A Review of Phytoremediation of Hydrocarbon-Contaminated Soil Using Legumes and Cereal Crops

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Abstract
Hydrocarbon contamination of soil is a significant environmental challenge that results from industrial activities, oil spills, and improper waste disposal. Phytoremediation, the use of plants to remediate polluted environments, has emerged as an eco-friendly and cost-effective solution. Legumes and cereal crops play an essential role in phytoremediation due to their unique biological and physiological characteristics. This paper reviews the mechanisms by which legumes and cereals facilitate hydrocarbon degradation, their synergistic effects, and factors influencing remediation efficiency. Additionally, it discusses case studies and challenges associated with phytoremediation in hydrocarbon-contaminated soils.

Keywords: *phytoremediation, hydrocarbon contamination, legumes, cereal crops, bioremediation, soil restoration*

Introduction

Hydrocarbon contamination of soil is a major environmental issue that results from petroleum spills, industrial activities, and improper disposal of organic pollutants (Ugochukwu & Ertel, 2018). Traditional methods such as soil excavation and chemical remediation are expensive and often disrupt soil ecosystems (Dixit *et al*., 2015). Phytoremediation, a plant-based remediation approach, has gained attention for its cost-effectiveness and environmental sustainability (Chirakkara *et al.*, 2016). Among the various plant groups used for phytoremediation, legumes and cereal crops have demonstrated promising potential in improving soil health and enhancing microbial degradation of hydrocarbons (Sun *et al.*, 2019).

Phytoremediation relies on several mechanisms to remove, degrade, or stabilize hydrocarbons in contaminated soil. These mechanisms involve plant-microbe interactions, contaminant uptake, transformation, and stabilization, each contributing to the detoxification of polluted environments. Rhizodegradation, also known as phytostimulation, occurs when plant roots release organic compounds (exudates) that stimulate microbial communities capable of degrading hydrocarbons. Root exudates, including sugars, amino acids, and secondary metabolites, enhance the activity of hydrocarbon-degrading bacteria and fungi in the rhizosphere (Gaskin *et al*., 2019). Certain plants, such as maize (*Zea mays*) and alfalfa (*Medicago sativa*), have been shown to promote microbial populations that break down petroleum hydrocarbons more effectively (Yousaf *et al.*, 2017). Studies have found that rhizosphere microbes, such as *Pseudomonas*, *Mycobacterium*, and *Rhizobium* species, play a crucial role in hydrocarbon degradation (Wu *et al*., 2021). Phytoextraction involves the uptake of hydrocarbons or their degradation products by plant roots, followed by translocation to aerial parts, where they are stored or transformed (Alkorta *et al.*, 2018). Certain plants, particularly hyperaccumulators such as *Brassica juncea* (Indian mustard) and *Helianthus annuus* (sunflower), have shown the ability to take up and sequester petroleum hydrocarbons (Peng *et al.*, 2017). However, the efficiency of phytoextraction varies depending on hydrocarbon type, plant species, and soil conditions. More research is needed to enhance plant uptake of high-molecular-weight hydrocarbons (Afzal *et al.*, 2017).

Phytostabilization prevents the spread of hydrocarbons by binding contaminants to root structures and organic matter in the soil. This mechanism is particularly effective in preventing hydrocarbon leaching into groundwater and reducing contaminant mobility in soils (Ramsay *et al.*, 2020). Certain grasses, such as *Panicum virgatum* erosion-prone (switchgrass) and *Hordeum vulgare* (barley), contribute to soil stabilization by forming dense root networks that trap pollutants (Rezek *et al.*, 2020). Additionally, plants promote soil aggregation and organic matter formation, further limiting contaminant spread (García-Sánchez *et al.*, 2018). Phytovolatilization involves the uptake of volatile hydrocarbons, their transformation within the plant, and subsequent release into the atmosphere as less toxic compounds (Doty *et al.*, 2017). Certain trees, such as *Populus* species (poplars), have been found to volatilize hydrocarbons such as benzene, toluene, ethylbenzene, and xylene (BTEX) (Kaunda *et al.*, 2020). However, the environmental impact of releasing transformed hydrocarbons into the atmosphere requires further study, as some by-products may still pose ecological risks (Huang *et al.*, 2020).

Phytodegradation refers to the breakdown of hydrocarbons within plant tissues through enzymatic activity. Plants produce enzymes such as peroxidases, dehydrogenases, and oxygenases that can transform hydrocarbons into less toxic compounds (Alkorta *et al.*, 2018). For example, soybean (*Glycine max*) has been shown to produce peroxidases capable of degrading petroleum hydrocarbons (Wu *et al.*, 2021). Additionally, genetic engineering has been explored to enhance phytodegradation efficiency, with studies demonstrating that transgenic plants expressing bacterial hydrocarbon-degrading enzymes can improve remediation rates (Doty *et al.*, 2017).

Role of Leguminous Plants in Phytoremediation

Leguminous plants play a crucial role in the phytoremediation of hydrocarbon-contaminated soils due to their nitrogen-fixing ability, deep root systems, and ability to enhance microbial activity in the rhizosphere. Commonly used legumes in remediation efforts include alfalfa (*Medicago sativa*), cowpea (*Vigna unguiculata*), and soybean (*Glycine max*), which have demonstrated significant potential in improving soil conditions and facilitating hydrocarbon degradation (Zhang *et al.*, 2016).

Leguminous plants establish symbiotic relationships with nitrogen-fixing bacteria, such as *Rhizobium* and *Bradyrhizobium* species, which improve soil fertility by converting atmospheric nitrogen into bioavailable forms (Yousaf *et al.*, 2017). This nitrogen enrichment promotes plant growth and enhances microbial communities responsible for hydrocarbon degradation (Ojewumi *et al.*, 2018). The improved soil conditions support a diverse population of hydrocarbon-degrading bacteria, such as *Pseudomonas*, *Bacillus*, and *Mycobacterium* species, which accelerate the breakdown of petroleum hydrocarbons (Wu *et al.*, 2021).

Legume root exudates contain organic compounds, including sugars, amino acids, flavonoids, and phenolic acids, which stimulate microbial activity and hydrocarbon degradation (Ite *et al.*, 2019). Studies have shown that alfalfa (*Medicago sativa*) secretes specific flavonoids that attract hydrocarbon-degrading bacteria, enhancing the degradation of polycyclic aromatic hydrocarbons (PAHs) (Huang *et al.*, 2020). Similarly, cowpea (*Vigna unguiculata*) has been found to release organic acids that support microbial diversity, leading to increased breakdown of petroleum hydrocarbons (Ojewumi *et al.*, 2018).

Legumes possess deep and extensive root systems that improve soil aeration, facilitate water infiltration, and provide a large surface area for microbial colonization (Chen *et al.*, 2020). These root networks enable legumes to access contaminants in deeper soil layers, promoting the biodegradation of hydrocarbons beyond the topsoil (Rezek *et al.*, 2020). Additionally, root structures help stabilize hydrocarbons, reducing their mobility and limiting environmental spread through leaching or erosion (Peng *et al.*, 2017).

Legumes can also play a role in phytostabilization by reducing the bioavailability of hydrocarbons. Their roots bind contaminants to soil organic matter, preventing the spread of pollutants into surrounding ecosystems (Ramsay *et al.*, 2020). In a study by García-Sánchez *et al.* (2018), the intercropping of legumes with grasses significantly reduced the mobility of petroleum hydrocarbons while improving microbial enzymatic activity.

Several field studies have demonstrated the effectiveness of legumes in remediating hydrocarbon-contaminated soils. For example, Huang *et al.* (2020) found that alfalfa significantly enhanced PAH degradation, with microbial enzymatic activity increasing by 40% in contaminated soil. Similarly, Wu *et al.* (2021) reported that soybean (*Glycine max*) improved soil microbial biomass and hydrocarbon degradation rates when grown in diesel-contaminated soil. These findings highlight the potential of legumes as both phytoremediators and soil fertility enhancers in polluted environments.

Role of Cereal Crops in Phytoremediation

Cereal crops, including maize (Zea mays), wheat (Triticum aestivum), and barley (Hordeum vulgare), contribute to phytoremediation through their widespread root systems and high biomass production (Muratova *et al.*, 2015). These crops improve soil aeration, stimulate microbial degradation, and stabilize hydrocarbons in contaminated sites (Ite *et al.*, 2019). Their ability to tolerate moderate levels of hydrocarbon contamination makes them suitable candidates for phytoremediation efforts in polluted soils. For example, maize has shown to promote microbial communities that degrade hydrocarbons effectively (Bento *et al.*, 2018). Maize roots excrete organic compounds that support hydrocarbon-degrading bacteria, thus enhancing bioremediation efficiency. Additionally, maize's deep root system allows it to reach deeper contamination zones, promoting greater hydrocarbon breakdown.

Similarly, wheat and barley enhance hydrocarbon degradation by increasing microbial enzymatic activity in the rhizosphere (Chen *et al.*, 2020). Wheat root exudates contain phenolic compounds that stimulate microbial activity, thereby accelerating the breakdown of hydrocarbons. Barley has demonstrated resilience in harsh contaminated environments, making it effective in stabilizing hydrocarbons and preventing their migration through leaching or erosion. Additionally, wheat and barley contribute to the formation of stable soil aggregates, reducing soil erosion and limiting the spread of contaminants (Rezek *et al.*, 2020).

Field studies have shown that the introduction of cereal crops to hydrocarbon-contaminated soil significantly enhances microbial populations associated with hydrocarbon degradation. For instance, research conducted by García-Sánchez *et al.* (2018) revealed that intercropping wheat with nitrogen-fixing plants resulted in increased microbial enzymatic activity, which accelerated the degradation of total petroleum hydrocarbons (TPHs). Furthermore, cereal crops are capable of phytostabilizing hydrocarbon pollutants by binding contaminants to root structures and organic matter in the soil, reducing their bioavailability to surrounding ecosystems (Peng *et al.*, 2017). In summary, cereal crops play an essential role in phytoremediation by improving soil conditions, stimulating microbial hydrocarbon degradation, and stabilizing contaminants. The use of cereal crops, either as monocultures or in combination with legumes, enhances bioremediation efficiency or promotes long-term soil recovery.

Synergistic Effects of Legumes and Cereal Crops

Intercropping legumes and cereal crops can significantly enhance phytoremediation efficiency. Legumes improve soil fertility through nitrogen fixation, which benefits cereal crops and hydrocarbon-degrading bacteria (García-Sánchez *et al.*, 2018). This synergistic relationship increases biomass production, microbial activity, and hydrocarbon degradation rates (Rezek *et al.*, 2020). A study by Wang *et al.* (2019) demonstrated that intercropping cowpea and maize in hydrocarbon-contaminated soil resulted in a 40% increase in hydrocarbon degradation compared to monocropping systems.

Factors Affecting Phytoremediation Efficiency

Several factors influence the effectiveness of legumes and cereals in phytoremediation. Soil properties such as pH, organic matter, and moisture levels impact microbial degradation (Peng *et al.*, 2017). Different plant species differ in their tolerance to hydrocarbon toxicity (Kaunda *et al.*, 2020), and thus the choice of the most tolerant species is substantially important. The presence of different bacterial taxa and facultative organisms with capacity to degrade hydrocarbons or at least their intermediary by-products is useful. According to Afzal *et al.* (2017), the presence of hydrocarbon-degrading bacteria enhances bioremediation. Availability of environmental conditions such as temperature and oxygen influence plant growth and microbial activity (Bento *et al.*, 2018).

Challenges and Limitations of Phytoremediation in Hydrocarbon-Contaminated Soils

Several studies have demonstrated the effectiveness of legumes and cereals in remediating hydrocarbon-contaminated soils. For example, maize and alfalfa intercropping was found to have improved total petroleum hydrocarbon (TPH) degradation by 45% within 90 days (Gaskin *et al.*, 2019). Also, Sun *et al.* (2019) reported that wheat and soybean cultivation in an oil-polluted site increased microbial enzyme activity and reduced hydrocarbon concentrations by 60%. Cowpea and barley rotation enhanced soil microbial diversity and hydrocarbon breakdown in a crude oil-contaminated area (Ojewumi *et al.*, 2018).

Despite its potential, phytoremediation faces several challenges that limit its widespread application in hydrocarbon-contaminated soils. One factor is the remediation rates, where hydrocarbon degradation in soil through plant-assisted remediation is a slow process, often taking months to years to achieve substantial reductions in contaminant levels (Ite *et al.*, 2019).

Factors such as hydrocarbon type, plant species, and microbial activity affects the overall remediation rate (Rezek *et al.*, 2020). High hydrocarbon concentrations can be toxic to plants, leading to reduced germination, stunted growth, and physiological stress (Zhang *et al.*, 2016). Some hydrocarbons interfere with water and nutrient uptake, causing oxidative stress and damage to cellular structures (Peng *et al.*, 2017). Another factor is site-specific variability, where the success of phytoremediation depends on site conditions, including soil composition, nutrient availability, and contamination levels (Huang *et al.*, 2020). Factors such as pH, organic matter content, and microbial diversity can influence hydrocarbon degradation efficiency García-Sánchez *et al.*, 2018). Plants and their associated microbes are effective at degrading simple hydrocarbons like alkanes, complex hydrocarbons such as polycyclic aromatic hydrocarbons and heavy petroleum fractions are more resistant to biodegradation (Alkorta *et al.*, 2018). Thus, degradation of such fractions may require additional improvements in technology like the use of genetically engineered species. Climate conditions, including temperature, moisture, and oxygen levels, affect plant growth and microbial activity, thus constituting environmental constraints influencing overall remediation effectiveness (Bento *et al.*, 2018).

Prospects

Genetic engineering of plants

Advances in biotechnology offer opportunities to enhance phytoremediation efficiency. Genetic modifications can improve hydrocarbon uptake, tolerance to toxic compounds, and root exudate production to stimulate microbial degradation (Doty *et al.*, 2017). For instance, transgenic plants expressing hydrocarbon-degrading enzymes have shown promise in laboratory studies (Afzal *et al*., 2017).

Enhancing plant-microbe interactions

Research on plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi can improve phytoremediation efficiency by boosting plant health and microbial hydrocarbon degradation (Yousaf *et al.*, 2017). Engineering rhizosphere microbiomes with hydrocarbon-degrading bacteria can further enhance remediation (Wu *et al.*, 2021).

Field-scale applications

While many studies have demonstrated the potential of phytoremediation under controlled conditions, large-scale field trials are necessary to assess its feasibility in real-world contaminated sites (García-Sánchez *et al.*, 2018). Developing best management practices and integrating phytoremediation with other remediation strategies (e.g., biostimulation and soil amendments) can improve success rates (Ramsay *et al.*, 2020).

Use of biochar and soil amendments

Organic amendments such as biochar, compost, and fertilizers can enhance soil structure, improve microbial activity, and mitigate the toxic effects of hydrocarbons on plants, increasing remediation efficiency (Peng *et al.*, 2017).

Phytoremediation in extreme environments

Future research should explore the potential of salt-tolerant and drought-resistant plants for hydrocarbon remediation in arid and saline-affected soils, where contamination is prevalent due to oil exploration and spills (Kaunda *et al.*, 2020).

With continued advancements in plant biotechnology, microbial engineering, and agronomic practices, phytoremediation has the potential to become a more efficient and scalable approach for remediating hydrocarbon-contaminated environments.

Conclusion

Phytoremediation using legumes and cereal crops is a sustainable and cost-effective method for restoring hydrocarbon-contaminated soils. The ability of legumes to fix nitrogen and enhance microbial degradation, combined with the extensive root systems of cereal crops, makes them ideal candidates for remediation. Intercropping and improving plant-microbe interactions can further enhance phytoremediation efficiency. Future research should focus on overcoming challenges and optimizing field applications to maximize hydrocarbon degradation.

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