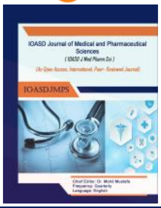
IOASD Journal of Medical and Pharmaceutical Sciences

IOASD J Med Pharm Sci, Vol-3, Iss-1, Jan-Mar., 2026
Frequency: Quarterly
ISSN: 3049-0294 (Online)
ISSN: 3049-3773 (Print)
Website: www.ioasdpublisher.com



Plant-Based Phytoremediation of Hydrocarbon-Contaminated Soils; A Review

M.A Nahari[1*], H.S Ibrahim[2], H.Y Rambo[1], and T.A Alfa[2]

[1]Department of Biology, Federal University of Agriculture, Zuru, Kebbi state, Nigeria.
[2]Department of Chemistry, Federal University of Agriculture, Zuru, Kebbi state, Nigeria.

Corresponding Author: M.A Nahari
Department of Biology, Federal University of Agriculture, Zuru, Kebbi state, Nigeria.

ABSTRACT

Soil contamination by petroleum hydrocarbons remains a widespread environmental challenge in oil-producing and industrial regions, where it poses serious threats to ecosystems, agricultural productivity, and human health. In recent years, plant-based phytoremediation has emerged as a sustainable and cost-effective approach for managing hydrocarbon-polluted soils. This review synthesises evidence from experimental and field-based studies assessing the ability of selected plant species to enhance the degradation and stabilisation of petroleum hydrocarbons in contaminated environments. Findings from pot experiments and field trials indicate that plant species such as *Mimosa pudica*, *Jatropha curcas*, and *Vetiveria zizanioides* are capable of significantly reducing total petroleum hydrocarbon concentrations while sustaining growth under polluted conditions. The effectiveness of phytoremediation is closely linked to extensive root systems, stimulation of rhizosphere microbial communities, and dynamic plant–soil–microbe interactions that promote hydrocarbon breakdown. The use of soil amendments and organic materials further enhances remediation efficiency by improving microbial activity and soil structure. Although remediation rates may be slower under conditions of severe contamination, the overall evidence consistently supports phytoremediation as an environmentally friendly alternative to conventional remediation technologies. This review highlights plant-based phytoremediation as a promising strategy for sustainable environmental management of hydrocarbon-contaminated soils, particularly in developing regions where low-cost, locally adaptable solutions are essential.

Keywords: Phytoremediation, Hydrocarbons, *Mimosa pudica*, *Jatropha curcas*, *Vetiveria zizanioides*, Sustainable environmental management, Soil remediation.

Review Article

Article History
Received: 17-12-2025
Accepted: 21-01-2026
Published: 11-02-2026

INTRODUCTION

The contamination of soils with petroleum hydrocarbons (PHCs) is a pervasive environmental challenge, particularly in oil-producing and industrial regions across the globe. In Nigeria and other developing countries, intensive exploration, extraction, and transportation of petroleum products have resulted in widespread soil degradation, posing severe risks to terrestrial ecosystems, agricultural productivity, and human health (Budhadev et al., 2014; Adenipekun et al., 2020). Hydrocarbon pollutants, including alkanes, polycyclic aromatic hydrocarbons (PAHs), and other complex organic compounds, are often recalcitrant, persist in the environment for extended periods, and disrupt soil physicochemical properties and microbial community structure (Liste & Alexander, 2000). Traditional remediation strategies, such as soil excavation, chemical oxidation, and thermal treatment, are frequently associated with high operational costs, energy consumption, and potential secondary pollution, limiting their practical application, especially in resource-constrained settings.

In response to these challenges, phytoremediation, the use of plants and their associated rhizosphere microbiota to remove, degrade, or stabilise contaminants—has emerged as a sustainable and environmentally sound alternative (Adenipekun et al., 2020). This approach exploits the natural capabilities of plants to tolerate and transform organic pollutants through direct uptake, enzymatic degradation, and stimulation of microbial activity in the rhizosphere. Extensive root systems and root exudates create a favourable microenvironment for hydrocarbon-degrading microorganisms, enhancing the breakdown of contaminants while simultaneously improving soil structure and fertility. The integration of soil amendments, such as organic compost or biochar, has been shown to further enhance phytoremediation efficiency by promoting microbial proliferation and facilitating contaminant bioavailability (Adenipekun et al., 2020; Liste & Alexander, 2000). Several plant species have been experimentally demonstrated to possess high remediation potential. *Mimosa pudica*, for instance, exhibits remarkable tolerance to crude oil contamination and has been shown to significantly reduce total petroleum hydrocarbons (TOG) in soil under controlled conditions (Budhadev et al., 2014). Similarly, field trials involving *Jatropha curcas* and *Vetiveria zizanioides* reveal substantial hydrocarbon degradation and sustainable plant growth, particularly when soil amendments are applied (Adenipekun et al., 2020). Indigenous and tropical plant species offer the additional advantage of local adaptability, enabling cost-effective and culturally acceptable remediation strategies in developing countries.

Despite these promising results, phytoremediation is not without limitations. The rate of contaminant degradation is often slower compared to conventional physicochemical methods, and effectiveness can be diminished in highly contaminated soils or under extreme environmental conditions. Nevertheless, the cumulative evidence from experimental and field studies underscores the potential of plant-based remediation as a viable strategy for sustainable environmental management. By harnessing plant–microbe interactions and optimizing soil conditions, phytoremediation presents an opportunity to restore hydrocarbon-impacted soils while promoting ecosystem recovery, food security, and human well-being.In light of these considerations, this review critically examines the current state of knowledge on plant-based phytoremediation of hydrocarbon-contaminated soils, with particular emphasis on mechanisms of contaminant removal, plant species efficacy, rhizosphere interactions, and strategies to enhance remediation efficiency. The synthesis aims to identify research gaps and future directions, thereby providing a robust foundation for the development of practical, low-cost, and locally adapted phytoremediation approaches in regions affected by petroleum hydrocarbon pollution.

Harmful Effects of Hydrocarbons on Soil

Soil contamination by petroleum hydrocarbons is a serious environmental problem, especially in areas with heavy oil production and industrial activity. When hydrocarbons enter the soil, they do more than just coat the surface; they affect the soil's structure, chemistry, and biology, making it less healthy and less productive (Budhadev et al., 2014; Adenipekun et al., 2020). Physically, hydrocarbons make the soil less porous and reduce its ability to hold water. This makes it harder for plant roots to grow and for soil organisms to survive. The soil can become compacted, poorly aerated, and less able to support natural processes like nutrient cycling (Liste & Alexander, 2000). Chemically, petroleum pollutants can change the soil's pH and reduce the availability of essential nutrients such as nitrogen and phosphorus. Some hydrocarbons, especially aromatic compounds, are very stable and persist in the soil for long periods. These compounds bind to soil particles, making it hard for plants and microbes to access nutrients and water (Budhadev et al., 2014). Biologically, hydrocarbons are toxic to many soil microorganisms. Microbes that normally break down organic matter or help plants absorb nutrients are often reduced in number or eliminated. This weakens the soil's natural ability to recover and disrupts the balance of the soil ecosystem (Adenipekun et al., 2020; Liste & Alexander, 2000).

Overall, hydrocarbons damage soil by making it less fertile, less structured, and less biologically active. Left untreated, contaminated soils can become degraded and unable to support crops, vegetation, or natural ecosystems. These harmful effects highlight the need for effective remediation methods. Plant-based phytoremediation, which uses plants and their root-associated microbes to remove or break down hydrocarbons, offers a simple, sustainable, and low-cost solution to restore contaminated soils.

Table 1: Hydrocarbon Types, Soil Effects, Exposure Routes, and Health Risks

Hydrocarbon Type	Effects on Soil	Human Exposure Route	Health Impact / Disease	References
Aliphatic hydrocarbons (e.g., alkanes from crude oil)	increase soil hydrophobicity; reduce water and oxygen infiltration; degrade soil structure and nutrient availability, inhibiting plant growth and microbial activity.	Inhalation of vapours; dermal contact with contaminated soil; ingestion through contaminated water/food chains.	Skin irritation, headaches, nausea; chronic exposure may affect nervous system and organ function.	Microbial Bioremediation of PetroleumContaminated Soil: A Sustainable Approach Ahmad Rizal Roslan Nordin, Ariela Rose Navarro, Juan Carlos Reyes,S. Maragathavalli,Risky Ayu Kristanti,Retno Wulandari,Seng Bunrith https://tecnoscientifica.com/journal/tasp/article/view/683

Hydrocarbon Type	Effects on Soil	Human Exposure Route	Health Impact / Disease	References
Aromatic hydrocarbons (BTEX) — Benzene, Toluene, Ethylbenzene, Xylene	Disrupt microbial diversity and soil enzyme activity; inhibit plant growth; persistent in soil, affecting long-term fertility.	Inhalation (vapour), dermal absorption, ingestion of contaminated water/soil.	Benzene is carcinogenic; prolonged exposure associated with leukemia, bone marrow damage; toluene and xylene can cause neurological symptoms.	Microbial Bioremediation of Petroleum Contaminated Soil: Structural Complexity, Degradation Dynamics and Advanced Pratik Kakde and Jaigopal SharmaPratik Kakde and Jaigopal Sharmahttps://microbiologyjournal.org/microbial-bioremediation-of-petroleum-contaminated-soil-structural-complexity-degradation-dynamics-and-advanced-remediation-techniques/
Heavy hydrocarbons / PAH fractions	Bind strongly to soil particles; virtually no degradation; reduce soil porosity, nutrient availability and influence microbial communities long-term; impede plant growth.	Ingestion of contaminated produce/dust; dermal contact; ingestion of contaminated water.	Long-term exposure is linked to cancer, immune dysfunction, cataracts, and cardiovascular issues.	Bioremediation of Soil Contamination with Polycyclic Aromatic Hydrocarbons—A Review Carmen Otilia Rusănescu,Irina Aura Istrate,Andrei Marian Rusănescu,Gabriel Alexandru Constantin https://www.mdpi.com/2073-445X/14/1/10
Polycyclic Aromatic Hydrocarbons (PAHs) (e.g., naphthalene, phenanthrene, benzo[a]pyrene	Strongly bind to soil organic matter; persist due to hydrophobicity; reduce microbial diversity and soil enzymatic functions; reduce soil fertility.	Inhalation of contaminated dust/vapour; ingestion of soil particles or contaminated food; dermal absorption.	Many PAHs are carcinogenic and mutagenic; associated with lung, skin, and bladder cancer; respiratory diseases; liver/kidney damage.	Petroleum-contaminated soil: environmental occurrence and remediation strategies. Dalel Daâssi,Fatimah Qabil Almaghribi https://pmc.ncbi.nlm.nih.gov/articles/PMC9133283/

Table 2: WHO Soil Quality Benchmarks for Hydrocarbon Contaminants and Associated Risks

Hydrocarbon / Organic Contaminant	WHO Maximum Tolerable Soil Concentration (mg/kg)
Benzene	0.14
Toluene	12
Chlorobenzene	211
PAHs (as benzo[a]pyrene equivalent)	16
Pyrene (non-carcinogenic PAH constituent but marker compound	41

Key Plants for Hydrocarbon Phytoremediation and Their Mechanistic Processes

Phytoremediation leverages the natural physiological and ecological traits of plants to remove, stabilise, or transform petroleum hydrocarbons in contaminated soils, achieving mitigation through mechanisms such as rhizodegradation, phytoextraction, and phytostimulation. Its effectiveness is largely dependent on extensive root systems that improve soil aeration, the stimulation of rhizosphere microbial communities, and species-specific metabolic or associative capabilities that facilitate the breakdown of both aliphatic and aromatic hydrocarbons. For example, *Vetiveria zizanioides* (vetiver grass) has been shown to accelerate total petroleum hydrocarbon (TPH) degradation; its dense, deep roots enhance oxygen diffusion into anaerobic soil zones, and root exudates provide substrates that stimulate hydrocarbon-degrading microbes, increasing microbial activity and degradation efficiency compared to unplanted soils (Rusănescu, Istrate, Rusănescu, & Constantin, 2022; Daâssi & Almaghribi, 2022). When used alongside soil amendments, vetiver further stabilises soil properties and improves remediation outcomes (Nordin, Navarro, Reyes, et al., 2021). Similarly, *Jatropha curcas*, a drought-tolerant shrub, demonstrates significant potential for remediating hydrocarbon-contaminated soils, particularly in tropical and subtropical regions. Its roots release organic compounds that stimulate microbial enzymatic activity and co-metabolic pathways, enhancing hydrocarbon degradation. Combined with organic amendments such as compost, *J. curcas* can simultaneously improve contaminant removal and soil fertility (Adenipekun, Akinola, & Ekeleme, 2020; Nordin et al., 2021).

Although less extensively studied, *Mimosa pudica* shows promise in the remediation of heavy crude oil-contaminated soils. Its fine root network increases hydrocarbon bioavailability and recruits rhizosphere and endophytic microbes capable of degrading hydrocarbons, allowing the plant to maintain growth while actively contributing to soil remediation (Budhadev, Sahu, & Tripathy, 2014). Wetland and riparian species, such as *Scirpus grossus*, are effective in saturated or flood-prone soils. These plants sequester hydrocarbons in root biomass while stimulating microbial activity in water-logged environments, highlighting the importance of plant–microbe interactions for enhanced degradation under hydric conditions (Rusănescu et al., 2022; Daâssi & Almaghribi, 2022).Indigenous species, including *Chromolaena odorata*, *Aspilia africana*, and *Uvaria chamae*, also tolerate petroleum contamination and support rhizosphere and endophytic microbes, offering cost-effective, locally adapted remediation solutions. Functional plant groups such as Poaceae (grasses) and Fabaceae (legumes) possess extensive root networks that enhance microbial hydrocarbon degradation, with legumes additionally supporting soil nutrient status through nitrogen fixation, promoting long-term ecosystem recovery (Adenipekun et al., 2020; Nordin et al., 2021).Overall, effective phytoremediation depends on the integration of root architecture, microbial stimulation, and plant metabolic functions, providing a sustainable and cost-effective strategy for restoring hydrocarbon-contaminated soils while enhancing ecosystem resilience.

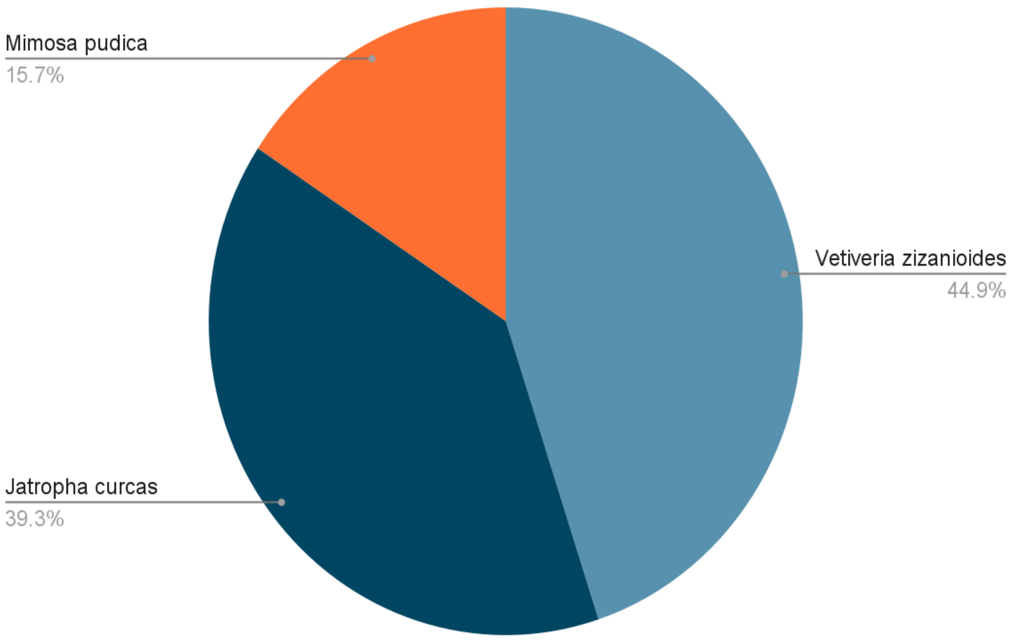


Figure 1: Proportional Hydrocarbon Removal by Vetiver, Jatropha, and Mimosa relative to each other in Contaminated Soils

Ecological Significance of Phytoremediating Plants for Long-Term Environmental Sustainability

Plant-based phytoremediation is increasingly recognised as a sustainable environmental management strategy for hydrocarbon-contaminated soils, particularly when compared with conventional remediation methods that are costly, energy-intensive, and disruptive to soil structure (Schnoor et al., 1995; USEPA, 2012). The establishment of vegetation on polluted sites contributes to soil stabilisation, reduces erosion and contaminant migration, and promotes the gradual recovery of essential soil functions, including nutrient cycling and biological activity (Pilon-Smits, 2005). Through root exudation and rhizosphere processes, plants stimulate indigenous hydrocarbon-degrading microorganisms, thereby enhancing the natural breakdown and immobilisation of petroleum compounds in soil (Liste & Alexander, 2000; Tang et al., 2010). This plant–microbe synergy allows environmental managers to utilise naturally occurring processes within a low-impact remediation framework. Although phytoremediation may require extended timeframes and shows reduced effectiveness under high contamination levels, its integration with soil amendments and nutrient management strategies can improve remediation efficiency and support long-term land stewardship goals (Tang et al., 2010; USEPA, 2012). Overall, phytoremediation represents a cost-effective, environmentally compatible, and locally adaptable approach for sustainable environmental management of hydrocarbon-impacted soils.

CONCLUSION

Plant-based phytoremediation offers a sustainable, cost-effective, and environmentally compatible approach for rehabilitating hydrocarbon-contaminated soils. Key species such as *Vetiveria zizanioides*, *Jatropha curcas*, and *Mimosa pudica* facilitate the breakdown, stabilisation, and removal of petroleum hydrocarbons through mechanisms including rhizodegradation, phytostimulation, and enhancement of microbial activity in the rhizosphere. The use of soil amendments further improves remediation efficiency by supporting microbial communities and restoring soil structure and fertility. Although remediation rates may be slower under high contamination, phytoremediation supports long-term environmental sustainability by stabilising soil, preventing erosion, and promoting ecosystem recovery. Overall, it represents a low-cost, locally adaptable, and ecologically resilient strategy for restoring hydrocarbon-impacted soils and enabling sustainable land use.

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