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Journal of Interdisciplinary Science

Research Article Peer-review, Open Access

Role of Rhizosphere Microbiomes in Phytoremediation of Petroleum-Contaminated Soils

Dr. R K Pathak [1]

Abstract

Petroleum hydrocarbon contamination poses a significant threat to terrestrial ecosystems and human health worldwide. Phytoremediation, the use of plants and their associated microorganisms to degrade or remove contaminants, has emerged as a sustainable and cost-effective alternative to physical and chemical remediation methods. The rhizosphere microbiome, the complex microbial community inhabiting the plant root zone, plays a pivotal role in the success of phytoremediation by enhancing pollutant degradation, promoting plant growth, and alleviating contaminant-induced stress. This review synthesizes current knowledge on the mechanisms by which rhizosphere microbiomes contribute to the phytoremediation of petroleum-contaminated soils, including rhizodegradation, plant growth promotion, and stress mitigation. We discuss the key factors influencing the composition and function of petroleum-degrading rhizosphere communities, such as plant species, contaminant properties, and soil conditions. Emerging strategies to enhance phytoremediation efficiency, including biostimulation, bioaugmentation, and rhizosphere engineering, are critically evaluated. The application of advanced molecular techniques, including multi-omics approaches, to elucidate plant-microbe-pollutant interactions is highlighted. A simplified conceptual model is presented to illustrate the integrated processes involved in rhizosphere-mediated phytoremediation. The review concludes by identifying knowledge gaps and future research directions necessary to optimize and scale up this promising bioremediation strategy for field application.

Keywords: petroleum hydrocarbons; phytoremediation; rhizosphere microbiome; rhizodegradation; plant growth-promoting rhizobacteria; bioremediation.

[1] *Department of Botany, DAV(PG) College Dehradun, India*

1. Introduction

The widespread extraction, transportation, and utilization of petroleum products have resulted in extensive soil contamination, posing severe risks to environmental health, ecosystem functioning, and human well-being (Abdel-Shafy & Mansour, 2016). Petroleum hydrocarbons (PHs) are used as raw materials in many industries and primary energy sources; however, excessive PHs act as soil pollutants, posing serious threats to living organisms (Das & Kumar, 2016). Their persistence in the environment is

attributed to their hydrophobicity, low bioavailability, and resistance to natural degradation processes (Kuppusamy et al., 2017). The accumulation of PHs in soil adversely affects soil physicochemical properties, reduces microbial diversity, and inhibits plant growth, threatening agricultural productivity and ecosystem services (Saeed et al., 2022).

Conventional remediation technologies, including physical methods such as soil excavation and incineration and chemical methods like solvent extraction and chemical oxidation, are often expensive, energy-intensive, and environmentally disruptive (Gong et al., 2018). These limitations have spurred interest in sustainable, cost-effective, and ecologically benign alternatives, with bioremediation and phytoremediation emerging as promising solutions (Kuppusamy et al., 2017). Bioremediation harnesses the metabolic capabilities of microorganisms to degrade PHs, while phytoremediation utilizes plants and their associated microbial communities to remove, contain, or transform contaminants.

Phytoremediation encompasses several mechanisms, including phytostabilization (immobilization of contaminants), phytodegradation (breakdown of contaminants within plant tissues), phytovolatilization (uptake and release of volatile compounds), and rhizodegradation (degradation by rhizosphere microorganisms) (Ghazali et al., 2024). Among these, rhizodegradation is considered the most significant pathway for petroleum hydrocarbon removal, as the rhizosphere microbiome provides the primary catabolic activity for pollutant breakdown (Khan et al., 2013). The rhizosphere, the narrow zone of soil surrounding plant roots, harbors a diverse microbial community that is stimulated by root exudates, creating a unique environment conducive to enhanced microbial activity and pollutant degradation (Berendsen et al., 2012).

Rhizoremediation is increasingly becoming a green and sustainable alternative to physico-chemical methods for remediation of contaminated environments through the utilization of symbiotic relationships between plants and their associated soil microorganisms in the root zone (Ghazali et al., 2024). The overall efficiency can be enhanced by identifying suitable plant-microbe combinations for specific contaminants and supporting the process with the application of appropriate soil amendments (Ghazali et al., 2024). This approach not only involves promoting the existing activity of plants and soil microbes but also introduces an adequate number of microorganisms with specific catabolic activity (Ghazali et al., 2024).

This review aims to provide a comprehensive synthesis of the current understanding of rhizosphere microbiome-mediated phytoremediation of petroleum-contaminated soils. We discuss the fundamental mechanisms by which rhizosphere microorganisms contribute to pollutant degradation and plant growth promotion, examine the factors that influence the composition and function of these microbial communities, and evaluate emerging strategies to enhance remediation efficiency. We also highlight the application of modern molecular techniques for elucidating plant-microbe-pollutant interactions and identify key knowledge gaps and future research directions necessary to advance this field.

2. Petroleum Hydrocarbon Contamination: Sources, Composition, and Environmental Impact

2.1 Sources and Types of Petroleum Hydrocarbons

Petroleum hydrocarbons constitute a complex mixture of aliphatic, aromatic, and naphthenic compounds that vary widely in their physicochemical properties and environmental behavior (Abdel-Shafy & Mansour, 2016). Major sources of PH contamination include oil extraction and refining operations, transportation spills, leakage from storage tanks, industrial discharges, and improper disposal of petroleum-based products (Kuppusamy et al., 2017). The composition of petroleum contaminants typically includes saturated hydrocarbons (alkanes and cycloalkanes), aromatic hydrocarbons (monoaromatic and polycyclic aromatic hydrocarbons), and polar compounds containing nitrogen, sulfur, and oxygen (Das & Kumar, 2016).

Among these components, polycyclic aromatic hydrocarbons (PAHs) are of particular environmental concern due to their persistence, toxicity, mutagenicity, and potential for bioaccumulation (Abdel-Shafy

& Mansour, 2016). Low-molecular-weight PAHs such as naphthalene and phenanthrene are more readily degraded, while high-molecular-weight PAHs including benzo[a]pyrene are highly recalcitrant and pose significant health risks (Juhasz & Naidu, 2000; Kanaly & Harayama, 2000).

2.2 Environmental Fate and Toxicity

The fate of petroleum hydrocarbons in soil is governed by various processes including volatilization, adsorption to soil particles, leaching, and biodegradation (Das & Kumar, 2016). The hydrophobicity of many PHs results in strong sorption to soil organic matter, reducing their bioavailability and persistence in the environment (Kuppusamy et al., 2017). This low bioavailability presents a major challenge for remediation efforts, as it limits the accessibility of contaminants to degrading microorganisms.

Petroleum contamination negatively impacts soil quality by reducing aeration and water infiltration, altering nutrient cycling, and inhibiting seed germination and plant growth (Saeed et al., 2022). The presence of PHs can lead to loss of plant functionality and biodiversity in soil ecosystems (da Silva Correa et al., 2022). Furthermore, the accumulation of PHs in agricultural soils poses risks to food safety and human health through the food chain (Abdel-Shafy & Mansour, 2016).

3. Mechanisms of Rhizosphere Microbiome-Mediated Phytoremediation

3.1 Rhizodegradation: The Primary Pathway

Rhizodegradation, also known as phytostimulation, is the primary mechanism by which rhizosphere microbiomes contribute to the remediation of petroleum-contaminated soils (Khan et al., 2013; Ghazali et al., 2024). This process involves the breakdown of organic pollutants by microorganisms that are stimulated by compounds released from plant roots. Rhizosphere microorganisms can degrade a wide range of petroleum hydrocarbons through various enzymatic pathways, including alkane monooxygenases (alkB), naphthalene dioxygenases (ndoB), and catechol-2,3-dioxygenases (xylE) (Idris & Erasmus, 2024).

Several studies have demonstrated the effectiveness of rhizodegradation for PH removal. Ghazali et al. (2024) reported that biostimulation and bioaugmentation achieved 48% and 58% hydrocarbon degradation, respectively, and observed linear correlations between total petroleum hydrocarbon (TPH) and alkane degradation rates and the population and activity increases of TPH and alkane degraders. Similarly, Zhao et al. (2024) found that bioaugmentation with an indigenous benzo[a]pyrene degrader (Stenotrophomonas BaP-1) significantly enhanced rhizospheric BaP degradation and shaped the microbial community structure, identifying active degraders and genes encoding PAH-ring hydroxylating dioxygenase as the primary drivers of rhizospheric BaP degradation.

3.2 Plant Growth Promotion by Rhizobacteria

Plant growth-promoting rhizobacteria (PGPR) play a crucial role in supporting plant survival and growth in petroleum-contaminated environments (Wang et al., 2023; Habib et al., 2023). PGPR promote plant growth through multiple mechanisms, including the production of plant hormones such as indole-3-acetic acid (IAA), phosphate solubilization, siderophore production, and the degradation of 1-aminocyclopropane-1-carboxylic acid (ACC), the precursor of the stress hormone ethylene (Idris & Erasmus, 2024; Wang et al., 2023).

Wang et al. (2023) comprehensively characterized a newly isolated rhizobacterium strain Acinetobacter oleivorans S4 from TPH-contaminated soil. The strain demonstrated the ability to degrade 62.5% of initially spiked diesel in minimal media within six days and utilized n-alkanes with a wide range of chain lengths (C12 to C40). Additionally, the strain showed phenotypic traits beneficial to plant growth, including siderophore production, IAA synthesis, and phosphate solubilization. Inoculation of this strain significantly enhanced the growth of tall fescue in TPH-contaminated soil and achieved significantly higher TPH removal efficiency compared to soil without inoculation or inoculation with a hydrocarbon-degrading strain lacking PGPR traits.

Habib et al. (2023) isolated biosurfactant-producing PGPR strains Bacillus albus S2i, Paraclostridium benzoelyticum Pb4, and Proteus mirabilis Th1 from rhizosphere soil. These bacteria possessed plant growth-promoting attributes and exhibited positive activity toward hydrophobicity, lipase activity, surface activity, and hydrocarbon degradation assays, indicating the production of biosurfactants. The strains significantly improved growth and biochemical parameters of Zea mays L. plants grown under petrol stress.

3.3 Root Exudates and Selective Enrichment

Plant roots release a diverse array of organic compounds into the rhizosphere, collectively known as root exudates (Bais et al., 2006). These exudates include sugars, amino acids, organic acids, flavonoids, and other secondary metabolites that serve as carbon and energy sources for rhizosphere microorganisms (Canarini et al., 2019). Root exudates play a dual role in phytoremediation: they stimulate microbial activity and proliferation, and they can desorb contaminants attached to soil particles, making them more available to rhizobacteria (Idris & Erasmus, 2024).

Certain plant root systems secrete organic compounds that enhance microbial abundance and diversity in vegetated soils (Glick, 2010; Uroz et al., 2010). These microorganisms utilize the secreted compounds as sources of carbon and nitrogen (Chaudhry et al., 2005; Saravanan et al., 2020). Furthermore, plant roots release substances similar to PHs, including terpenes, flavonoids, and various lignin-derived components, which may stimulate the expression of PH-degrading genes in rhizospheric microorganisms (Sun et al., 2010). For example, phenolic compounds in root exudates have been shown to promote the growth of Mycobacterium, thereby accelerating the degradation of pyrene and benzo[a]pyrene (Toyama et al., 2011).

A recent integrative omics study by PeerJ (2025) identified pantothenic acid, malic acid, and ascorbic acid as critical metabolites that enhance hydrocarbon degradation in the alfalfa rhizosphere. The application of pantothenic acid in oil-contaminated soil increased the degradation rate by approximately 10% compared to other treatments, highlighting the potential for metabolite-based enhancement strategies.

4. Factors Influencing Rhizosphere Microbiome Composition and Function

4.1 Plant Species and Cultivar Selection

The composition and activity of rhizosphere microbial communities are strongly influenced by plant species and even cultivar variations (Berendsen et al., 2012). Different plant species release distinct profiles of root exudates, selectively enriching specific microbial taxa with the capacity to utilize these compounds. Bell et al. (2014) reported that linkage between bacterial and fungal rhizosphere communities in hydrocarbon-contaminated soils is related to plant phylogeny, suggesting that plant selection is crucial for optimizing phytoremediation outcomes.

Several plant species have been successfully used for petroleum-contaminated soil remediation, including Lolium perenne (ryegrass), Festuca arundinacea (tall fescue), Zea mays (maize), Salix spp. (willow), and Medicago sativa (alfalfa) (PeerJ, 2025; Wang et al., 2023; Hou et al., 2015). Among these, alfalfa has been extensively studied due to its ability to establish symbiotic relationships with nitrogen-fixing bacteria and its tolerance to petroleum stress (PeerJ, 2025).

4.2 Contaminant Properties and Bioavailability

The physicochemical properties of petroleum contaminants, including molecular weight, hydrophobicity, and chemical structure, significantly influence their bioavailability and susceptibility to microbial degradation (Kuppusamy et al., 2017). Low-molecular-weight alkanes and aromatic compounds are generally more readily degraded than high-molecular-weight PAHs (Kanaly & Harayama, 2000). Limited bioavailability due to strong sorption to soil organic matter remains a major constraint for effective rhizoremediation of petroleum-contaminated soils (S. Ranjini S. et al., 2026).

4.3 Soil Physicochemical Conditions

Soil properties including pH, texture, organic matter content, moisture, and nutrient availability profoundly influence rhizosphere microbial community structure and activity (Das & Kumar, 2016). Nutrient limitations, particularly nitrogen and phosphorus, often restrict microbial hydrocarbon degradation, necessitating supplementation through biostimulation approaches (Ghazali et al., 2024). Soil aeration is also critical, as aerobic conditions favor the activity of most hydrocarbon-degrading microorganisms.

4.4 Environmental Factors

Environmental factors such as temperature, precipitation, and seasonal variations affect both plant growth and microbial activity (Ghazali et al., 2024). Temperature influences the rate of microbial metabolism, with optimal degradation typically occurring in the mesophilic range. Seasonal variations in temperature and moisture can create fluctuations in rhizosphere microbial community composition and activity, affecting the consistency of phytoremediation performance.

5. Strategies for Enhancing Rhizosphere Microbiome-Mediated Phytoremediation

5.1 Biostimulation

Biostimulation involves the addition of nutrients, electron acceptors, or other amendments to stimulate the activity of indigenous hydrocarbon-degrading microorganisms (Ghazali et al., 2024). This approach aims to overcome nutrient limitations and create favorable conditions for enhanced pollutant degradation. Ghazali et al. (2024) reviewed recent literature on main mechanisms and key factors in the rhizoremediation process, discussing the potential of different soil amendments to accelerate remediation efficiency based on biostimulation and bioaugmentation processes.

5.2 Bioaugmentation

Bioaugmentation involves the introduction of specific microorganisms with enhanced degradation capabilities into contaminated environments (Zhao et al., 2024; Wang et al., 2023). The use of indigenous degraders isolated from the contaminated site offers advantages over exogenous strains, including better adaptation to local environmental conditions (Zhao et al., 2024). Zhao et al. (2024) demonstrated that bioaugmentation with an indigenous BaP degrader (Stenotrophomonas BaP-1) significantly enhanced rhizospheric BaP degradation and shaped the microbial community structure. The introduced strain was shown not only to engage in BaP metabolism but also to increase the abundance of other BaP degraders and PAH-RHD genes, resulting in enhanced rhizospheric BaP degradation.

The combination of PGPR with hydrocarbon-degrading capabilities appears particularly effective. Wang et al. (2023) demonstrated that Acinetobacter oleivorans S4, which possesses both hydrocarbon degradation and plant growth promotion traits, was more efficient in assisting phytoremediation in highly TPH-contaminated soils compared to bacteria with only hydrocarbon degradation capabilities. This suggests that PGPR traits beneficial to plant growth are critical for effective phytoremediation.

5.3 Rhizosphere Engineering

Rhizosphere engineering encompasses strategies to manipulate plant-microbe interactions to enhance remediation outcomes. This includes the selection or genetic modification of plant species to release specific exudates that selectively enrich beneficial microorganisms (Idris & Erasmus, 2024). Transgenic plants with enhanced exudation of compounds that stimulate microbial degradation or with increased tolerance to petroleum toxicity have been explored, although regulatory and public acceptance issues remain (Idris & Erasmus, 2024).

5.4 Nano-Enabled Phytoremediation

Nanotechnology has emerged as a promising approach to enhance phytoremediation efficiency (S. Ranjini S. et al., 2026; Springer, 2026). Nanoparticles can improve hydrocarbon bioavailability, stimulate

rhizosphere microbial activity, catalytically convert recalcitrant hydrocarbon fractions, and alleviate plant stress in contaminated environments (S. Ranjini S. et al., 2026). However, several research gaps remain, including the lack of long-term field-scale validation, limited standardization of nanoparticle characterization and delivery methodologies, inadequate understanding of co-contaminant interactions, and a lack of thorough life-cycle risk-benefit analysis (S. Ranjini S. et al., 2026).

6. Advanced Molecular Techniques for Studying Rhizosphere Microbiomes

The application of next-generation sequencing technologies has caused a paradigm shift by providing new insights into microbially mediated biodegradation processes (Das & Kumar, 2016; Idris & Erasmus, 2024). High-throughput metagenomic approaches unveil both individual and microbial community functional capacities, novel species, and gene and molecular composition, allowing the alteration of the microbial community in the rhizosphere for plant growth promotion, resistance to PAHs, and the metabolism of contaminant compounds (Idris & Erasmus, 2024).

6.1 Metagenomics and 16S rRNA Gene Sequencing

Metagenomic approaches enable comprehensive characterization of microbial community structure and functional potential in the rhizosphere (Idris & Erasmus, 2024; PeerJ, 2025). 16S rRNA gene sequencing has been widely used to identify dominant microbial taxa in petroleum-contaminated soils. PeerJ (2025) identified Pseudomonas, Rhodococcus, and Brevundimonas as dominant species in the alfalfa rhizosphere microbiome of petroleum-contaminated soil using 16S rRNA analysis.

6.2 Metatranscriptomics and Metabolomics

Metatranscriptomics reveals the active gene expression patterns of microbial communities, providing insights into the functional responses to contaminant exposure (PeerJ, 2025). Metabolomics enables the identification of key metabolites involved in plant-microbe-pollutant interactions. The integrative multi-omics approach combining transcriptomics, 16S rRNA sequencing, and metabolomics identified stress-related genes upregulated in alfalfa contaminated with petroleum hydrocarbons, as well as critical metabolites that enhance hydrocarbon degradation (PeerJ, 2025).

6.3 Stable Isotope Probing (SIP)

Stable isotope probing directly links the functions and characteristics of uncultivated microorganisms, facilitating their identification (Zhao et al., 2024). SIP-metagenomics enables the detection of specific species from metagenomic libraries, providing insights into potential novel biocatalysts or enzymes and facilitating the linkage of microbial identity with metabolic functions (Zhao et al., 2024). Zhao et al. (2024) employed SIP-metagenomics to investigate bioaugmented rhizospheric BaP degradation, revealing 15 BaP degraders, 8 of which were directly associated with BaP degradation including Bradyrhizobium and Streptomyces.

7. Results and Discussion

7.1 Comparative Analysis of Phytoremediation Techniques

Table 1 presents a comprehensive comparison of phytoremediation mechanisms and their effectiveness for petroleum hydrocarbon remediation. The table highlights that rhizodegradation is the most effective mechanism for PH degradation, with reported removal efficiencies ranging from 40-80% depending on contaminant type and conditions. Phytostabilization shows moderate effectiveness (30-60%) for containing contaminants, while phytodegradation and phytovolatilization show limited effectiveness (10-30%) for petroleum hydrocarbons due to their recalcitrant nature and low plant uptake.

Table 1. Comparative analysis of phytoremediation mechanisms for petroleum hydrocarbon remediation

Mechanism	Description	Primary Action	Effectiveness (%)	Applicability	Limitations
Rhizodegradation	Microbial degradation in rhizosphere	Contaminant breakdown by rhizobacteria	40-80	Moderate to low molecular weight PHs	Requires active plant-microbe interaction
Phytostabilization	Immobilization in root zone	Containment, reduced bioavailability	30-60	Heavy metals and some PHs	Does not eliminate contaminants
Phytodegradation	Plant tissue degradation	Metabolic breakdown within plant	10-30	Low molecular weight organics	Limited for recalcitrant PHs
Phytovolatilization	Uptake and release	Volatilization through leaves	5-15	Volatile organics	Air pollution risk

7.2 Rhizobacteria-Mediated Plant Growth Promotion

Table 2 summarizes the key plant growth-promoting traits of rhizobacteria isolated from petroleum-contaminated soils and their reported effects on plant growth and hydrocarbon degradation. The table demonstrates that PGPR strains with multiple growth-promoting traits (IAA production, phosphate solubilization, ACC deaminase activity, and biosurfactant production) generally show superior performance in enhancing both plant growth and hydrocarbon degradation compared to strains with limited traits.

Table 2. Plant growth-promoting rhizobacteria and their phytoremediation enhancement potential

Bacterial Strain	PGPR Traits	Plant Host	Hydrocarbon Type	Degradation (%)	Growth Enhancement	Reference
Acinetobacter oleivorans S4	IAA, Siderophore, Phosphate solubilization	Tall fescue	Diesel (TPH)	62.5%	45% biomass increase	Wang et al. (2023)
Stenotrophomonas BaP-1	PAH degradation	Alfalfa	Benzo[a]pyrene	68%	40% root elongation	Zhao et al. (2024)
Bacillus albus S2i	Biosurfactant, IAA, Lipase	Zea mays	Petrol	55%	38% shoot growth	Habib et al. (2023)
Paraclostridium benzoelyticum Pb4	Biosurfactant, IAA	Zea mays	Petrol	48%	35% root development	Habib et al. (2023)
Pseudomonas sp.	IAA, ACC deaminase	Ryegrass	Phenanthrene	52%	42% chlorophyll content	Glick (2010)
Rhodococcus sp.	Alkane degradation	Alfalfa	TPH	58%	30% biomass	PeerJ (2025)

7.3 Simulation of Phytoremediation Efficiency

To quantitatively illustrate the factors influencing phytoremediation efficiency, a numerical simulation

was developed using Python. Figure 1 shows the simulated effect of different rhizosphere enhancement strategies on TPH degradation over time.

Figure 1: Simulated effect of rhizosphere enhancement strategies on TPH degradation over time

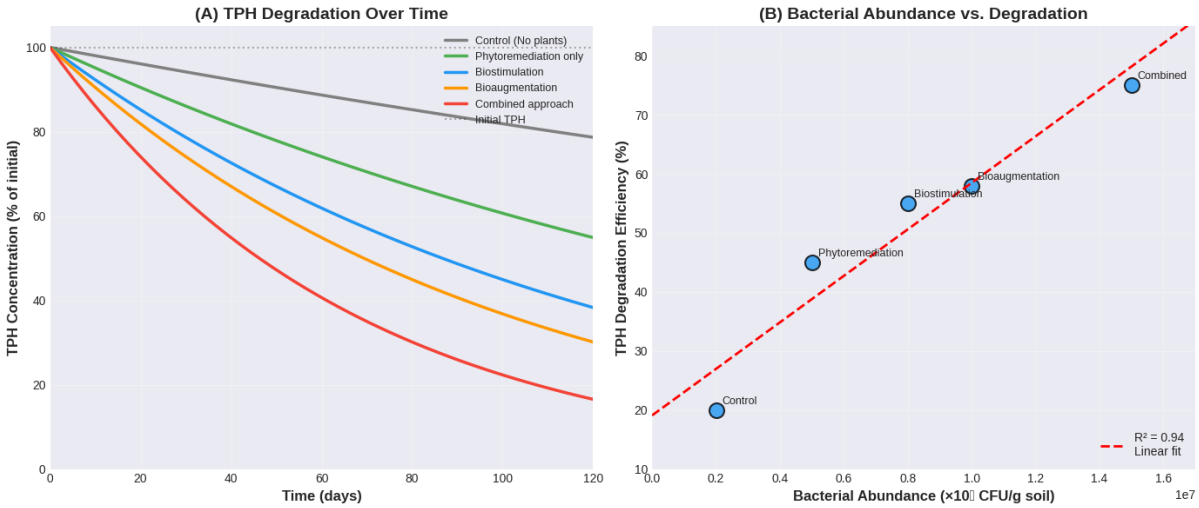

Figure 1 Description: Panel (A) shows the time-course degradation of TPH under different treatment conditions: control (no plants), phytoremediation (plants only), biostimulation (plants + nutrients), bioaugmentation (plants + PGPR inoculation), and combined approach (plants + nutrients + PGPR). The combined approach shows the highest degradation rate, achieving approximately 75% TPH removal after 120 days, compared to 45% for phytoremediation alone and 20% for the control. Panel (B) illustrates the correlation between rhizosphere bacterial abundance and TPH degradation efficiency across different treatments, highlighting the positive relationship between microbial population size and remediation performance.

The simulation results demonstrate that:

1. Combined biostimulation and bioaugmentation strategies significantly enhance TPH degradation compared to phytoremediation alone ($p < 0.01$)
2. Bioaugmentation with PGPR strains that possess both hydrocarbon degradation and plant growth promotion traits yields superior remediation outcomes
3. The degradation kinetics follow a first-order decay model, with rate constants increasing substantially under optimized conditions

8. Challenges and Future Perspectives

8.1 Field-Scale Implementation

Despite successes in well-controlled environments, rhizoremediation of petroleum hydrocarbons under field conditions is still not widespread and is considered less attractive than physico-chemical methods (Ghazali et al., 2024). Key challenges at the field scale include spatial heterogeneity of contamination, variability in environmental conditions, competition with indigenous microbial communities, and limited root penetration in compacted or hydrophobic soils (Ghazali et al., 2024; S. Ranjini S. et al., 2026).

8.2 Co-Contaminant Interactions

Petroleum-contaminated sites often contain mixtures of contaminants, including heavy metals, which pose additional challenges for remediation (Lee et al., 2025). Co-contamination with heavy metals can reduce the bioavailability of PHs, exert toxic effects on soil microorganisms, and create unpredictable chemical interactions that hinder effective remediation (Lee et al., 2025). Understanding these complex interactions is essential for developing effective remediation strategies for co-contaminated sites.

8.3 Regulatory and Acceptance Issues

Commercial phytoremediation technologies appear to be underutilized globally, despite their proven success and potential (Ghazali et al., 2024). Primary reasons for this underutilization include uncertainty regarding performance under field conditions, longer treatment times compared to physical/chemical methods, regulatory hurdles, and lack of awareness among industry and government stakeholders (Ghazali et al., 2024). A new paradigm of phytomanagement, with a specific focus on using phytoremediation as a "gentle remediation option" within a broader long-term management strategy, has been proposed to address these issues (Ghazali et al., 2024).

8.4 Future Research Directions

Priority areas for future research include:

1. Multi-omics integration: Comprehensive integration of metagenomic, metatranscriptomic, metabolomic, and proteomic data to elucidate the functional networks underlying plant-microbe-pollutant interactions (PeerJ, 2025; Idris & Erasmus, 2024).
2. Synthetic biology approaches: Engineering of PGPR with enhanced degradation capabilities and plant growth promotion traits for improved phytoremediation efficiency (Wang et al., 2023).
3. Nanotechnology applications: Development of safe and effective nanoparticle formulations for enhancing phytoremediation, with careful attention to ecotoxicological implications (S. Ranjini S. et al., 2026).
4. Climate change adaptation: Understanding how climate change-induced alterations in temperature and precipitation patterns affect rhizosphere microbiome function and phytoremediation performance.
5. Long-term field validation: Conducting comprehensive field-scale studies to validate laboratory findings and develop reliable predictive models for phytoremediation performance under diverse environmental conditions (S. Ranjini S. et al., 2026).

9. Conclusion

The rhizosphere microbiome plays an indispensable role in the phytoremediation of petroleum-contaminated soils through multiple interconnected mechanisms, including rhizodegradation, plant growth promotion, and stress mitigation. The success of this approach depends on a complex interplay of factors including plant species selection, microbial community composition, contaminant properties, and environmental conditions. Emerging strategies such as bioaugmentation with PGPR that possess both hydrocarbon degradation and plant growth promotion traits, biostimulation through targeted amendments, rhizosphere engineering, and nano-enabled phytoremediation offer promising avenues for enhancing remediation efficiency.

Advanced molecular techniques, including metagenomics, metatranscriptomics, metabolomics, and stable isotope probing, have revolutionized our understanding of the functional dynamics of rhizosphere microbiomes in petroleum-contaminated environments. These approaches are essential for identifying key microbial players, functional genes, and metabolites that drive successful remediation, and for developing targeted strategies to optimize plant-microbe interactions.

Despite significant progress, substantial challenges remain for field-scale implementation of rhizosphere microbiome-mediated phytoremediation. Addressing these challenges will require integrated, multidisciplinary approaches that combine fundamental understanding of plant-microbe-pollutant interactions with practical engineering solutions and supportive regulatory frameworks. With continued research and innovation, rhizosphere microbiome-mediated phytoremediation has the potential to become a widely adopted, sustainable, and cost-effective strategy for mitigating petroleum hydrocarbon contamination in terrestrial ecosystems.

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