MATERIALS AND METHODS

Study Area and Soil Sample Collection

Four representative soil types, namely loamy, sandy, silt, and clay soils, were used in this study. The soil samples were collected from Kpea Community, Khana Local Government Area, Rivers State, Nigeria. The study area is located within the Ogoni region of the Niger Delta, an area characterized by extensive agricultural activities and exposure to petroleum-related environmental challenges. Surface soil samples were collected using a clean shovel and transferred into properly labelled sack bags. Care was taken to minimize cross-contamination during sampling. The collected samples were transported to the Department of Chemical/Petrochemical Engineering Laboratory, Rivers State University, Port Harcourt, Nigeria, for experimental preparation and physicochemical analysis. The soil samples were separately homogenized and prepared for subsequent characterization and crude oil contamination experiments. Soil texture and other physicochemical properties were determined to establish the initial characteristics of the selected soils before contamination and treatment.

Collection and Preparation of Moringa and Neem Roots

Fresh roots of Moringa (*Moringa oleifera*) and Neem (*Azadirachta indica*) were collected from Wiiyaakara Community in Khana Local Government Area, Rivers State, Nigeria. The roots were carefully washed with distilled water to remove adhering soil particles and other debris. The cleaned root samples were subsequently sun-dried under ambient conditions until adequate dryness was achieved. The dried roots were separately prepared for extraction and physicochemical characterization. The use of both Moringa and Neem roots was intended to evaluate their potential as locally available plant-derived materials for the treatment of crude oil-contaminated soils.

Preparation of Aqueous and Alcoholic Root Extracts

The dried Moringa and Neem roots were separately subjected to extraction using water and alcohol as extraction solvents. Distilled water obtained from the laboratory was used for aqueous extraction, while alcohol with a concentration of approximately 97–98% (v/v) was used for alcoholic extraction. Separate portions of the prepared roots were soaked in the respective solvents for two weeks to extract soluble plant constituents. The

resulting aqueous and alcoholic root extracts were used as plant-derived treatment amendments applied to the crude-oil-contaminated soils. The study did not use intact plants; therefore, the treatment should be interpreted as extract-assisted soil remediation rather than phytoremediation. At the end of the extraction period, the four formulations were collected and stored separately for the soil-treatment experiments.

- Moringa root aqueous extract;
- Moringa root alcoholic extract;
- Neem root aqueous extract; and
- Neem root alcoholic extract.

These formulations were subsequently applied to crude oil-contaminated soils to evaluate changes in physicochemical properties and hydrocarbon degradation during the treatment period.

Crude Oil Contamination of Soil Samples

The prepared loamy, sandy, silt, and clay soils were separately weighed into experimental vessels. Two soil masses, 500 g and 600 g, were used in the treatment design. Each vessel was contaminated with 50 mL of crude oil and thoroughly mixed using a stirrer to promote uniform distribution throughout the soil matrix. Thus, MW-500, NW-500, MA-500, and NA-500 denote treatments containing 500 g of soil, whereas the corresponding 600 treatments contain 600 g of soil; the numerical suffix denotes soil mass rather than extract concentration. The contaminated soils were allowed to stand undisturbed for three days before application of the plant-derived extracts. The three-day period allowed interaction between the crude oil and soil particles before treatment (Ayotamuno et al., 2011). On a volume-to-soil-mass basis, the 50 mL crude-oil loading corresponds to 10.0 mL per 100 g of soil for the 500-g vessels and 8.33 mL per 100 g for the 600-g vessels. These values describe the applied crude-oil loading; the manuscript does not convert this loading to a mass-based initial TPH concentration.

Two reference conditions were used. Soil measurements obtained before crude-oil addition served as the uncontaminated baseline reference for each soil type, while crude-oil-contaminated soil without root-extract treatment served as the untreated contaminated control. These controls allowed changes associated with contamination and treatment to be described separately.

Experimental Design and Treatment Formulations

The experiment was designed to compare the response of four soil types to crude-oil contamination and treatment with Moringa and Neem root extracts. The study used aqueous and alcoholic extracts of the two root materials at two soil-mass levels (500 and 600 g) and an untreated contaminated-soil control.

The investigated soil types were:

- Loamy soil;
- Sandy soil;
- Silt soil; and
- Clay soil.

Each contaminated soil type was subjected to treatment with extracts prepared from Moringa and Neem roots using water and alcohol as extraction solvents. The treatment formulations consisted of:

- Moringa-water extract treatment;

- Moringa-alcohol extract treatment;
- Neem-water extract treatment;
- Neem-alcohol extract treatment; and
- Untreated contaminated soil control.

Following the three-day stabilization period, 100 mL of the appropriate root extract was applied to each designated treatment vessel. The same extract volume was used for the treatment vessels, while the 500-g and 600-g labels identify the mass of soil in each vessel. The soil-extract mixtures were maintained under laboratory conditions throughout the 84-day experimental period. The design enabled comparison of soil type, root material, extraction medium, and soil mass with respect to changes in soil physicochemical properties, total bacterial count, and TPH reduction. On a volume-to-soil-mass basis, 100 mL extract corresponds to 20.0 mL per 100 g of soil in the 500-g vessels and 16.67 mL per 100 g in the 600-g vessels. Accordingly, the 500-g and 600-g treatments represent different soil and treatment loading conditions rather than identical extract-to-soil ratios.

Physicochemical Characterization of Soil Samples

The physicochemical properties of the soils were determined before crude oil contamination, after contamination, and during the bioremediation treatment period.

The investigated parameters included:

- Bulk density;
- pH;
- Electrical conductivity;
- Moisture content;
- Total organic carbon;
- Total nitrogen; and
- Available phosphorus.

The analyses were conducted to evaluate changes in soil condition resulting from crude oil contamination and subsequent treatment with Moringa- and Neem-derived extracts.

Bulk Density

The bulk density of the soil samples was determined by measuring the mass of a known volume of soil. The bulk density was calculated using:

$$\rho_b = \frac{M}{V} \quad (1)$$

Where ρ_b is the bulk density of the soil, M is the mass of the soil sample, and V is the volume occupied by the soil sample. Changes in soil bulk density were monitored to assess the influence of crude oil contamination and plant-derived treatment on the physical condition of the soils.

Soil pH

The pH of the soil samples was determined using a calibrated pH/electrical conductivity meter.

Approximately 10 g of homogenized soil, previously ground and passed through a 2 mm sieve, was weighed into a clean container. Twenty-five millilitres of deionized water was added to obtain a soil-to-water ratio of 1:2.5. The resulting suspension was stirred for approximately 1 h to ensure adequate interaction between the soil and water. The pH electrode was subsequently inserted into the soil suspension, and the pH value was recorded. The pH meter was calibrated before use, and the electrode was rinsed with distilled water between measurements to minimize cross-contamination.

Electrical Conductivity

Electrical conductivity (EC) was measured using the same soil-water suspension prepared for pH determination. The electrical conductivity probe was immersed in the prepared soil suspension, and the readings were recorded in microsiemens per centimetre ($\mu\text{S}/\text{cm}$). The electrode was thoroughly rinsed with distilled water between successive measurements. Electrical conductivity was monitored as an indicator of changes in soluble ionic constituents within the soil during crude oil contamination and treatment.

Moisture Content

Soil moisture content was determined using the oven-drying method described by Ayotamuno *et al.* (2011). Approximately 10 g of soil sample was weighed into a pre-weighed crucible and dried in an oven at 105°C for 24 h. The dried sample was subsequently cooled in a desiccator for approximately 30 min and reweighed. The moisture content was calculated using:

$$MC(\%) = \frac{W_1 - W_2}{W_1} \times 100 \quad (2)$$

Where MC = moisture content (%), W_1 = initial mass of the wet soil sample (g); and W_2 = mass of the oven-dried soil sample (g).

Total Organic Carbon

Total organic carbon (TOC) was determined using the wet oxidation procedure described by Umeda *et al.* (2017). Approximately 1.0 g of finely prepared representative soil sample was weighed into a 250 mL beaker. Potassium dichromate solution was added to the soil sample, followed by the careful addition of concentrated sulfuric acid. The mixture was gently rotated to ensure uniform contact between the soil and reagents and subsequently allowed to stand for approximately 30 min to facilitate oxidation. After the reaction period, distilled water and diphenylamine indicator were added. The resulting solution was titrated with standardized ferrous sulfate solution until the appropriate endpoint colour change was observed. A blank determination was simultaneously conducted without soil to standardize the dichromate solution. The TOC concentration was subsequently calculated from the difference between the blank and sample titration values.

Total Nitrogen

Total nitrogen (TN) was determined using the Kjeldahl digestion procedure. A representative quantity of soil sample was subjected to acid digestion using concentrated sulfuric acid and appropriate digestion reagents. The nitrogen-containing compounds in the soil were converted to ammonium during digestion. The digest was subsequently processed through distillation and titration procedures, and the total nitrogen concentration was calculated from the amount of ammonia recovered. Total nitrogen was determined because nitrogen availability is an important factor influencing microbial growth and petroleum hydrocarbon biodegradation in contaminated soils.

Available Phosphorus

Available phosphorus was determined using an appropriate colorimetric laboratory procedure.

Representative soil samples were extracted using the designated phosphorus extraction solution. The extracted phosphorus concentration was subsequently determined spectrophotometrically.

Phosphorus was monitored because it is an essential nutrient for microbial growth and metabolic activity during bioremediation. The nitrogen and phosphorus results were also considered together with soil carbon characteristics to provide insight into the nutrient condition of the contaminated and treated soils.

Characterization of Moringa and Neem Root Extracts

The dried Moringa and Neem roots were used to prepare the four treatment formulations described in Section 2.3. The physicochemical characterization reported in this study concerns the prepared extracts before application rather than a separate proximate analysis of the dried root biomass. The alcoholic extracts were characterized by refractive index, boiling point, viscosity, density, and colour, while the aqueous extracts were characterized by pH, chloride, sulphate, total hardness, iron, conductivity, total dissolved solids, total suspended solids, nitrate, calcium, salinity, temperature, and density. These measurements were used to document the properties of the treatment amendments before they were applied to contaminated soils.

Microbial Analysis and Total Bacterial Count

The microbial response of the soil samples was evaluated through total bacterial count (TBC) analysis. Prepared nutrient agar plates were used according to the manufacturer's specifications. The culture medium was prepared from nutrient agar supplied by University of Port Harcourt Chemistry Laboratories Choba Nigeria. A serially diluted soil suspension was prepared, and approximately 0.1 mL of the appropriate dilution was inoculated onto the nutrient agar plates. The inoculum was evenly distributed over the agar surface using a sterile glass spreader. The inoculated plates were incubated at 37°C for 24 h. Plates that did not show sufficient visible bacterial growth after the initial incubation period were incubated for an additional 24 h. Following incubation, visible bacterial colonies were counted, and the total bacterial population was expressed as colony-forming units per millilitre (CFU/mL), based on the dilution factor used. The bacterial count was monitored to assess changes in microbial activity during the treatment of crude oil-contaminated soils.

Monitoring of Total Petroleum Hydrocarbon

Total petroleum hydrocarbon (TPH) concentration was determined using ASTM D3921-based procedures. Hydrocarbons were extracted from representative soil samples using dichloromethane. The extract was subsequently treated with activated silica gel to remove interfering polar compounds. The TPH concentration was determined using a Gas Chromatograph equipped with a Flame Ionization Detector (GC-FID; HP 5890 Series II, USA).

The percentage removal of TPH at a given sampling time was calculated as:

$$TPH_R(\%) = \frac{TPH_i - TPH_f}{TPH_i} \times 100 \quad (3)$$

Where TPH_R = percentage TPH removal, TPH_i = initial TPH concentration; and TPH_f = TPH concentration at a given sampling time. The TPH results were used to evaluate the extent of hydrocarbon degradation under the different soil and treatment conditions.

Experimental Duration and Sampling Intervals

The contaminated and treated soil samples were monitored for a total period of 84 days.

Representative samples were collected at seven-day intervals throughout the experimental period. Sampling was therefore conducted at the beginning of the treatment period and subsequently at weekly intervals. The monitored parameters included:

- Soil physicochemical properties;
- Total petroleum hydrocarbon concentration; and
- Total bacterial count.

The periodic monitoring approach enabled the temporal changes in soil condition and hydrocarbon concentration to be evaluated during the bioremediation process.

Data Analysis

The experimental results were organized according to soil type, treatment formulation, treatment concentration, and treatment duration. Total petroleum hydrocarbon (TPH) concentrations and percentage degradation were evaluated to determine the temporal effectiveness of the Moringa and Neem root extracts in the different soil matrices. The results were presented in tabular and graphical forms to facilitate comparison of treatment performance and degradation trends.

The TPH degradation percentage was calculated from the initial and residual TPH concentrations according to the expression:

$$TPH_D (\%) = \frac{C_0 - C_t}{C_0} \times 100 \quad (4)$$

where (C_0) is the initial TPH degradation and (C_t) is the TPH concentration at time (t).

The temporal degradation data were further subjected to kinetic analysis using first-order and second-order models, as described in Section 2.12. The coefficients of determination (R^2) obtained from the respective kinetic fits were used to assess and compare the suitability of the models for describing the observed TPH degradation behaviour.

Biodegradation Kinetic Modelling

To complement the experimental assessment of TPH removal, the biodegradation behaviour of petroleum hydrocarbons was analysed using kinetic models derived from mass conservation principles. The experimental vessels were treated as batch reactors because there was no continuous inflow or outflow of material during the treatment period. For a general batch system, the mass balance can be expressed as:

$$\text{Accumulation} = \text{Input} - \text{Output} - \text{Reaction}$$

Since the experimental system operated as a closed batch reactor, Therefore, the change in TPH concentration with time is governed by:

$$-\frac{dC}{dt} = r \quad (5)$$

Where C is the instantaneous TPH concentration, t is the treatment time; and r is the biodegradation rate. The experimental TPH data were subsequently fitted to first-order and second-order kinetic models.

First-Order Kinetic Model

For first-order biodegradation kinetics:

$$-\frac{dC}{dt} = k_d C \quad (6)$$

where k_d is the first-order degradation rate constant. Separating variables and integrating between the initial concentration C_0 and concentration C_t at time t :

$$\int_{C_0}^{C_t} \frac{dC}{C} = -k_d \int_0^t dt \quad (7)$$

Equation (7) gives:

$$\ln C_t - \ln C_0 = -k_d t \quad (8)$$

A plot of $\ln C_t$ against time provides a linear relationship, from which the degradation rate constant can be determined. The predictive form of the first-order model is:

$$C_t = C_0 e^{-k_d t} \quad (9)$$

Where C_t = TPH concentration at time t , C_0 = initial TPH concentration, k_d = degradation rate constant; and t = treatment time.

Second-Order Kinetic Model

For second-order degradation kinetics:

$$-\frac{dC}{dt} = k_d C^2 \quad (10)$$

Integrating equation (10) gives:

$$\frac{1}{C_t} - \frac{1}{C_0} = k_d t \quad (11)$$

A plot of $1/C_t$ against time provides the basis for estimating the second-order degradation rate constant. Rearranging the equation gives the predictive model:

$$C_t = \frac{C_0}{1 + C_0 k_d t} \quad (12)$$

The suitability of the first-order and second-order models for describing TPH degradation can subsequently be evaluated by comparing the goodness-of-fit statistics, including the coefficient of determination (R^2), between the models.

RESULTS AND DISCUSSION

Analysis of Treatments and Soil Physicochemical Properties

The physicochemical properties of the Moringa- and Neem-based treatment extracts were determined before application and are presented in Tables 1 and 2.

Tables 3-10 present the physicochemical properties of the four soil types before and after crude-oil contamination and after 84 days of treatment. The untreated contaminated soil provides the treatment-control reference, while the pre-contamination measurements provide the baseline condition.

Table 1. Physicochemical Properties of Alcoholic Moringa and Neem Root Extracts before Application

Parameters	Fresh Alcohol	Moringa-Alcohol Extract	Neem-Alcohol Extract
Refractive Index	1.3493	1.3453	1.3463
Boiling Point (°C)	79.20	83.90	86.50
Viscosity (cst)	3.2000	2.4600	2.3065
Density (g/cm ³)	0.9343	0.9498	0.9466
Colour	Clourless	Clourless	Clourless

The alcoholic extracts showed small changes in refractive index relative to fresh alcohol, while their boiling points and densities were higher and their viscosities were lower than those of the fresh solvent.

These differences indicate that soluble constituents from the roots were present in the alcoholic extracts. However, the measurements characterize the extracts and do not by themselves establish the specific chemical compounds responsible for the observed changes.

Table 2. Physicochemical Properties of Aqueous Moringa and Neem Root Extracts before Application

Parameters	Water	Moringa-Water Extract	Neem-Water Extract
pH	6.39	6.18	6.25
Chloride (mg/l)	43.70	64.85	83.51
Sulphate (mg/l)	6.26	20.63	20.80
Total hardness	28.17	49.14	47.30
Iron Content (mg/l)	0.030	0.281	0.269
Conductivity (µS/cm)	41.04	1.052	1.665
TDS (mg/l)	2.80	86.92	8.06
TSS (mg/l)	2.80	5.98	8.06
Nitrate (mg/l)	0.22	6.20	5.99
Calcium (mg/l)	39.88	18.27	15.36
Salinity (mg/l)	53.88	89.80	91.41

Temperature (°C)	29.1	29.5	29.7
Density (g/cm ³)	1.0007	1.0002	0.9974

The aqueous extracts differed from water in pH, ionic constituents, conductivity, total dissolved and suspended solids, nitrate, salinity, temperature, and density. These differences confirm that the extraction process produced treatment solutions with physicochemical properties distinct from the extraction medium.

Table 3. Physicochemical Properties of Loamy Soil before and after Pollution

Parameters	Before Pollution	After Pollution
Density (g/cm ³)	1.75	4.80
E.C (μS/cm)	10	15.6
pH	5.85	5.48
MC (%)	9.0	30.5
TOC (%)	2.64	4.77
TN (mg/kg)	2.27	6.46
TP (mg/kg)	1.14	4.68

Table 4. Physicochemical Properties of Loamy Soil after 84 Days Treatment

Parameters	Control	MW-500	NW-500	MA-500	NA-500	MW-600	NW-600	MA-600	NA-600
Density (g/cm ³)	3.94	2.39	2.74	3.22	3.59	1.97	2.29	2.93	3.17
E.C (μS/cm)	14.20	13.53	13.73	13.67	13.85	11.72	12.01	13.60	13.82
pH	5.81	6.92	6.74	6.63	6.53	6.98	6.94	6.67	6.63
MC (%)	25.01	15.16	17.39	20.44	22.81	12.51	14.55	18.61	20.13
TOC (%)	3.72	2.37	2.61	2.90	2.95	1.96	2.28	2.72	2.82
TN (mg/kg)	3.36	1.85	2.07	2.39	2.89	1.36	1.79	2.26	2.71
TP (mg/kg)	2.43	1.34	1.50	1.73	2.10	0.98	1.30	1.64	1.97

Table 5. Physicochemical Properties of Silt Soil before and after Pollution

Parameters	Before Pollution	After Pollution
Density (g/cm ³)	9.84	13.52
E.C (μS/cm)	40	60

pH	5.64	5.34
MC (%)	8.5	30.5
TOC (%)	4.71	4.86
TN (mg/kg)	2.03	6.22
TP (mg/kg)	1.28	3.74

Table 6. Physicochemical Properties of Silt Soil after 84 Days Treatment

Parameters	Control	MW-500	NW-500	MA-500	NA-500	MW-600	NW-600	MA-600	NA-600
					10.11				
Density (g/cm ³)	11.09	6.72	7.71	9.06		5.54	6.45	8.25	8.92
E.C (μS/cm)	54.60	52.02	52.80	52.56	53.28	45.06	46.20	52.32	53.16
pH	5.76	6.86	6.68	6.58	6.48	6.92	6.88	6.61	6.57
MC (%)	25.01	15.16	17.39	20.44	22.81	12.51	14.55	18.61	20.13
TOC (%)	3.79	2.42	2.66	2.95	3.00	1.99	2.32	2.78	2.88
TN (mg/kg)	3.23	1.79	1.99	2.30	2.79	1.31	1.72	2.18	2.61
TP (mg/kg)	1.94	1.07	1.20	1.38	1.68	0.79	1.04	1.31	1.57

Table 7. Physicochemical Properties of Clay Soil before and after Pollution

Parameters	Before Pollution	After Pollution
Density (g/cm ³)	3.17	5.11
E.C (μS/cm)	20	29.12
pH	5.36	5.27
MC (%)	5.0	36.4
TOC (%)	4.065	4.665
TN (mg/kg)	3.88	7.86
TP (mg/kg)	2.47	5.68

Table 8. Physicochemical Properties of Clay Soil after 84 Days Treatment

Parameters	Control	MW-500	NW-500	MA-500	NA-500	MW-600	NW-600	MA-600	NA-600
Density (g/cm ³)	4.19	2.54	2.91	3.42	3.82	2.10	2.44	3.12	3.37

E.C ($\mu\text{S/cm}$)	26.50	25.25	25.63	25.51	25.86	21.87	22.42	25.39	25.80
pH	5.75	6.85	6.68	6.57	6.47	6.91	6.88	6.60	6.56
MC (%)	29.85	18.09	20.75	24.39	27.23	14.92	17.36	22.20	24.02
TOC (%)	3.64	2.32	2.55	2.83	2.88	1.91	2.23	2.66	2.76
TN (mg/kg)	4.09	2.26	2.52	2.91	3.52	1.65	2.18	2.75	3.30
TP (mg/kg)	2.95	1.63	1.82	2.10	2.54	1.19	1.57	1.99	2.39

Table 9. Physicochemical Properties of Sandy Soil before and after Pollution

Parameters	Before Pollution	After Pollution
Density (g/cm^3)	0.43	1.06
E.C ($\mu\text{S/cm}$)	20.00	26.90
pH	5.93	5.50
MC (%)	2.30	42.00
TOC (%)	0.96	3.77
TN (mg/kg)	3.72	7.18
TP (mg/kg)	2.33	5.52

Table 10. Physicochemical Properties of Sandy Soil after 84 Days Treatment

Parameters	Control	MW-500	NW-500	MA-500	NA-500	MW-600	NW-600	MA-600	NA-600
Density (g/cm^3)	0.87	0.53	0.60	0.71	0.79	0.43	0.51	0.65	0.70
E.C ($\mu\text{S/cm}$)	24.48	23.32	23.67	23.56	23.89	20.20	20.71	23.46	23.83
pH	5.83	6.95	6.77	6.66	6.56	7.01	6.97	6.69	6.65
MC (%)	34.44	20.87	23.94	28.14	31.42	17.22	20.03	25.62	27.72
TOC (%)	2.94	1.87	2.06	2.29	2.33	1.55	1.80	2.15	2.23
TN (mg/kg)	3.73	2.06	2.30	2.66	3.22	1.51	1.99	2.51	3.02
P (mg/kg)	2.87	1.58	1.77	2.04	2.47	1.16	1.53	1.93	2.32

Tables 3, 5, 7, and 9 show the physicochemical properties of the loamy, silt, clay, and sandy soils before and after crude-oil contamination, respectively, while Tables 4, 6, 8, and 10 show the corresponding values after 84 days of treatment. Following crude-oil addition, the reported density, EC, MC, TOC, TN, and P values increased in all four soils, whereas pH decreased slightly. After treatment, the measured values generally decreased relative to the contaminated condition, while pH increased toward neutral values. The magnitude of the response varied

among soil types and treatment formulations, indicating that the soil matrix and treatment formulation were associated with the observed physicochemical changes.

The observed physicochemical changes should be interpreted together with the TPH and bacterial-count measurements because changes in soil properties alone do not establish hydrocarbon remediation. The combined measurements provide a basis for describing the relationship between soil conditioning and TPH reduction during treatment.

TPH Reduction under Moringa and Neem Root-Extract Treatments

The TPH results were compared across soil type, root material, extraction medium, and soil-mass level. Because the reported values are descriptive observations without replicate variability, the comparisons below describe the observed trends rather than statistically significant differences.

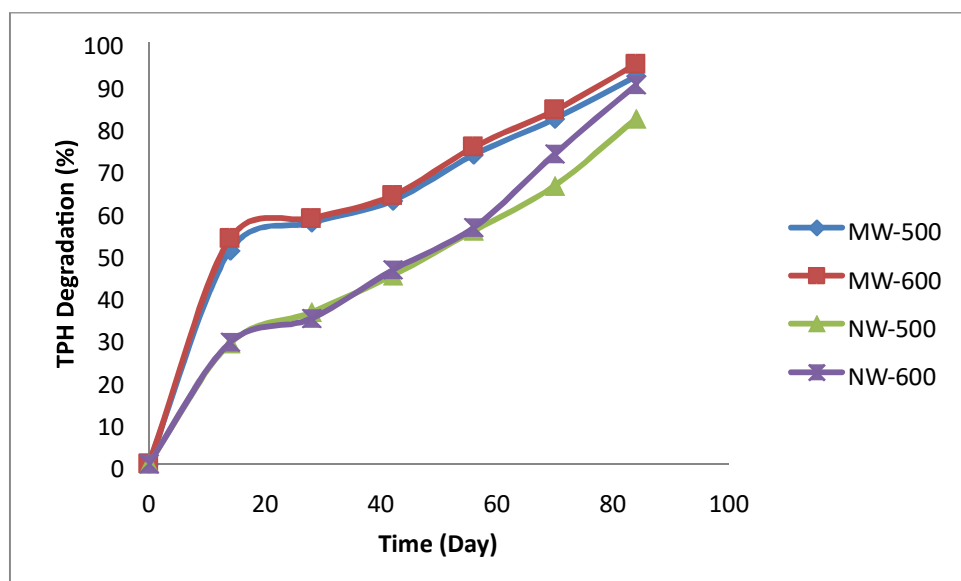


Figure 1. Comparison of Moringa and Neem Aqueous Root Extracts in Loamy Soil

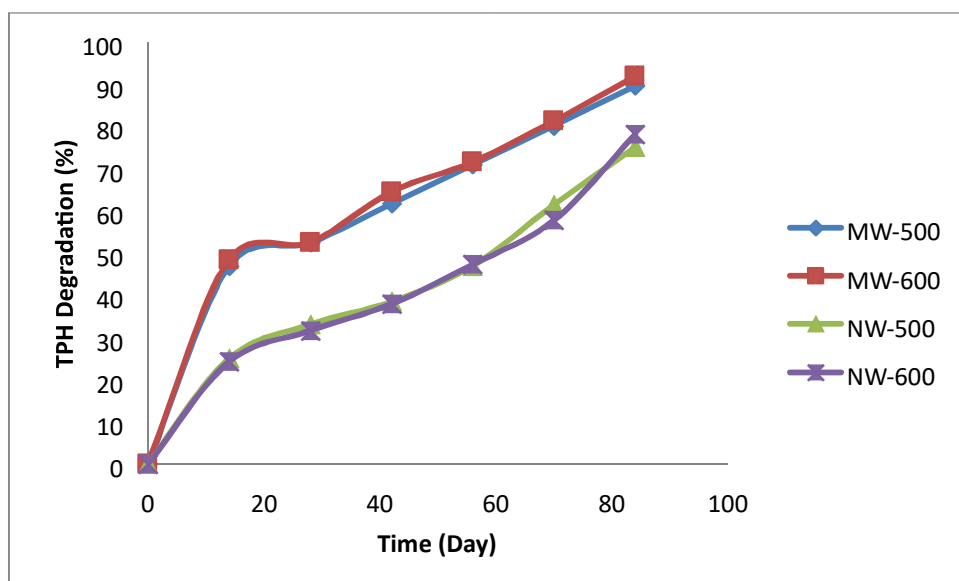


Figure 2. Comparison of Moringa and Neem Aqueous Root Extracts in Silt Soil

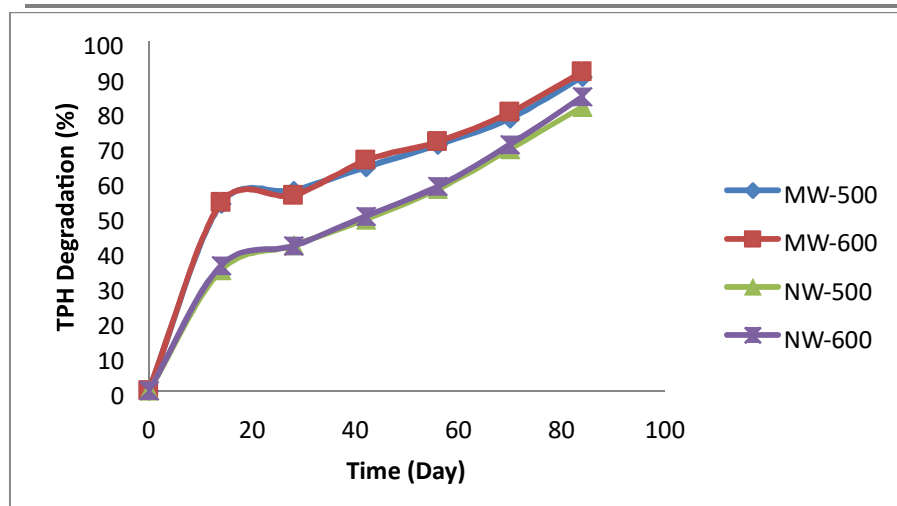


Figure 3. Comparison of Moringa and Neem Aqueous Root Extracts in Clay Soil

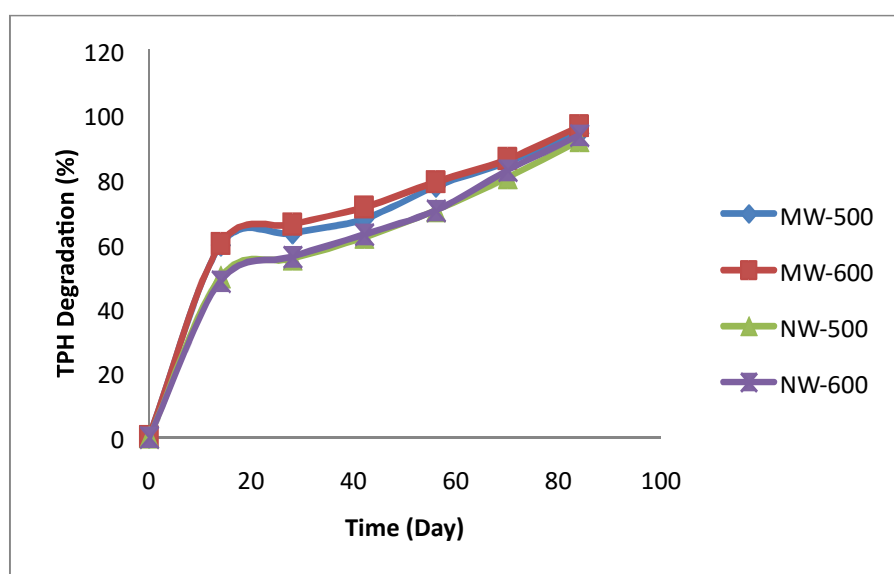


Figure 4. Comparison of Moringa and Neem Aqueous Root Extracts in Sandy Soil

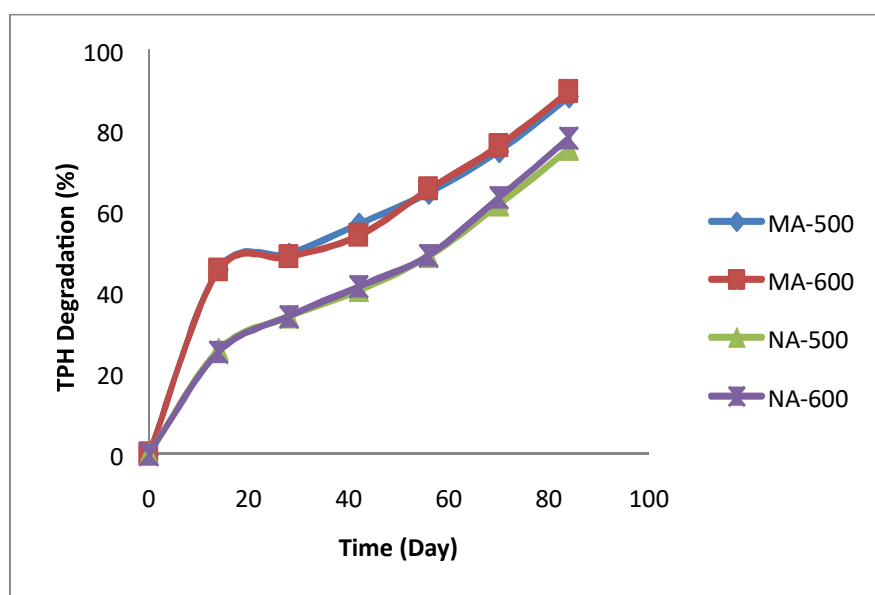


Figure 5. Comparison of Moringa and Neem Alcoholic Root Extracts in Loamy Soil

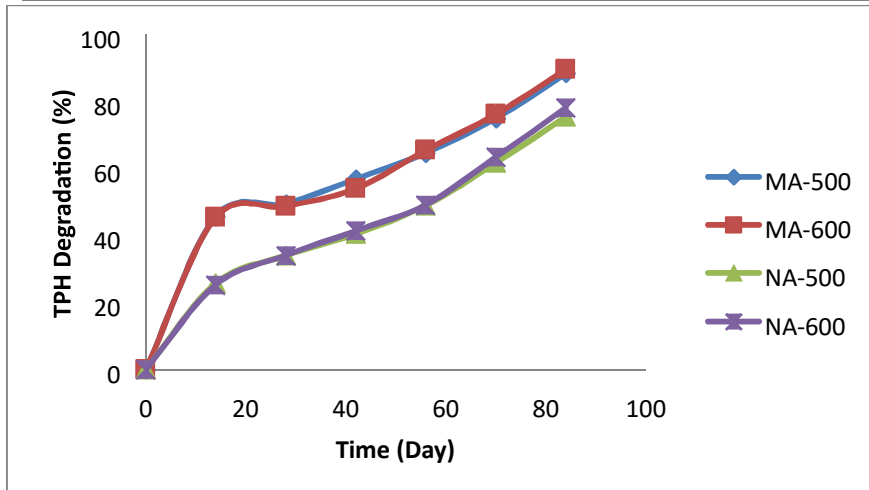


Figure 6. Comparison of Moringa and Neem Alcoholic Root Extracts in Silt Soil

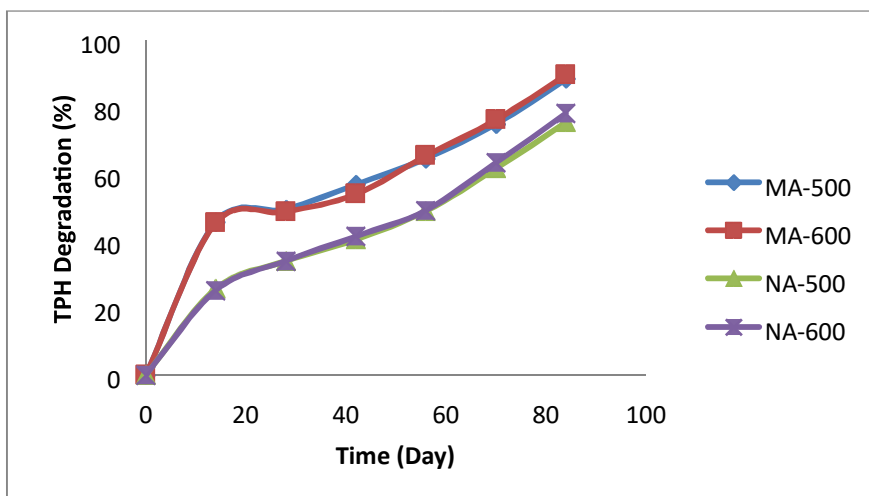


Figure 7. Comparison of Moringa and Neem Alcoholic Root Extracts in Clay Soil

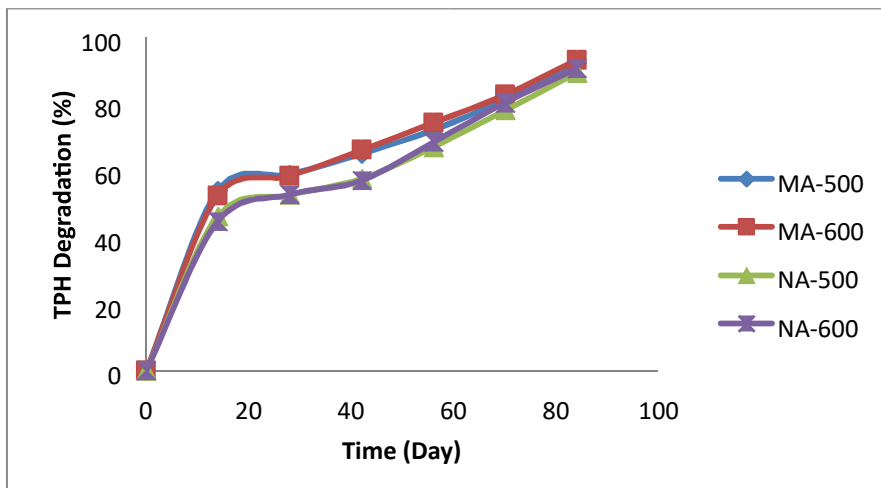


Figure 8. Comparison of Moringa and Neem Alcoholic Root Extracts in Sandy Soil

Figures 1–8 show the temporal percentage TPH reduction in the four soil types treated with aqueous and alcoholic Moringa and Neem root extracts. Across the treatment formulations, TPH reduction increased with treatment time. For aqueous extracts, the day-84 reductions in loamy soil were 91.85% (MW-500), 94.69% (MW-600), 81.75% (NW-500), and 89.84% (NW-600). In silt soil, the corresponding values were 89.61%,

91.90%, 75.07%, and 78.07%. In clay soil, the values were 89.88%, 91.19%, 81.18%, and 84.11%, while sandy soil showed 94.04%, 96.14%, 91.83%, and 93.46% for MW-500, MW-600, NW-500, and NW-600, respectively. For alcoholic extracts, day-84 TPH reductions in loamy soil were 86.63%, 88.60%, 69.88%, and 69.03% for MA-500, MA-600, NA-500, and NA-600, respectively. In silt soil, the corresponding values were 85.44%, 87.96%, 69.94%, and 72.34%; in clay soil, 88.44%, 89.67%, 75.51%, and 78.14%; and in sandy soil, 92.32%, 93.20%, 89.37%, and 90.65%, respectively. These results show that the magnitude of TPH reduction varied with both soil type and extract formulation.

Kinetic Modelling of TPH Reduction

To further evaluate the TPH reduction behaviour, the experimental data for the 600-g treatments (MW-600, MA-600, NW-600, and NA-600) were fitted to first-order and second-order kinetic models. The resulting rate constants, coefficients of determination (R^2), and first-order half-lives are presented in Table 11.

Table 11. Kinetic parameters for TPH reduction in soils treated with Moringa and Neem root extracts using 600-g soil treatments.

Soil type	Treatment	First-order k_1 (d^{-1})	R^2	Second-order k_2	R^2	Half-life, $t_{1/2}$ (d)	Best-fit model
Loamy	MW-600	0.0292	0.9011	4.0×10^{-6}	0.6227	23.74	First-order
Loamy	MA-600	0.0219	0.9106	2.0×10^{-6}	0.7003	31.65	First-order
Loamy	NW-600	0.0235	0.8671	2.0×10^{-6}	0.6312	29.49	First-order
Loamy	NA-600	0.0132	0.9470	6.0×10^{-7}	0.8574	52.50	First-order
Silt	MW-600	0.0257	0.9354	3.0×10^{-6}	0.7109	26.97	First-order
Silt	MA-600	0.0217	0.9121	2.0×10^{-6}	0.6954	31.94	First-order
Silt	NW-600	0.0153	0.8877	9.0×10^{-7}	0.7248	45.29	First-order
Silt	NA-600	0.0139	0.9002	7.0×10^{-7}	0.7698	49.86	First-order
Clay	MW-600	0.0239	0.9145	3.0×10^{-6}	0.7118	29.00	First-order
Clay	MA-600	0.0226	0.9004	2.0×10^{-6}	0.6894	30.66	First-order
Clay	NW-600	0.0189	0.9296	1.0×10^{-6}	0.7655	36.67	First-order
Clay	NA-600	0.0159	0.9290	1.0×10^{-6}	0.7898	43.58	First-order
Sandy	MW-600	0.0299*	0.9167	5.0×10^{-6}	0.6494	23.21	First-order
Sandy	MA-600	0.0270	0.9256	3.0×10^{-6}	0.6831	25.67	First-order
Sandy	NW-600	0.0274	0.9083	4.0×10^{-6}	0.6501	25.30	First-order
Sandy	NA-600	0.0244	0.9291	3.0×10^{-6}	0.7252	28.40	First-order

The first-order model produced higher R^2 values than the second-order model for all 600-g treatment combinations. For Moringa treatments, first-order R^2 values ranged from 0.9004 to 0.9354, compared with 0.6227–0.7118 for the second-order model. For Neem treatments, first-order R^2 values ranged from 0.8671 to

0.9296, compared with 0.6312–0.7898 for the second-order model. Thus, within the supplied dataset, the first-order model provided the closer fit to the observed TPH time-series data. The first-order half-life was calculated as $t_{1/2} = \ln(2)/k_1$.

The first-order rate constants varied with soil type and treatment. For Moringa treatments, k_1 ranged from 0.0217 to 0.0299 d⁻¹, while the corresponding Neem values ranged from 0.0132 to 0.0274 d⁻¹. The calculated half-lives ranged from 23.21 to 52.50 days. These differences indicate that the observed kinetic behaviour varied with both root-extract formulation and soil matrix.

The first-order half-lives provide a complementary description of the observed degradation rates. Shorter half-lives correspond to larger first-order rate constants, whereas longer half-lives correspond to smaller rate constants. The values in Table 11 therefore indicate variation in the apparent TPH reduction rate among the 600-g treatment combinations.

The kinetic results should not be interpreted as proof of a specific microbial degradation mechanism. They provide empirical descriptions of the reported TPH concentration changes under the experimental conditions. The accompanying bacterial-count measurements and physicochemical data provide supporting context, but additional microbial and mechanistic analyses would be required to identify the processes responsible for TPH reduction.

CONCLUSION

Based on the experimental investigation of the physicochemical characteristics of selected soils and the application of Moringa and Neem root-derived treatments for crude oil-contaminated soil remediation, the following conclusions are drawn:

Crude-oil contamination altered the measured physicochemical properties of the four investigated soil types, with reported increases in density, EC, MC, TOC, TN, and P and a decrease in pH. The magnitude of the changes differed among loamy, silt, clay, and sandy soils, demonstrating that the initial soil matrix is an important consideration when evaluating contaminated-soil treatment.

The Moringa and Neem materials were applied as aqueous and alcoholic root extracts rather than as intact plants. The extracts had measurable physicochemical differences from their corresponding solvents, and their application was associated with changes in the physicochemical properties of the contaminated soils.

TPH reduction increased progressively during the 84-day treatment period. At day 84, the reported TPH reduction values ranged from 69.03% to 96.14% across the treatment formulations and soil types. For the 600-g treatments, first-order kinetic fits gave R^2 values of 0.8671–0.9470, compared with lower second-order R^2 values.

The observed TPH reduction varied with soil type, root material, extraction medium, and soil-mass level. The results therefore support the use of soil physicochemical characterization alongside direct TPH measurement when evaluating plant-derived treatment amendments.

The untreated contaminated soil and pre-contamination measurements provided reference conditions for interpreting treatment-associated changes. However, because the supplied dataset does not contain replicate variability or inferential statistical tests, the observed differences should be regarded as descriptive rather than statistically confirmed.

Moringa and Neem root extracts show potential as locally available treatment amendments for crude-oil-contaminated soils. Further work should include replicated experimental designs, mean $\pm$ SD reporting, appropriate inferential statistics, detailed microbial community analysis, potassium and other relevant nutrient measurements where appropriate, and field-scale validation.

Future studies should also optimize extract preparation, extract-to-soil ratio, application frequency, treatment duration, and nutrient balance, and should quantify initial and residual hydrocarbon fractions where feasible to strengthen mechanistic interpretation.

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