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Phytoremediation Plants in Oil Contaminated Soil: A Review of The Niger Delta Region

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Abstract

Petroleum hydrocarbon pollution caused by crude oil exploration, transportation, and spill incidents remains a serious environmental problem, especially in the Niger Delta region of Nigeria. This study evaluated the effectiveness of phytoremediation and integrated biological remediation strategies for restoring soils contaminated with 2–20% petroleum hydrocarbons. Both natural phytoremediation using naturally occurring vegetation and technical phytoremediation involving selected oil-tolerant and hyperaccumulator plants were examined under greenhouse and field conditions. Alfalfa (Medicago sativa) and ryegrass (Lolium perenne) were cultivated in contaminated soils for 60–120 days, while untreated contaminated soils served as controls. Plant performance was assessed through germination rate, shoot and root growth, biomass production, chlorophyll content, and root-to-shoot ratio. Microbial activity in the rhizosphere was analyzed using microbial isolation, colony counts, and PCR-based identification techniques. Total petroleum hydrocarbons (TPH) were quantified using GC–MS analysis, while soil enzyme activities were evaluated spectrophotometrically. Results showed that vegetated soils consistently recorded lower residual TPH concentrations than unplanted soils, confirming enhanced rhizosphere-mediated biodegradation. Combined plant–bacteria–fungi treatments achieved greater hydrocarbon reduction than single remediation methods, demonstrating strong synergistic interactions between plants and hydrocarbon-degrading microorganisms. Dominant bacterial genera included Pseudomonas, Bacillus, Acinetobacter, and Rhodococcus, while fungal genera included Aspergillus, Penicillium, Trichoderma, and Fusarium. Multi-Process Phytoremediation Systems (MPPS), integrating landfarming, microbial inoculation, phytoremediation, and plant growth-promoting rhizobacteria (PGPR), showed the highest remediation efficiency. Indigenous tropical grasses and wetland plants also demonstrated strong adaptability and sustainable remediation potential, supporting their use as low-cost, environmentally friendly solutions for oil-polluted soils in tropical ecosystems.

Keywords

Phytoremediation; Petroleum hydrocarbons; Rhizosphere microorganisms; Hydrocarbon degradation; Bioremediation; Oil-contaminated soil; Niger Delta.

1. Introduction

The presence of Petroleum related particles and contaminants found in terrestrial and aquatic ecosystem are caused by anthropogenic activities such as mining, pipeline transportation and illegal bunkery are sources of threat to the Niger Delta region (Adesola et al,2022). So many sites with oil spillage has become a source of concern to nature, community affected and the public and even depicted in places like Mexico (The 2010 deepwater Horizon disaster in Gulf Mexico), coastal creek and groundwater of Ogoniland (Lindel & Palsson,2013), Santa Barbara River blowout Oil spew in 2021 in Nembe, Bayelsa State and others (Agbonifo,2016). These regions have been rendered impotent as it relates to the health of their ecosystem particularly,the mangroves and wetlands and no much attention is given to them (Ofigo *et al*,2026). Oil polluted areas have limitations for the organisms dwelling in them as their mobility is impaired and waxes are deposited on their bodies bringing about increased death rate among Sea birds and other essential wildlife (Akpoghelie *et al*,2021).There is also the problem of ingeston and absorption of toxic aromatic hydrocarbon compounds which can be broken down to an extent through microbial action. Though this destructive ability of the contamination last for a period of time. It was documented that about 2,000,000 tons of Oil run into the environment yearly as a result of natural seepage and human activities (Meltzer,2024)

The Niger Delta, serving as the confluence tributaries to the Niger and Venue rivers at the Gulf of Guinea and one of the largest Mangrove and freshwater swamp is rich fauna, floral and mineral deposits but degraded by incessant logging, consistent flooding, Agricultural encroachment, Combustion , Oil spillage and other anthropogenic activities (Oyegun *et al*,2023, Ogbeibu & Orhibahor,2023). Nigeria, being an exporter of crude oil since the oil boom with petroleum serving as her major exchange earnings (Asekunowo & Olaiya,2012).The crude oil produced in the Oil industry have low sulfur and are sources of severe contamination in the ecosystem such that oil pollution is the order of the day in the wetlands, mangroves, groundwater and soil (Kuta,2023). The source of spillages are traced to vandalized pipelines, incessant illegal Oil bunkery/theft and crude refining practices and these processes transmit the contamination and spillages through flooding and groundwater systems which now become a major health issue to various local communities.(Solo-Gabriele *et al*,2015).

Modern Scientific methods such as digital elevation models have been developed to study the contamination pattern in the Niger Delta. It uses analysis of sediments, underground and surface water samples where the Total Petroleum Hydrocarbons (TPH) and Polycyclic Aromatic Hydrocarbons (PAHs) are hidden. The TPH sediment levels is between 20,600mg/kg and 729 mg/kg. There is also a higher concentration of PAH in sediment and surface water. 10 to 620 mg/L of TPH concentrations and up to 473 mg/L TPH are for groundwater levels with attendant PAH have been discovered (Chinedu & Chukwuemeka,2018). When the Concentration exceeds environmental quality standards of 54%-100% in monitoring regions, it reveals a very high biological adverse effect on aquatic sediment dwelling organisms. This range of assessment classified Niger Delta as a heavily Oil Contaminated region in combination with inadequate spill management techniques making persistent Oil pollution to breed through our soil and water threatening human life(NDES,2023)

Phytoremediation has to do with the process of using live plants to clean up contaminated ecosystem which may be either water, soil or air. It was discovered in recent times as a useful and lasting remedy to environmental pollution (Ogunkunle *et al*,2016). It involves the using bacteria, fungi and green plants to detoxify environmental contaminants. Phytoremediation works on the principle of using hyperaccumulators to bioaccumulates chemicals and toxins in order to harvest pollutants from the tissues of plants. It has been recorded that heavy metals like lead, aluminum , arsenic and antimony can bring about oxidative stress in plants and affect the cell membrane (Kanwar *et al,*2020)

The beauty of phytoremediation is that it is cost effective when related simultaneously with the other remediation approach particularly the traditional one, it is also sustainable as it helps to reduce erosion and metal leaching (Yan *et al*,2020), it helps to improve soil health and plant yields. Phytoremediation make use of different techniques such as Phytoextraction, Phytodegradation, Phytostabilization, Phytostimulation and Phytovolatilization. While Phytoextraction helps to remove contaminants from water or soil, Phytostabilization reduce the mobility and high rate of contaminants in the ecosystem/environment (Shimming *et al*,2020). While Phytodegradation make use of microorganisms and plants to breakdown organic pollutants, Phytostimulation increases soil microbial action for degradation of organic contaminants. However, Phytovolatilization involves the removal of contaminants from the soil or water by evaporation process into the atmosphere. There are plants prone to accumulating certain amounts of specific contaminants, for instance, Willow(Salix viminalis) for Cadmium, Sunflowers(Helianthus annuus) for Arsenic, Indian Mustard (Brassica juncea) for Lead and Alyssum (Alyssum murale and Berkheya coddii) are famous for accumulating high levels of Nickel (Aryal,2024). These plants are phytoremediation mitigating plants (Ivan *et al*,2023).

Several phytoremediators (plants/vegetables) have been studied in the last decades to determine their phytoremediation potential as shown in Table 1 below:

Plant Species	**Common Name**	**Ecological zone**	**Habits**	**Phytoremediation Ability**	**Author Citation.**
Chromolaena odorata	Siam weed	Tropical Rainforest	Shrubs	Act as Phytostabilizer. Help to clean up heavy metal polluted and oil contaminated soil.	Oyedeji et al, (2021)
Lycopersicon esculentum	Tomato	Tropical rainforest, Savannah and	Herbs	Phytoextraction of heavy metals like Lead (Pb), Cadmium (Cd) and Zinc ((Zn from	Oyedeji et al,(2022), Ortega, (2026)

		temperate zone		contaminated soil.	
Rumex acetosa	Sorrel	Temperate grassland	Herb	Heavy Metal accumulation and tolerance	Zhao et al,(2022)
Solanum melongena	Garden egg	Tropical Cultivated zone	Herbs/Shrubs	Phytoaccumulation of Cd and Pb.	Khan et al, (2022)
Acacia pycnantha	Golden Wattle	Woodland and Savannah	Tree	Phytostabilization and metal uptake	Masvodza et al,(2013)
Eucalyptus camaldulensis	River red gum	Semi arid and riparian zone	Tree	Uptake of hydrocarbons and heavy metals	Madejón et al,(2017)
Ipomoea aquatica	Water spinach	Wetland and Aquatic zone	Herbs/Creeper	Removal of Pb, Cd and wastewater pollutants	Hisam et al,(2022)
Abelmoschus esculentus	Okra	Tropical Cultivated zone	Herbs/Shrub	Phytoextraction of heavy metals from the soil	Akpan et al,(2022)
Amaranthus dubius	Spleen Amaranth	Tropical and subtropical zone	Herbs	Hyperaccumulation of Cd and Pb.	Shankar et al,(2011)
Hibiscus sabdariffa	Rosella	Tropical Cultivated zone	Shrubs	Bioaccumulation of heavy metals	Nizam et al,(2016)
Artemisia alba	White Mugwort, White wormwood	Dry grassland	Herbs/Shrubs	Tolerance and stabilization of contaminated soil	Ţicolea et al,(2025)

Tetrenae qataranse	Haram	Arid desert zone	Shrubs	Salt and heavy metals tolerance	Al-Thani & Yasseen,(2020)
Telfaira occidentalis	Fluted pumpkin	Tropical rainforest	Herbs/Climber	Uptake of heavy metals from the soil	Ok on, (2017)
Pteris vittata	Ladder Brake	Tropical moist zone	Fern/Herbs	Hyperaccumulator of arsenic	Gupta et al,(2022)
Epipremnum aureum	Money Plant, Devil's Vine or Pathos	Tropical humid Zone	Climber/herbs	removes VOCs (benzene, toluene), heavy metals (lead, chromium, copper), crude oil, and fluoride.	Lastiri-Hernández et al,(2023)
Mucuna bracteata	Mucuna	Tropical rainforest	Creeper, Climber/Herbs	Soil restoration and heavy metals uptake	Tang & Angela, (2019)
Imperata cylindrica	Cogon grass	Grassland	Grass /herbs	Phytostabilization and erosion control	Moktar & Tajuddin, (2019).
Pisum sativum	Pea	Temperate zone	Herbs/Climbers	Uptake of Trace metals and soil remediation	Efe & Okpai,(2012) Trotsenko et al,(2024)

In conclusion, phytoremediation is a promising technology for environmental remediation that offers a sustainable and cost-effective solution for contaminated sites. The specific objectives of this research is to :

1. To evaluate the effectiveness of phytoremediation in reducing petroleum hydrocarbon contamination in polluted soils.

2. To investigate the role of plant–bacterial–fungal interactions in enhancing hydrocarbon degradation.

3. To assess the growth performance and tolerance of selected oil-resistant plants in contaminated soils.

4. To compare the remediation efficiency of Multi-Process Phytoremediation Systems (MPPS) with individual remediation techniques.

2. Materials and Methods..

Soil samples used for this study were collected from oil-contaminated locations containing approximately 2–20% petroleum hydrocarbons. Both natural and technical phytoremediation approaches were investigated to evaluate their effectiveness in reducing soil contamination. In the natural phytoremediation setup, the growth and adaptation of naturally occurring wild plants on contaminated soil were monitored over time. For the technical phytoremediation treatment, selected oil-tolerant and hyperaccumulator plant species, including alfalfa and ryegrass, were cultivated in greenhouse pots and field plots under controlled conditions.

The experiment lasted between 60 and 120 days, depending on the treatment conditions. Unplanted contaminated soil served as the control to allow comparison of remediation efficiency. Seeds of hyperaccumulator plants and oil-resistant grasses were sown at planting densities of approximately 100–200 seeds per square meter using either manual broadcasting or a calibrated seed drill. Throughout the study, plant growth performance was monitored by measuring germination rate, shoot height, root length, fresh and dry biomass, root-to-shoot ratio, and chlorophyll content using measuring tapes, rulers, weighing balances, and chlorophyll meters.

Rhizosphere soil samples were collected to assess microbial activity associated with plant roots. Microbial populations were isolated and quantified using serial dilution and agar plating techniques in Petri dishes, while colony-forming units were counted with a colony counter. Further microbial identification and confirmation were carried out using polymerase chain reaction (PCR) analysis with a thermocycler and gel electrophoresis apparatus. Increased microbial activity observed in planted soils contributed significantly to enhanced hydrocarbon degradation.

For chemical analysis, total petroleum hydrocarbons (TPH) were extracted from soil samples using a Soxhlet extraction apparatus with hexane as the extraction solvent. The extracted hydrocarbons were then quantified using gas chromatography–mass spectrometry (GC–MS) to determine the level of contaminant reduction after treatment. Degradation efficiency was calculated as the percentage reduction in TPH concentration relative to the unplanted control samples.

In addition, soil enzyme activities, particularly dehydrogenase and urease, were analyzed as indicators of microbial and biochemical activity in the contaminated soils. These enzymes were measured spectrophotometrically using a UV–Visible spectrophotometer by recording absorbance at specific wavelengths.

3. Results and Discussion

3.1. Techniques used to enhance phytoremediation

3.1.1. Impacts of Plant-Bacterial-Fungal Interaction

The microcosm experiments demonstrated the contribution of plant–bacterial–fungal interactions to total petroleum hydrocarbon (TPH) degradation in oil-contaminated soils. Figure 1 shows TPH levels after 36 weeks, with unplanted soils generally exhibiting higher residual TPH concentrations than vegetated soils under the different treatment conditions. This trend suggests that rhizospheric activities may facilitate bioremediation processes. However, the extent of this effect depends on whether the observed differences are statistically significant. Similarly, Figure 2 compares TPH concentrations (mg/kg) in planted soils with and without supplemental bacteria and fungi after 36 weeks. Planted microcosms tended to show lower TPH concentrations, while combined plant–bacteria–fungi treatments produced greater reductions compared to bare soils or single-component treatments, indicating possible synergistic interactions among the biological components.

The experiment used oil-tolerant and hyperaccumulator plant species, namely Alfalfa and Ryegrass, because these plants are known to survive and grow well in petroleum hydrocarbon–contaminated soils. Their extensive root systems also help stimulate microbial activity in the rhizosphere, thereby enhancing hydrocarbon degradation.

The rhizosphere soils associated with these plants contained several hydrocarbon-degrading microorganisms. The bacterial genera identified included *Pseudomonas*, *Bacillus, Acinetobacter*, and *Rhodococcus*, while the fungal genera included Aspergillus, Penicillium, Trichoderma, and Fusarium. These bacterial and fungal species are commonly reported in petroleum-contaminated environments because of their ability to tolerate oil pollution and utilize hydrocarbons as energy sources. Their association with the rhizosphere of alfalfa and ryegrass contributed to the enhanced degradation of total petroleum hydrocarbons (TPH) observed in the planted treatments compared to the unplanted control soils.

Although Mustard and Vetch are commonly used in phytoremediation studies because of their ability to tolerate and accumulate petroleum-related contaminants, they are not native tropical species commonly found in the Niger Delta region of Nigeria. Since native plants are generally more adaptable to local environmental and climatic conditions, tropical indigenous species are considered more suitable for phytoremediation in the region. Therefore, native plants such as Vetiver Grass, Elephant Grass, Bahama Grass, and Spear Grass can serve as appropriate tropical alternatives because they are naturally adapted to the Niger Delta environment and have demonstrated strong tolerance to petroleum hydrocarbon contamination. These plants possess extensive root systems and high biomass production, which help stimulate rhizosphere microbial activity and enhance total petroleum hydrocarbon (TPH) degradation in contaminated soils. Their ability to survive and grow under polluted conditions makes them more environmentally sustainable and effective for long-term phytoremediation applications in tropical oil-producing regions such as the Niger Delta.

Plant growth performance in contaminated soils (1517 mg TPH/kg) was assessed after 95 days as shown in Figure 3. Crops like mustard and vetch produced substantial shoot and root dry matter, with mustard achieving the highest biomass despite phytotoxic stress, correlating with superior TPH removal. Error bars (LSD, $P < 0.05$; n=6) confirm significant differences, highlighting species-specific tolerances.

These results align with observed rhizosphere synergies, where vegetation supplies root exudates, oxygen, and nutrients, while mycorrhizal fungi enhance nutrient uptake and hydrocarbon breakdown. However, variability across plant species, ontogenetic stages, and contaminants (e.g., PAHs) emphasizes the need for tailored approaches

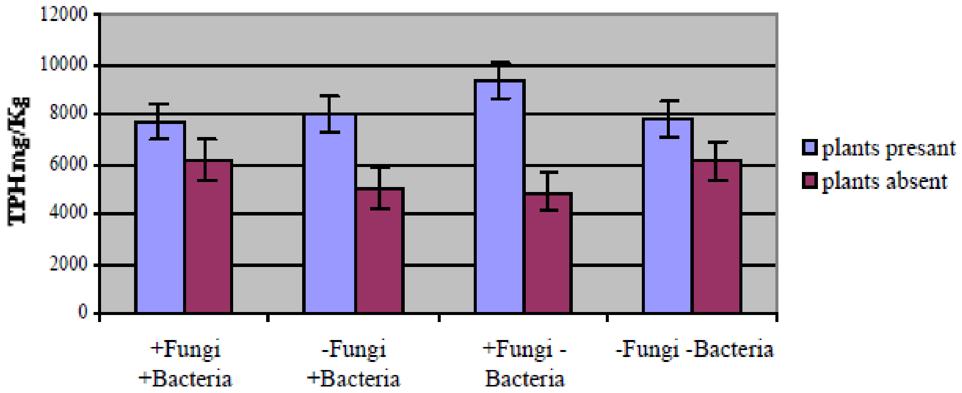


Figure 1: A bar chart compares TPH levels, showing higher levels when plants are present under various conditions. Total petroleum hydrocarbon present in microcosm soils after 36 weeks

Source: Vavrek & Campbell (2000) ; Olanipekun, 2017

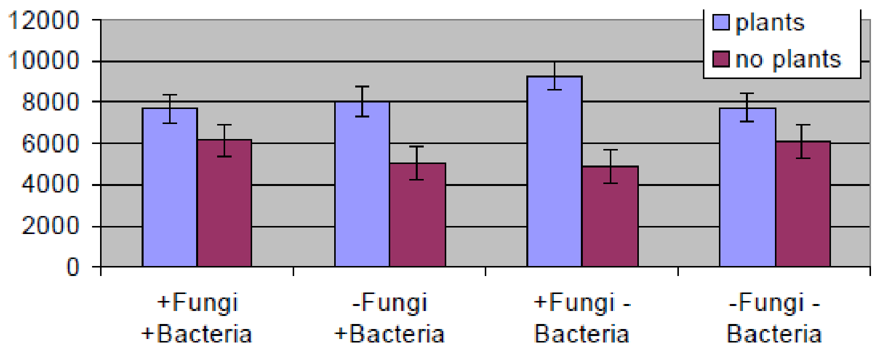
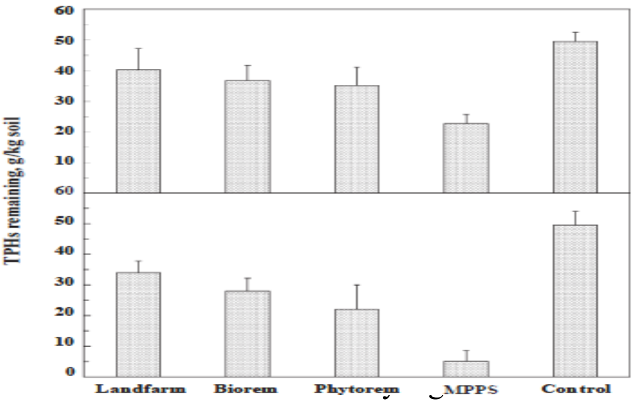


Figure 2: This bar chart illustrates TPH (mg/Kg) with/without plants under various microbial conditions.Total petroleum hydrocarbon present in soils after 36 weeks in the presence of plants, and combinations of bacteria and fungi
Source: Vavrek & Campbell (2000); Olanipekun,2017

Figure 3:: Shoot and root dry matter yields in petrol hydrocarbon contaminated soil (1517 mg TPHs kg/1) after 95 days of crop growth in the greenhouse. The error bars indicate the least significant difference (LSD) (P < 0.05; n = 6).
Source: (Liste and Felgentreu, 2006).



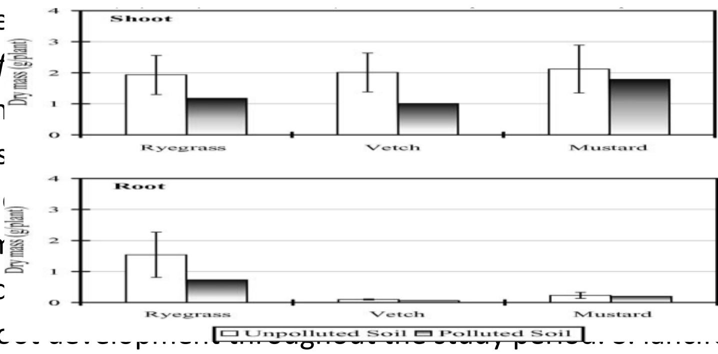
3.1.2. M ... (MPPS)

Laboratory ... MultiProcess Phytoremediatio ... g, microbial inoculation with ... ted by plant growth-promoti ... l 50% greater polycyclic arom ... o standalone methods, reduci ... utperforming landfarming (34 ... one (22 kg) . Figure 4 illustra ... , with MPPS yielding the low ... .05) from the untreated control (labeled 'a') and other single methods (labeled 'b'), as confirmed by standard error bars (n=3). Field trials using site-derived contaminated soils further corroborated these gains,demonstrating accelerated TPH and PAH degradation through synergistic boosts in root biomass and microbial activity. These outcomes address key limitations of individual techniques, such as TPH phytotoxicity inhibiting plant growth (Burd *et al*.,1998) and depleted microbial populations in polluted matrices.

Figure 4: Effectiveness of TPHs removal by each component of the MPPS. Data were generated from TPH analyses of the soil samples collected after 120 days of remediation. The treatments are land-farming, bioremediation, phytoremediation and the MPPS. The control was the untreated contaminated soil. The error bars are standard errors (n =3). Labels (a) and (b) indicate statistically significant differences from the untreated control and the MPPS, respectively (P b0.05).

Source: (Huang *et al*., 2005).

3.2. Assessment of plants for their suitability for remediation



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oil loading rates up to 24 L m^{-2} and continued regrowth through tuber formation after contamination exposure (Figure 6). At the end of the experiment, *P. hemitomon* produced the highest biomass among the evaluated marsh plants. These observations resemble conditions commonly reported in the freshwater swamps of the Niger Delta, where recurrent crude oil spills frequently damage wetland vegetation, yet some indigenous marsh species continue to survive and regenerate despite prolonged hydrocarbon exposure.

In petroleum-contaminated soils collected from the Shangli oilfield in China, *Mirabilis jalapa* achieved total petroleum hydrocarbon (TPH) removal efficiencies ranging from 41.62% to 63.20% after 127 days, while unplanted controls recorded 19.75%–36.90% removal (Figures 7 and 8). The highest removal efficiency (63.20%) was observed in soils containing 5000 mg/kg petroleum hydrocarbons under planted treatment conditions, compared with 36.90% in the corresponding control. At 10,000 mg/kg contamination, *M. jalapa* still achieved 60.18% TPH removal. Plant height and biomass showed only slight reductions across contamination levels, and the species remained viable at concentrations up to 20,000 mg/kg. Similar scenarios occur in many Niger Delta communities where farmlands exposed to repeated oil spills often become unsuitable for sensitive crops, while more tolerant plant species persist and contribute to gradual natural attenuation of petroleum contaminants in the soil.

Similarly, the tropical grass *Eleusine indica* (Figure 9) maintained relatively stable root characteristics, including specific root length, root surface area, root volume, and root diameter, under hydrocarbon stress conditions. In some treatments, TPH reduction did not differ significantly from unplanted controls. However, nutrient-amended soils contaminated with 5000 mg/kg petroleum hydrocarbons showed approximately 30–40% TPH removal, representing values several times higher than those observed in untreated control soils. This finding reflects remediation practices in parts of the Niger Delta, where nutrient supplementation and the establishment of tolerant grasses are increasingly considered as low-cost approaches for restoring oil-pollut ... tional ... r t

Figure 5: *Panicum hemitomon* Plant.

Figure 6: *Saggitaria lancifolia* plant.

Source: NatureServe,(2023) NRCS, (2015)

Figure 7: Tall fescue (*Festuca arundinacea*) plant. Source: Wasowski, (1991)

Figure 9: *Mirabilis jalapa* plant. Zhang et al,(2022)

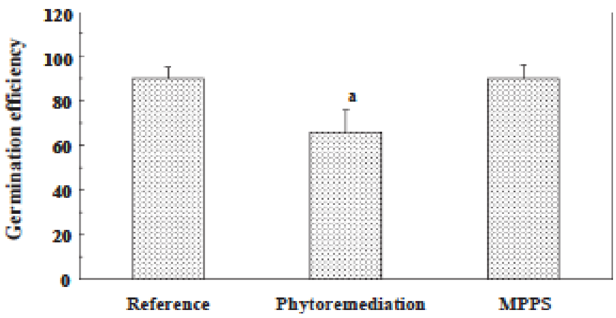

Figure 8: Degradation of TPHs in *Mirabilis jalapa* L. planted soil compared withthe unplanted control. Data were presented on graphs with means andstandard deviation (S.D.), PA: planted in soil A; CA: unplanted soil A; PB: planted in soil B; CB: unplanted soil B; PC: planted in soil C; CC: unplanted soil C.

Source: Peng *et al.* (2009).

Discussion

Oil spills significantly disrupt terrestrial and wetland soil ecosystems by altering soil chemistry, reducing oxygen availability, limiting nutrient cycling, and suppressing the biodiversity of indigenous plant and microbial communities responsible for hydrocarbon degradation (Ullah *et al,*2025). These disturbances negatively affect the natural attenuation capacity of soils and reduce the efficiency of biological remediation processes. The comparatively lower residual TPH concentrations recorded in planted microcosms after 36 weeks therefore suggest that vegetation enhanced rhizosphere-driven biodegradation processes relative to the unplanted soils. This observation agrees with previous findings that vegetated systems stimulate hydrocarbon degradation through root exudation, oxygen transfer, and microbial recruitment within the rhizosphere (Azcón & Barea, 2010; Asghar *et al.*, 2025). Root exudates such as sugars, amino acids, and phenolic compounds serve as carbon sources for hydrocarbon-utilizing microorganisms, thereby accelerating petroleum degradation in contaminated soils (Eze & Amuji,2024).

The results obtained from the planted treatments further indicate that the combined interactions among plants, bacteria, and fungi contributed substantially to enhanced TPH degradation. Treatments containing both microbial inoculants and vegetation consistently recorded lower TPH concentrations than bare soils or single-component systems, demonstrating synergistic relationships between rhizosphere microorganisms and host plants. Similar observations were reported by Zuzolo *et al*. (2021), who documented 75–85% TPH reduction in rhizospheres of *Brassica juncea* inoculated with arbuscular mycorrhizal fungi (AMF) and hydrocarbon-degrading *Pseudomonas species.* Following their observations(Zuzolo *et al*),fungal hyphal networks improved contaminant bioavailability while bacterial populations utilized root-derived substrates to accelerate petroleum hydrocarbon degradation. Likewise, Feng *et al.* (2023) observed that *Medicago sativa* (alfalfa) associated with endophytic fungi enhanced bacterial diversity and promoted degradation of heavy PAHs by approximately 68% within 120 days.

The use of alfalfa and ryegrass in the present study also contributed significantly to the remediation performance observed. These plant species are recognized for their tolerance to petroleum hydrocarbons and their extensive fibrous root systems, which stimulate microbial proliferation and increase rhizosphere surface area (Alotaibi *et al*,2021; Aryal,2024). The identification of bacterial genera such as *Pseudomonas, Bacillus, Acinetobacter*, and *Rhodococcus* alongside fungal genera including *Aspergillus, Penicillium, Trichoderma*, and *Fusarium* further supports the enhanced degradation recorded in the vegetated soils. These microorganisms are widely reported as efficient hydrocarbon degraders because they possess catabolic enzymes capable of utilizing petroleum compounds as energy and carbon sources (Dania *et al*,2016). Recent studies have additionally shown that Pseudomonas and Rhodococcus species produce biosurfactants that improve hydrocarbon solubility and increase contaminant bioavailability for microbial degradation (Ma *et al*., 2024). Fungal genera such as Trichoderma and Aspergillus also contribute through extracellular oxidative enzymes that degrade complex hydrocarbon fractions, including polycyclic aromatic hydrocarbons (PAHs)(Asemeloye *et al,*2020)

Although mustard and vetch demonstrated substantial biomass production and high TPH removal efficiencies in contaminated soils, their application in the Niger Delta may be limited by climatic adaptability because they are not indigenous tropical species (Ansah *et al* ,2022). The superior biomass accumulation observed in mustard despite phytotoxic stress suggests that certain tolerant plant species can maintain active metabolism and remediation capacity under hydrocarbon contamination. Similar findings by Liste and Felgentreu (2006) showed that stressed plants sometimes exhibit enhanced hydrocarbon degradation because petroleum stress stimulates the release of phenolic compounds such as salicylates, which indirectly promote co-metabolic degradation by rhizosphere microorganisms. The significant differences observed among plant species in biomass production and TPH reduction therefore confirm that remediation efficiency is strongly influenced by species-specific tolerance and rhizosphere competence (Aryal,2024).

In the context of the Niger Delta, the discussion of indigenous tropical grasses such as Vetiver grass, Elephant grass, Bahama grass, and Spear grass is particularly important. These plants are naturally adapted to the environmental and climatic conditions of the region and possess dense root systems capable of stabilizing contaminated soils while supporting active microbial communities. Their ecological compatibility makes them more sustainable for long-term remediation programs in tropical oil-producing environments (Teshale & Legasse,2020). Recent studies on tropical phytoremediation systems have shown that native grasses establish more rapidly, tolerate recurrent oil exposure better, and maintain rhizosphere microbial activity longer than many introduced temperate species. This supports the recommendation that remediation programs in the Niger Delta should prioritize indigenous plant species for improved ecological restoration and sustainability (Acharya *et al*,2025).

The findings from the marsh mesocosm studies involving *Panicum hemitomon* and *Sagittaria lancifolia* also reinforce the importance of plant tolerance in hydrocarbon-contaminated wetland systems. The ability of these marsh species to maintain active root development, tolerate high oil loading rates, and regenerate after contamination exposure indicates strong adaptive mechanisms against hydrocarbon stress (Dowty *et al* ,2001; Wills *et al* ,2004). The enhanced degradation observed under fertilization and aeration treatments demonstrates the importance of nutrient availability and oxygen diffusion in stimulating rhizosphere microbial activity. Similar ecological conditions exist in the freshwater swamps of the Niger Delta, where some indigenous wetland plants survive repeated oil spills despite severe ecosystem disturbances. Their persistence contributes to gradual natural attenuation processes within polluted marshlands (Nwankoaala & Okujagu,2021).

The results obtained from Mirabilis jalapa and Eleusine indica further demonstrate that hydrocarbon-tolerant plants can sustain growth and remediation activity even at relatively high contamination levels. The significantly higher TPH removal efficiencies recorded in planted soils compared to unplanted controls indicate that vegetation enhances microbial degradation and soil recovery (Peng *et al* ,2009). The ability of *M. jalapa* to remain viable at contamination levels up to 20,000 mg/kg suggests strong physiological tolerance mechanisms, while the relatively stable root architecture of *E. indica* under hydrocarbon stress indicates adaptive resilience. Nutrient supplementation additionally improved remediation efficiency, confirming previous reports that biostimulation enhances microbial metabolism and accelerates petroleum degradation in nutrient-deficient contaminated soils. This finding is particularly relevant to many polluted communities in the Niger Delta where low-cost remediation strategies involving nutrient amendment and tolerant grasses may provide practical alternatives to expensive conventional cleanup technologies (Fenibo *et al*,2025).

The superior performance of Multi-Process Phytoremediation Systems (MPPS) observed in both laboratory and field experiments highlights the advantages of integrating physical, biological, and microbial remediation strategies. MPPS combines landfarming, microbial inoculation, phytoremediation, and plant growth-promoting rhizobacteria (PGPR), thereby overcoming the limitations associated with single remediation methods. The significantly lower residual TPH and PAH concentrations recorded in MPPS-treated soils compared to standalone treatments demonstrate the effectiveness of synergistic remediation mechanisms. These findings are consistent with reports by Liu *et al*. (2013), Wang *et al.* (2023), and Guarino *et al.* (2020), who observed substantial improvements in hydrocarbon degradation following the combined application of PGPR, hydrocarbon-degrading bacteria, and phytoremediation systems.

The enhanced remediation efficiency achieved in MPPS may be attributed to several complementary mechanisms. Landfarming improves aeration and contaminant dispersion, bacterial inoculants initiate degradation of toxic hydrocarbons, while PGPR stimulate root elongation, nutrient acquisition, and stress tolerance through phytohormone production and ethylene regulation (Upadhyay *et al.*, 2023; He *et al.*, 2024). Increased root biomass consequently expands rhizosphere surface area and supports larger microbial populations capable of hydrocarbon degradation. Furthermore, AMF associations improve nutrient uptake and enhance contaminant bioavailability through fungal hyphal networks. A recent meta-analysis by Chen *et al.* (2025) confirmed that MPPS improves TPH and PAH degradation efficiencies by approximately 45–60% compared with individual remediation techniques, emphasizing its suitability for large-scale hydrocarbon remediation projects.

Despite these promising outcomes, phytoremediation systems remain influenced by several site-specific factors including contaminant composition, pollutant aging, soil properties, climatic conditions, and microbial competition. Recent studies indicate that remediation efficiency may decline in multi-contaminant environments where interactions between fungi and bacteria become antagonistic rather than synergistic (Kafle *et al,*2022). A 2024 meta-analysis similarly reported that although phytoremediation increases degradation efficiency by 40–60% on average, performance may decrease by 20–30% in highly complex contaminated sites due to reduced microbial compatibility and contaminant bioavailability. Consequently, successful field application requires careful selection of tolerant plant species, appropriate microbial consortia, nutrient management, and continuous monitoring of rhizosphere conditions (Wang *et al*,2026)

The study also highlighted that interactions between plants, bacteria, and fungi are central to improving the breakdown of petroleum hydrocarbons in contaminated soils. Vegetated systems consistently reduced total petroleum hydrocarbon (TPH) levels more effectively than bare soils, largely because plant roots release exudates, supply oxygen to the rhizosphere, and support mycorrhizal fungi that stimulate microbial activity. Supporting evidence shows that stressed but actively growing plants such as mustard and vetch can enhance microbial stimulation through phenolic exudates, leading to significantly improved hydrocarbon removal over time (Liste and Felgentreu, 2006).

The findings also reinforce that integrated remediation approaches, particularly Multi-Process Phytoremediation Systems (MPPS), are the most effective, achieving up to 50% greater reductions in TPH and PAHs compared to single-method approaches (Huang *et al.*, 2004a, 2005). In addition, plant-specific performance varies widely, with species such as Panicum hemitomon and Sagittaria lancifolia showing strong resilience in marsh environments due to their specialized root structures that enhance microbial colonization (Dowty *et al*., 2001).

Similarly, *Mirabilis jalapa* has been reported to remove between 41–63% of TPH under high contamination conditions (Peng *et al.*, 2009), while Eleusine indica demonstrates moderate effectiveness (30–40% removal) when nutrient conditions are improved, although its root structure limits its standalone efficiency (Jing *et al*., 2008).

However, the study also underscores important limitations. Most current evidence comes from short-term greenhouse or mesocosm experiments (typically 95–150 days), meaning long-term field performance and ecosystem recovery remain uncertain. In addition, the dynamics of rhizosphere microbial communities across different plant growth stages and soil conditions are still poorly understood (Beckers *et al*., 2017; Pérez-Izquierdo *et al*., 2019), and the relationships between root traits, exudation patterns, and degradation efficiency across different hydrocarbon types require further clarification (Alotaibi *et al*., 2021). Some studies also report potential drawbacks, such as nutrient competition slowing remediation or nitrogen depletion effects in certain grass systems (Liste and Felgentreu, 2005; McIntosh *et al*., 2016).

Finally, while species like Eleusine indica show promise, their structural limitations suggest that genetic improvement or integration into MPPS frameworks may be necessary for better performance. There is also a clear gap in long-term tropical field validation, particularly within oil-polluted regions such as Nigeria, where site-specific studies remain limited (Adekola, 2021). Conclusively, the evidence supports phytoremediation as a promising, eco-friendly strategy, but one that requires more long-term, field-based, and system-optimized research to reach full scalability and reliability.

Implications

i. This study reinforces the idea that petroleum-contaminated soils can be effectively restored using nature-based solutions, particularly through phytoremediation supported by beneficial microorganisms. The consistent reduction of total petroleum hydrocarbons (TPH) in planted soils compared to unplanted controls shows that vegetation does more than simply survive in polluted environments: it actively drives the cleanup process. Plant roots create a biologically active zone where microbes thrive, oxygen is introduced into the soil, and natural exudates stimulate the breakdown of hydrocarbons.

ii. A key implication is that soil remediation should no longer be viewed as a single-factor process. The strong performance of plant–bacteria–fungi partnerships demonstrates that successful remediation depends on collaboration within the soil ecosystem. Microorganisms such as Pseudomonas, Bacillus, Rhodococcus, and fungal species like Aspergillus and Trichoderma function as essential partners in breaking down complex hydrocarbons. Their presence in the rhizosphere confirms that biological diversity is central to restoring contaminated environments.

iii. The study also highlights the practical value of integrated remediation systems such as Multi-Process Phytoremediation Systems (MPPS). The significantly higher removal efficiencies observed under MPPS indicate that combining physical soil treatment, microbial enhancement, and plant-based remediation produces faster and more complete cleanup outcomes than any single approach. This has direct implications for environmental management practices, suggesting that hybrid systems should become the standard for treating heavily polluted sites.

iv. Another important implication is the role of plant selection in determining remediation success. The superior performance of hardy species such as alfalfa, ryegrass, and tropical grasses like vetiver and elephant grass shows that locally adapted plants are more reliable for field application. These species not only tolerate petroleum stress but also sustain microbial activity through extensive root systems and high biomass production. This makes them particularly suitable for long-term restoration in oil-impacted tropical ecosystems.

v. The study demonstrates that phytoremediation does more than remove contaminants; it gradually restores soil biological health. Improvements in microbial activity and soil enzyme functions indicate a broader ecological recovery process, which is essential for returning degraded land to productive use.

Recommendations

Based on the findings, several key recommendations are proposed to strengthen future remediation efforts.

i. integrated remediation approaches such as MPPS should be adopted more widely in both research and field applications. The combination of landfarming, microbial inoculation, and phytoremediation has proven significantly more effective than individual techniques and should be prioritized for large-scale cleanup projects.

ii. future phytoremediation strategies should intentionally incorporate beneficial microorganisms, particularly plant growth-promoting rhizobacteria (PGPR) and hydrocarbon-degrading fungi. Strengthening plant–microbe partnerships will enhance degradation rates and improve system resilience under high contamination stress.

iii. greater emphasis should be placed on the use of indigenous plant species in tropical regions. In environments such as the Niger Delta, native grasses like vetiver, elephant grass, and spear grass are recommended due to their adaptability, strong root systems, and proven tolerance to petroleum contamination. Their use will improve survival rates and ensure long-term ecological stability.

iv. there is a clear need for long-term field-based studies. Most existing research, including this study, is limited to short experimental periods of a few months. Longer monitoring periods are essential to understand sustainability, seasonal variation, and post-remediation soil recovery.

v. future research should focus on understanding how plant growth stages, root exudates, and microbial communities interact under different contamination types. This will help refine plant selection and improve the predictability of remediation performance across different soil conditions.

vi. more site-specific studies should be conducted in oil-producing regions, particularly the Niger Delta. The unique environmental conditions and history of repeated oil spills require locally tailored solutions rather than generalized models. Strengthening field validation will ensure that phytoremediation strategies are both scientifically sound and practically applicable in real-world contaminated sites.

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