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THE ROLE OF PHYTOREMEDIATION IN RESTORING OIL-CONTAMINATED SOILS: PROGRESS AND LIMITATIONS

Jimoh Ahmed[1]; Ahmad Abdulrazaq Itopa[1]

[1]Kogi State Polytechnic, Lokoja, Kogi State

Abstract

Oil contamination of soils, resulting from industrial activities, spills, and improper waste disposal, poses significant environmental and health risks. Phytoremediation, the use of plants and associated microorganisms to degrade, remove, or stabilize contaminants, has emerged as a cost-effective and eco-friendly approach to restore oil-contaminated soils. This article reviews the mechanisms of phytoremediation, recent progress in its application for petroleum hydrocarbon removal, and the limitations that hinder its widespread adoption. Key plant species, microbial interactions, and technological advancements are discussed, alongside challenges such as slow remediation rates, contaminant toxicity, and site-specific constraints. Future research directions are proposed to enhance the efficacy of phytoremediation for sustainable soil restoration.

Keywords: Phytoremediation, oil-contaminated soils, petroleum hydrocarbons, plant-microbe interactions, environmental restoration

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1.0 Introduction

Oil contamination of soils, resulting from spills, industrial activities, and improper disposal of petroleum products, poses significant environmental and ecological challenges. Crude oil and its derivatives, such as polycyclic aromatic hydrocarbons (PAHs), heavy metals, and volatile organic compounds (VOCs), can persist in soils, disrupting ecosystems, reducing soil fertility, and posing risks to human health through food chain contamination (Agnello et al., 2016). Traditional remediation methods, such as excavation, incineration, or chemical treatments, are often costly, energy-intensive, and environmentally disruptive. In response to these challenges, phytoremediation has emerged as a sustainable, cost-effective, and eco-friendly alternative for restoring oil-contaminated soils. Phytoremediation leverages the natural abilities of plants and their associated microorganisms to degrade, stabilize, or remove contaminants from the soil environment (Pilon-Smits, 2005).

1.1 Definition of Phytoremediation

Phytoremediation is an environmentally sustainable, cost-effective bioremediation technology that utilizes plants and their associated microbial communities to remove, degrade, stabilize, or sequester contaminants from soil, water, or air. This approach leverages the natural physiological and biochemical processes of plants, including uptake, transformation, immobilization, and volatilization, to address a wide range of pollutants, such as heavy metals, organic compounds (e.g., polycyclic aromatic hydrocarbons [PAHs], pesticides), and radionuclides (Pilon-Smits, 2005). Phytoremediation is particularly valued for its ability to restore contaminated sites with minimal environmental disruption, preserving soil structure and promoting ecosystem recovery compared to conventional methods like excavation or chemical treatments (Salt et al., 1998).

1.2 Mechanisms of Phytoremediation

Phytoremediation encompasses several mechanisms, including phytoextraction, phytodegradation, rhizodegradation, phytostabilization, and phytovolatilization, each suited to specific types of contaminants and environmental conditions. In the context of oil-contaminated soils, rhizodegradation and phytodegradation are particularly relevant, as they involve the degradation of organic pollutants like PAHs by plant roots and their associated microbial communities in the rhizosphere (Alkorta & Garbisu, 2001). The progress in phytoremediation research has demonstrated its potential to restore contaminated sites, improve soil health, and promote biodiversity. However, limitations such as slow remediation rates, plant tolerance to contaminants, and site-specific constraints have hindered its widespread adoption. This introduction explores the mechanisms, progress, and limitations of phytoremediation in addressing oil-contaminated soils, providing a foundation for understanding its practical applications and future research needs.

The process encompasses several distinct mechanisms, each suited to specific contaminants and environmental conditions:

1.2.1 Phytoextraction

Plants absorb contaminants, typically heavy metals, from the soil or water and accumulate them in their harvestable tissues (e.g., shoots). This is effective for metals like cadmium, zinc, and nickel, with hyperaccumulator plants like Thlaspi caerulescens being commonly used (Raskin et al., 1997).

1.2.2 Phytodegradation

Plants take up organic contaminants and metabolize them into less toxic forms within their tissues using enzymes such as cytochrome P450 or peroxidases. This is suitable for organic pollutants like chlorinated solvents or PAHs (Pilon-Smits, 2005).

1.2.3 Rhizodegradation

The degradation of organic contaminants, such as petroleum hydrocarbons, occurs in the rhizosphere (the soil zone surrounding plant roots) through the activity of microorganisms stimulated by root exudates, including sugars, amino acids, and enzymes (Alkorta & Garbisu, 2001).

1.2.4 Phytostabilization

Plants reduce the mobility and bioavailability of contaminants by immobilizing them in the soil or root zone, preventing their migration to groundwater or adjacent areas. This is effective for heavy metals and certain organic compounds (Salt et al., 1998).

1.2.5 Phytovolatilization

Plants take up volatile contaminants or their metabolites and release them into the atmosphere through transpiration. This is applicable to contaminants like mercury or volatile organic compounds (VOCs) (Pilon-Smits, 2005).

1.2.6 Rhizofiltration

Plants, typically aquatic or hydroponically grown, absorb or adsorb contaminants from water or wastewater, primarily heavy metals, through their root systems (Raskin et al., 1997).

Phytoremediation is applicable to diverse environmental contexts, including oil-contaminated soils, heavy metal-polluted sites, and wastewater treatment systems. Its advantages include low cost (estimated at $0.02–$1.00 per cubic meter of soil compared to $100–$1000 for traditional methods), aesthetic improvement of contaminated sites, and carbon sequestration potential (Pilon-Smits, 2005). However, limitations include slow remediation rates, dependency on plant tolerance to contaminants, shallow root zone effectiveness (typically 0–30 cm), and site-specific factors such as soil pH, climate, and contaminant bioavailability (Alkorta & Garbisu, 2001).

Recent advancements in phytoremediation include the use of genetically modified plants to enhance contaminant uptake or degradation, bioaugmentation with specific microbial strains, and integration with soil amendments like biochar to improve efficiency (Agnello et al., 2016). Despite these advances, challenges such as regulatory acceptance, disposal of contaminated biomass, and scalability for highly contaminated or deep subsurface sites remain areas for further research.

Table 1: Mechanisms of Phytoremediation for Oil-Contaminated Soils

Mechanism	Description	Target Contaminants	Example Plants
Rhizodegradation	Microbial degradation in the rhizosphere	PAHs, TPH	Festuca arundinacea, Medicago sativa
Phytodegradation	Plant-mediated breakdown of contaminants	Low-molecular-weight PAHs	Populus spp., Salix spp.
Phytostabilization	Immobilization of contaminants in soil/root zone	Heavy metals, PAHs	Brassica spp.
Phytoextraction	Uptake and accumulation in plant tissues	Heavy metals	Helianthus annuus
Phytovolatilization	Volatilization of contaminants via transpiration	VOCs	Populus spp.

Purpose: This table would summarize the mechanisms, their applications, and suitable plant species, providing a quick reference for researchers and practitioners.

1.3 Progress in Phytoremediation of Oil-Contaminated Soils

Significant progress has been made in understanding and applying phytoremediation for oil-contaminated soils: Research has identified plant species with high tolerance to oil contaminants and robust root systems, such as grasses, legumes, and trees (Populus and Salix spp.). Genetic engineering has further enhanced plant capabilities, with transgenic plants expressing microbial genes for enhanced PAH degradation (Agnello et al., 2016); The synergy between plants and rhizosphere microorganisms has been a focal point of research. Bioaugmentation with hydrocarbon-degrading bacteria, such as Pseudomonas spp., has improved remediation efficiency (Muratova et al., 2008); Successful field trials have demonstrated phytoremediation's effectiveness in real-world settings. For instance, studies in oil-contaminated sites in Nigeria and Canada have shown significant reductions in total petroleum hydrocarbons (TPH) using native plants like Vetiveria zizanioides (vetiver grass) (Truong et al., 2010); Phytoremediation is less invasive than traditional methods, preserving soil structure and reducing secondary environmental impacts. It is also cost-effective, with estimates suggesting costs as low as $0.02–$1.00 per cubic meter of soil compared to $100–$1000 for excavation and incineration (Pilon-Smits, 2005).

1.4 Limitations of Phytoremediation

Despite its promise, phytoremediation faces several limitations that restrict its scalability and applicability: Phytoremediation is a relatively slow process, often requiring multiple growing seasons to achieve significant contaminant reduction. This makes it less suitable for sites

requiring rapid cleanup (Alkorta & Garbisu, 2001), High concentrations of oil contaminants can be toxic to plants, limiting their growth and remediation efficiency. Selecting tolerant species or using amendments (e.g., biochar, compost) is necessary but adds complexity (Agnello et al., 2016), Soil properties (e.g., pH, salinity), climate, and contaminant composition influence phytoremediation success. For example, high-molecular-weight PAHs are recalcitrant and less amenable to degradation (Muratova et al., 2008), Phytoremediation is most effective in the root zone (typically 0–30 cm), making it less suitable for deep contamination or groundwater remediation, and Regulatory acceptance of phytoremediation varies, and concerns about the disposal of contaminated plant biomass (e.g., through incineration or composting) remain unresolved (Truong et al., 2010).

Table 2: Advantages and Limitations of Phytoremediation for Oil-Contaminated Soils

Aspect	Advantages	Limitations
Speed	Gradual, long-term remediation	Slow, requiring multiple seasons
Cost	Low cost ($0.02–$1.00/m³)	Initial setup and monitoring costs
Environmental Impact	Eco-friendly, preserves soil structure	Limited to shallow contamination
Applicability	Suitable for large, low-risk sites	Less effective for high-toxicity or deep contamination
Scalability	Applicable to diverse plant species	Site-specific constraints (soil, climate)

Purpose: This table would provide a concise comparison of the benefits and challenges, aiding decision-makers in evaluating phytoremediation's feasibility.

2.0 Mechanisms of Phytoremediation for Oil-Contaminated Soils

Phytoremediation is a bioremediation technique that employs plants and their associated microbial communities to remediate contaminated environments, including soils polluted with petroleum hydrocarbons such as crude oil, polycyclic aromatic hydrocarbons (PAHs), and total petroleum hydrocarbons (TPH). In the context of oil-contaminated soils, phytoremediation leverages specific mechanisms to degrade, stabilize, or remove organic pollutants and associated heavy metals. These mechanisms include rhizodegradation, phytodegradation, phytostabilization, phytoextraction, and phytovolatilization, with rhizodegradation and phytodegradation being the most relevant for organic contaminants like oil (Pilon-Smits, 2005). Below, each mechanism is described in detail, focusing on its application to oil-contaminated soils, supported by examples and scientific insights.

2.1 Rhizodegradation

Rhizodegradation, also known as enhanced rhizosphere biodegradation, is the primary mechanism for remediating oil-contaminated soils. It involves the degradation of organic pollutants, such as PAHs and TPH, by microorganisms in the rhizosphere—the soil zone surrounding plant roots. Plant roots exude organic compounds (e.g., sugars, amino acids, and organic acids) and enzymes that stimulate microbial activity, enhancing the breakdown of

hydrocarbons into simpler, less toxic compounds like carbon dioxide and water (Alkorta & Garbisu, 2001). The rhizosphere provides a nutrient-rich environment that supports a diverse microbial community, including hydrocarbon-degrading bacteria such as Pseudomonas spp., Bacillus spp., and Mycobacterium spp.

2.1.1 Application to Oil-Contaminated Soils

Rhizodegradation is highly effective for degrading low- to medium-molecular-weight PAHs (e.g., naphthalene, phenanthrene) and aliphatic hydrocarbons found in oil. Plants with extensive, fibrous root systems, such as grasses (Festuca arundinacea, Vetiveria zizanioides) and legumes (Medicago sativa), are particularly effective due to their large root surface area, which maximizes microbial interactions (Muratova et al., 2008). For example, a study by Muratova et al. (2008) demonstrated that alfalfa enhanced the degradation of bitumen-related hydrocarbons by stimulating rhizosphere microbial activity.

The key Factors include: Root exudates increase microbial biomass and activity, Oxygen released by roots supports aerobic degradation of hydrocarbons, and Soil structure is improved, enhancing contaminant bioavailability

2.2 Phytodegradation

Phytodegradation involves the uptake of organic contaminants by plants, followed by their metabolism or transformation into less toxic compounds within plant tissues. Plants produce enzymes, such as cytochrome P450, nitroreductases, and peroxidases, that break down organic pollutants (Pilon-Smits, 2005). This mechanism is less dominant than rhizodegradation for oil-contaminated soils but complements it by addressing contaminants that are absorbed by the plant. Application to Oil-Contaminated Soils Phytodegradation is effective for less recalcitrant organic compounds, such as low-molecular-weight PAHs and certain VOCs present in oil. Plants like poplars (Populus spp.) and willows (Salix spp.) can take up and metabolize lighter hydrocarbons, reducing their concentration in the soil (Pilon-Smits, 2005). However, high-molecular-weight PAHs (e.g., benzo[a]pyrene) are less bioavailable and more resistant to plant metabolism, limiting the scope of phytodegradation for complex oil contaminants. The key Factors includes: Effective for soluble, less recalcitrant hydrocarbons, Limited by plant tolerance to high contaminant concentrations, and Often works in tandem with rhizodegradation for comprehensive remediation.

2.3 Phytostabilization

Phytostabilization reduces the mobility and bioavailability of contaminants in the soil by immobilizing them in the root zone or soil matrix. Plants achieve this through root uptake, adsorption onto root surfaces, or precipitation of contaminants in the rhizosphere, preventing their migration to groundwater or adjacent areas (Salt et al., 1998).

2.3.1 Application to Oil-Contaminated Soils

While primarily used for heavy metals, phytostabilization is relevant for oil-contaminated soils containing metal co-contaminants (e.g., nickel, lead) often found in crude oil. Plants like Brassica spp. or vetiver grass can stabilize metals in the soil, reducing their environmental risk while simultaneously supporting rhizodegradation of organic pollutants (Agnello et al., 2016). This mechanism does not remove contaminants but minimizes their spread, making it suitable for sites where complete removal is not feasible. The key Factors includes: Prevents leaching of heavy metals into groundwater, Enhances soil stability through root systems, and Less effective for organic pollutants unless combined with other mechanisms.

2.4 Phytoextraction

Phytoextraction involves the uptake and accumulation of contaminants, typically heavy metals, into harvestable plant tissues (e.g., shoots). The contaminated biomass is then removed from the site, effectively reducing soil contaminant levels (Raskin et al., 1997).

2.4.1 Application to Oil-Contaminated Soils

Phytoextraction is less common for oil-contaminated soils, as it primarily targets inorganic pollutants like heavy metals. However, crude oil often contains trace metals (e.g., cadmium, chromium), and plants like sunflowers (Helianthus annuus) or Indian mustard (Brassica juncea) can extract these metals while supporting rhizodegradation of hydrocarbons (Raskin et al., 1997). The harvested biomass must be disposed of carefully to prevent secondary contamination.

The key Factors includes: Limited to metal contaminants in oil-polluted soils, Requires proper disposal of contaminated plant material, and Can be integrated with rhizodegradation for holistic remediation.

2.5 Phytovolatilization

Phytovolatilization involves the uptake of volatile contaminants or their metabolites by plants, followed by their release into the atmosphere through transpiration. This mechanism is less common for oil contaminants but applicable to volatile fractions like benzene or toluene (Pilon-Smits, 2005).

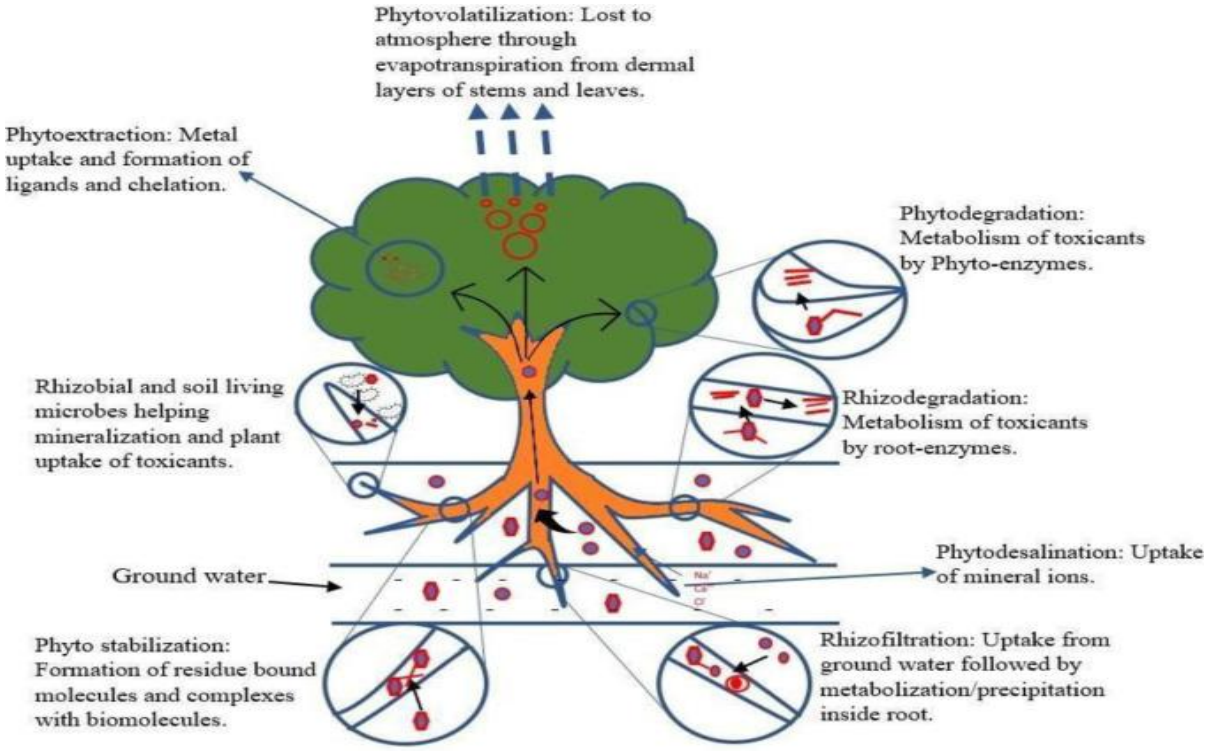
2.5.1 Application to Oil-Contaminated Soils

Phytovolatilization is of limited relevance for oil-contaminated soils, as most petroleum hydrocarbons (e.g., PAHs) are semi-volatile or non-volatile. However, for lighter fractions like VOCs in refined oil spills, plants like poplars can volatilize these compounds, reducing soil concentrations (Pilon-Smits, 2005). This mechanism raises concerns about air pollution, as released contaminants may require further management. The key Factors includes: Suitable for volatile hydrocarbons like benzene, Limited applicability for heavy oil fractions and Requires monitoring to prevent atmospheric pollution.

Table 3: Mechanisms of Phytoremediation for Oil-Contaminated Soils

Mechanism	Description	Target Contaminants	Example Plants	Relevance to Oil Contamination
Rhizodegradation	Microbial degradation of contaminants in the rhizosphere, enhanced by root exudates	PAHs, TPH, aliphatic hydrocarbons	Festuca arundinacea, Medicago sativa, Vetiveria zizanioides	Primary mechanism; degrades organic pollutants effectively
Phytodegradation	Plant uptake and metabolism of contaminants within tissues	Low-molecular-weight PAHs, VOCs	Populus spp., Salix spp.	Secondary; effective for lighter, soluble hydrocarbons
Phytostabilization	Immobilization of contaminants in soil or root zone	Heavy metals, some PAHs	Brassica spp., Vetiveria zizanioides	Stabilizes metals in oil-contaminated soils
Phytoextraction	Uptake and accumulation of contaminants in harvestable plant tissues	Heavy metals	Helianthus annuus, Brassica juncea	Limited; targets metals co-present with hydrocarbons
Phytovolatilization	Uptake and release of volatile contaminants via transpiration	VOCs (e.g., benzene, toluene)	Populus spp.	Minor; applicable to volatile oil fractions

The table 3 shows the summarized mechanisms, their target contaminants, example plants, and relevance to oil-contaminated soils, providing a concise reference for researchers and practitioners.



(Arjun K et al., 2022)

Figure 1: Diagram of Phytoremediation Mechanisms in Oil-Contaminated Soils

Based on the processes of phytoremediation involved in the remediation of toxic contaminants from soil and water, the overall mechanisms of phytoremediation depicted in Fig. 1 are explained in detail.

3.0 Progress in Mechanisms for Oil-Contaminated Soils

Research has focused on optimizing plant-microbe interactions, with studies showing that bioaugmentation with hydrocarbon-degrading bacteria (e.g., Pseudomonas spp.) enhances rhizodegradation efficiency (Muratova et al., 2008). Plants like vetiver grass have been widely tested in field trials, reducing TPH by up to 40–60% within 12–24 months (Truong et al., 2010). Grasses and legumes with fibrous roots are preferred for their ability to support rhizodegradation. For example, Festuca arundinacea has shown significant PAH removal in field studies (Agnello et al., 2016). Transgenic plants expressing microbial genes (e.g., alkB for alkane degradation) have been developed to enhance phytodegradation and rhizodegradation (Pilon-Smits, 2005). The addition of organic amendments (e.g., compost, biochar) improves contaminant bioavailability and plant growth, boosting rhizodegradation and phytostabilization (Agnello et al., 2016).

3.1 Role of Phytoremediation in Restoring Oil-Contaminated Soils

Phytoremediation leverages the natural abilities of plants and their rhizosphere microorganisms to remediate oil-contaminated soils through several mechanisms:

Plants absorb contaminants, such as heavy metals associated with petroleum, into their tissues, which can then be harvested to remove pollutants from the soil (Yan et al., 2020). Plants and their associated microbes break down organic pollutants, such as total petroleum hydrocarbons (TPHs), into less harmful compounds through enzymatic processes (Ekperusi & Aigbodion, 2015). Microorganisms in the rhizosphere, stimulated by plant root exudates,

degrade hydrocarbons, enhancing microbial activity and pollutant breakdown (Hou et al., 2015). Plants immobilize contaminants, reducing their bioavailability and preventing migration through soil or water (Sharma et al., 2023). Volatile organic compounds are taken up by plants and released into the atmosphere, though this is less common for petroleum hydrocarbons (Lakshmi et al., 2017).

These mechanisms make phytoremediation a sustainable alternative to conventional methods like incineration, solvent extraction, or landfilling, which are costly and often cause secondary environmental damage. Phytoremediation is particularly advantageous in oil-rich regions where native plants, adapted to local conditions, can be used to restore contaminated sites while enhancing biodiversity and aesthetic value (Panchenko et al., 2017).

3.2 Recent Studies on Phytoremediation of Oil-Contaminated Soils

Recent research has demonstrated significant progress in phytoremediation, focusing on plant selection, microbial interactions, and enhancement strategies. Below is a summary of key studies:

3.2.1 Plant Selection and Performance

A study in Iran, 2024 field-scale study investigated the phytoremediation potential of Alhagi camelorum for TPHs and heavy metals (Pb, Cr, Ni, Cd) in oil-contaminated soils from the Gachsaran oil field. Over six months, A. camelorum significantly reduced TPHs and heavy metals, with kinetic modeling showing effective pollutant removal rates. The study highlighted the plant's tolerance to drought, salinity, and contamination, making it suitable for oil-rich regions (Scientific Reports, 2024).

A study in China's Shengli Oil Field tested 14 ornamental plants, including Gaillardia aristata, Echinacea purpurea, and Medicago sativa, for TPH degradation. After 30 days, removal rates ranged from 37.16% to 49.42%, significantly higher than the control (12.93%). The study emphasized the dual role of ornamental plants in remediation and aesthetic enhancement (Hou et al., 2015).

A 2022 study demonstrated that Ipomoea batatas (sweet potato) and Melampodium palusodum (show star grass) reduced TPH content in motor oil-contaminated laterite soil by 60.14% after 16 weeks, with projections suggesting complete remediation in 27 weeks (Ekperusi & Aigbodion, 2015).

3.3 Natural vs. Technical Phytoremediation

A five-year study in Russia's Middle Volga region compared natural and technical phytoremediation. Technical phytoremediation, using Medicago sativa and Lolium perenne with nitrogen fertilization and soil tilling, achieved 72–90% TPH reduction per year, compared to natural phytoremediation, which reached similar levels only after five years. The study highlighted the role of nitrogen in stimulating microbial activity and accelerating revegetation (Panchenko et al., 2017).

3.4 Microbial Interactions

A study in northwest China examined bacterial community dynamics in petroleum-contaminated soils treated with Agropyron cristatum and Cynodon dactylon. High-throughput sequencing revealed that dominant bacterial groups (Proteobacteria, Actinobacteria, Acidobacteria) increased with petroleum concentration, enhancing degradation. Nitrogen fertilization further boosted microbial diversity and activity, improving remediation efficiency (Hou et al., 2015).

Research in Venezuela screened 60 plant species, finding that warm-season grasses and legumes significantly increased microbial degrader populations in the rhizosphere, reducing TPH levels by up to 58% in six months when combined with nutrient amendments (Sayre, 2016).

3.5 Enhancement Strategies

A 2024 study used vermiculite and agrobasalt to enhance phytoremediation with Zea mays in diesel- and gasoline-contaminated soils. These sorbents improved soil physicochemical properties and enzyme activity, supporting plant growth and reducing TPH levels (Wyszkowska et al., 2024).

Advances in biotechnology have explored transgenic plants with enhanced pollutant-degrading enzymes. For instance, genetically modified plants with increased glutathione S-transferases (GSTs) expression showed improved heavy metal detoxification in oil-contaminated soils (Sharma et al., 2023).

Table 4: Summary of Recent Phytoremediation Studies

Study Location	Plant Species	Contaminant	Duration	TPH Removal Rate	Key Findings	Reference
Gachsaran, Iran	Alhagi camelorum	TPHs, Heavy Metals	6 months	Significant reduction	Drought-tolerant, effective for heavy metals	
Shengli Oil Field, China	Gaillardia aristata, Echinacea purpurea, Medicago sativa	TPHs	30 days	37.16–49.42%	Ornamental plants enhance aesthetics	
Nigeria	Ipomoea batatas, Melampodium palusodum	Motor Oil	16 weeks	60.14%	Projected full remediation in 27 weeks	
Middle Volga, Russia	Medicago sativa, Lolium perenne	TPHs	5 years	72–90% (technical)	Nitrogen fertilization boosts efficiency	
Northwest China	Agropyron cristatum, Cynodon dactylon	TPHs	Variable	Up to 58%	Microbial diversity enhances degradation	

4.0 Limitations of Phytoremediation

Despite its advantages, phytoremediation faces several limitations that impact its efficacy and scalability for restoring oil-contaminated soils. These challenges are summarized in Table 1 and discussed in detail below.

Table 5: Summary of Limitations of Phytoremediation in Oil-Contaminated Soils

Limitation	Description	Impact	Source
Slow Processing Time	Requires multiple growing seasons or years to achieve significant contaminant removal.	Delays site restoration, limiting economic use of land.	Ruley et al., 2022; McGrath & Zhao, 2003
Dependence on Climatic Conditions	Effectiveness varies with temperature, precipitation, and soil conditions.	Reduced applicability in harsh climates (e.g., semi-arid or cold regions).	Ruley et al., 2022; McCutcheon & Schnoor, 2003
Plant Tolerance to Contaminants	High TPH or HM concentrations can be toxic to plants, limiting growth and remediation efficiency.	Restricts use of certain plant species in heavily contaminated sites.	Abdollahzadeh et al., 2024; Wei et al., 2014
Limited Contaminant Bioavailability	Low solubility of HMs and hydrophobic TPHs reduces uptake by plants.	Decreases remediation efficiency, requiring amendments like chelators.	Arshad et al., 2008; Abdollahzadeh et al., 2024
Biomass Disposal Challenges	Contaminated plant biomass requires safe disposal or processing, which can be costly.	Increases operational costs and environmental risks if not managed properly.	McGrath & Zhao, 2003; Lone et al., 2008
Limited Field-Scale Data	Most studies are lab-based, with few large-scale field trials.	Uncertainty about real-world performance and scalability.	Ruley et al., 2022; Frick et al., 1999
Site-Specific Variability	Soil type, pollutant concentration, and land use goals affect outcomes.	Requires tailored approaches, increasing complexity and cost.	Ruley et al., 2022; Abdollahzadeh et al., 2024

4.1 Slow Processing Time

Phytoremediation is inherently slow, often requiring several years or decades to achieve significant cleanup (McGrath & Zhao, 2003). For example, Ruley et al. (2022) note that while technical phytoremediation can achieve 72–90% decontamination per year, natural phytoremediation may take five years to match these results. This slow pace limits the economic viability of contaminated sites, as they remain unavailable for sale or rent during remediation (McGrath & Zhao, 2003). A figure illustrating the time-dependent reduction in

TPH concentrations for technical versus natural phytoremediation could highlight this disparity.

4.2 Dependence on Climatic and Environmental Conditions

The efficacy of phytoremediation is highly dependent on environmental factors such as temperature, precipitation, and soil properties (Ruley et al., 2022). In harsh climates, such as semi-arid regions or areas with short growing seasons, plant growth and microbial activity are restricted, reducing remediation efficiency (McCutcheon & Schnoor, 2003). For instance, studies in western Canada highlight challenges in applying phytoremediation in cold, semi-arid environments due to limited plant growth periods (McCutcheon & Schnoor, 2003). A map figure showing global regions with climatic constraints for phytoremediation could visually contextualize this limitation.

4.3 Plant Tolerance to Contaminants

High concentrations of TPHs and HMs can be toxic to plants, inhibiting growth and reducing remediation potential (Abdollahzadeh et al., 2024). While hyperaccumulator plants like Brassica juncea or Pteris vittata tolerate certain HMs, few plants are resilient to the complex mixture of hydrocarbons and metals in oil-contaminated soils (Wei et al., 2014). This necessitates careful plant selection, often requiring species like A. camelorum that are adapted to local stressors such as salinity and drought (Abdollahzadeh et al., 2024).

4.4 Limited Contaminant Bioavailability

The low solubility of HMs and hydrophobic TPHs in soil limits their bioavailability for plant uptake or microbial degradation (Arshad et al., 2008). For example, heavy metals like Pb and Cr often bind to soil particles, reducing their accessibility to plant roots (Abdollahzadeh et al., 2024). Amendments like chelators (e.g., EDTA) or biosurfactants can enhance bioavailability, but these increase costs and may introduce secondary environmental risks (Arshad et al., 2008). A schematic figure of the rhizosphere showing contaminant bioavailability barriers could clarify this issue.

4.5 Biomass Disposal Challenges

Plants used in phytoremediation accumulate contaminants in their tissues, creating contaminated biomass that requires careful disposal (McGrath & Zhao, 2003). Burning or ashing is unsuitable for volatile metals like mercury, and improper disposal can reintroduce contaminants into the environment (Lone et al., 2008). Developing cost-effective and safe disposal methods, such as bioenergy production from non-volatile contaminants, remains a significant challenge (McGrath & Zhao, 2003). A flowchart figure depicting biomass disposal options could illustrate potential solutions and challenges.

4.6 Limited Field-Scale Data

Most phytoremediation studies are conducted in controlled laboratory settings, with few large-scale field trials (Ruley et al., 2022). This gap limits understanding of real-world performance, as field conditions introduce variables like soil heterogeneity and fluctuating weather (Frick et al., 1999). For example, Ruley et al. (2022) found that field trials in Russia's Middle Volga region showed significant variability in decontamination rates (72–90%) depending on site-specific factors, underscoring the need for more field data.

4.7 Site-Specific Variability

The effectiveness of phytoremediation varies with soil type, pollutant concentration, and land use goals (Ruley et al., 2022). For instance, clay soils may retain contaminants more strongly than sandy soils, reducing remediation efficiency (Abdollahzadeh et al., 2024). Additionally, the economic purpose of the land (e.g., agricultural vs. industrial) influences the choice of phytoremediation strategy, complicating standardization (Ruley et al., 2022). A figure comparing remediation outcomes across different soil types could highlight this variability.

4.8 Strategies to Overcome Limitations

To address these limitations, recent research suggests several strategies: Transgenic plants with enhanced metal uptake or hydrocarbon degradation capabilities can improve efficiency (Lone et al., 2008); Inoculating soils with plant growth-promoting bacteria (e.g., Pseudoarthrobacter phenanthrenivoran) enhances rhizodegradation and plant tolerance (Saeed et al., 2021); Adding biochar or chelators can increase contaminant bioavailability and improve soil conditions (Abdollahzadeh et al., 2024); Using aesthetically pleasing plants like Gaillardia aristata can enhance public acceptance and provide dual benefits in urban settings (Wei et al., 2014); and Combining phytoremediation with other methods (e.g., bioremediation or nanoremediation) can accelerate cleanup and address complex contaminant mixtures (Saeed et al., 2021).

5.0 Conclusion

Phytoremediation is a promising, sustainable approach for restoring oil-contaminated soils, with significant advances in plant selection, microbial interactions, and technological enhancements. Studies demonstrate its efficacy, with technical phytoremediation achieving up to 90% TPH removal annually (Muratova et al., 2022). However, its limitations—slow processing, climatic dependence, plant toxicity, bioavailability constraints, biomass disposal challenges, limited field data, and site-specific variability—restrict its scalability and universal application. Future research should focus on field-scale trials, genetic and microbial enhancements, and safe biomass disposal methods to overcome these challenges and realize phytoremediation’s full potential.

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