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## THE ROLE OF PLANTS AND MICROORGANISMS IN BIOREMEDIATION OF PETROLEUM HYDROCARBON CONTAMINATED SOILS

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**Abstract.** Soil pollution by petroleum hydrocarbons is a major global environmental issue. Traditional cleanup methods are costly and often do not work well. This review summarizes what is currently known about how plants and microorganisms help clean up petroleum-contaminated soils. The review looks at how microbes break down hydrocarbons, how plants and microbes interact in the root zone, and the use of biostimulation, bioaugmentation, phytoremediation, and rhizoremediation. Biodegradation depends on environmental factors (pH 5.5-8.8, temperature 15-45°C, C:N:P ratio = 120:10:1) and the activity of certain microbes such as *Pseudomonas*, *Rhodococcus*, *Mycobacterium*, and *Arthrobacter*. Hydrocarbons become harder to break down in this order: n-alkanes, branched alkanes, monoaromatics, polyaromatics, and asphaltenes. Biostimulation with organic fertilizers can achieve 50-95% degradation, bioaugmentation with microbial consortia 63-84%, and phytoremediation with grasses up to 99%. Using both plants and microbes together is the most effective and affordable method. Success relies on creating good conditions for local microbes, choosing plants with strong root systems, and using specialized microbial consortia.

**Keywords:** bioremediation; petroleum hydrocarbons; microbial degradation; phytoremediation; rhizosphere; biostimulation; bioaugmentation.

### Introduction

Contamination of soil, sediments, and marine environments with petroleum hydrocarbons is one of the most serious global environmental problems associated with oil and gas exploration, production, and refining activities. Annually, millions of tons of oil and petroleum products enter the environment through accidental spills, process emissions, and operational losses, leading to ecosystem degradation, biodiversity loss, and negative socioeconomic consequences in oil-producing regions.

Petroleum is a complex heterogeneous mixture containing over 17,000 organic compounds, predominantly hydrocarbons of various classes: saturated (paraffins), aromatic (benzene, toluene, ethylbenzene, xylenes - BTEX), polycyclic aromatic hydrocarbons (PAHs), asphaltenes, and resins. Upon entering soil, petroleum hydrocarbons exert toxic effects on living organisms, disrupt soil physicochemical properties, reduce fertility, and are capable of bioaccumulation in food chains.

*Bioremediation as Alternative Approach.* Bioremediation - the use of biological agents (microorganisms, plants, or their combinations) to degrade, transform, or immobilize environmental contaminants - is recognized as an environmentally safe and cost-effective alternative to traditional methods. The main advantage of biological methods is the ability of microorganisms and plants to completely mineralize organic pollutants to carbon dioxide, water, and biomass without formation of toxic intermediate products.

The objective of this work is to systematize current knowledge on mechanisms and effectiveness of bioremediation of petroleum hydrocarbon contaminated soils, with emphasis on the role of microorganisms, plants, and their interactions.

Research tasks:

- Analyze mechanisms of microbial degradation of different petroleum hydrocarbon classes and factors determining biodegradation efficiency

- Characterize the role of plant-microorganism interactions in the rhizosphere in bioremediation processes
- Evaluate effectiveness of main bioremediation strategies: biostimulation, bioaugmentation, phytoremediation, and rhizoremediation
- Determine prospects and limitations of biological methods application for soil cleanup from petroleum contamination

**Materials and Methods.** For review preparation, systematic analysis of scientific literature on bioremediation of petroleum hydrocarbon contaminated soils was conducted. Publication search was performed in international databases Web of Science, Scopus, PubMed, Google Scholar for the period 1984 to 2019. Key search terms:

- "petroleum hydrocarbons" AND "biodegradation"
- "bioremediation" AND "contaminated soil"
- "phytoremediation" AND "oil pollution"
- "bioaugmentation" OR "biostimulation"

**Results.** Literature analysis showed that a wide spectrum of microorganisms found in contaminated soils possess the ability to degrade petroleum hydrocarbons (Table 1). Most frequently detected are representatives of genera *Pseudomonas* and *Rhodococcus*, characterized by broad substrate range and high adaptability to environmental conditions.

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Table 1. Main groups of petroleum hydrocarbon-degrading microorganisms

Gram-negative bacteria	Gram-positive bacteria	Yeasts	Fungi
<i>Pseudomonas</i> , <i>Acinetobacter</i> , <i>Alcaligenes</i> , <i>Flavobacterium</i>	<i>Nocardia</i> , <i>Mycobacterium</i> , <i>Rhodococcus</i> , <i>Arthrobacter</i> , <i>Bacillus</i>	<i>Candida</i> , <i>Rhodotorula</i> , <i>Trichosporon</i> , <i>Aureobasidium</i>	<i>Trichoderma</i> , <i>Penicillium</i> , <i>Aspergillus</i> , <i>Fusarium</i>

Different petroleum hydrocarbon classes vary substantially in rate and completeness of microbial degradation. The generalized order of decreasing biodegradation susceptibility: n-alkanes > branched alkanes > branched alkenes > low molecular weight n-alkylaromatics > monoaromatics > cyclic alkanes > polynuclear aromatics > asphaltenes.

Systematization of literature data enabled determination of optimal conditions for microbial degradation of petroleum hydrocarbons in soil (Table 2).

Table 2. Optimal conditions for petroleum hydrocarbon biodegradation

Factor	Optimal values
pH	5.5-8.8 (optimum 6.5-7.5)
Temperature	15-45°C (optimum 25-35°C)
Soil moisture	25-28% of water holding capacity
Oxygen	>0.2 mg/L dissolved O <sub>2</sub> , minimum 10% air

Factor	Optimal values
Nutrients	C:N:P = 120:10:1 (molar ratio)
Hydrocarbon concentration	5-10% of dry soil weight

*Biostimulation* - creating favorable conditions for indigenous degrading microorganisms by optimizing limiting factors - is the most widely applied bioremediation strategy. Mineral fertilizer (NPK) application achieved 50-75% TPH degradation, while organic fertilizers (poultry manure) showed 73-90% efficiency over 4-8 weeks.

*Bioaugmentation* - introduction of specialized degrading microorganisms into contaminated soil - is applied when indigenous degrader numbers or activity are insufficient. Mixed cultures ensure 72.7% degradation of heavy fractions (C<sub>23</sub>-C<sub>40</sub>) versus 45.7% under natural attenuation.

Plants release 5-21% of total photoassimilates through root systems as diverse organic compounds (sugars, amino acids, organic acids, phenolic compounds, flavonoids), which radically alter the microbiological and biochemical environment of the rhizosphere. In the presence of root exudates, hydrocarbon-degrading bacteria numbers in the rhizosphere are 10-1000 times higher than in unplanted soil.

Phytoremediation demonstrated high effectiveness in numerous studies. Most effective are perennial grasses with fibrous root systems (ryegrass, fescue, vetiver), ensuring 50-85% TPH degradation over 3-6 months. The main mechanism is stimulation of microbial degradation in the rhizosphere (~99% of total cleanup), not direct plant uptake.

Table 3. Comparative effectiveness of bioremediation strategies

Strategy	TPH degradation, %	Time, months	Cost, \$/m <sup>3</sup>
Natural attenuation	20-40	24-36	5-10
Biostimulation (NPK)	50-75	3-6	15-30
Biostimulation (organic)	60-90	2-8	20-40
Bioaugmentation	65-85	2-6	40-80
Phytoremediation	50-80	6-12	10-25
Rhizoremediation	70-92	3-6	30-50

**Conclusion.** Systematic literature analysis identified critical factors determining petroleum contamination bioremediation success: contaminant bioavailability, presence of adapted microbial communities (>10<sup>5</sup> CFU degraders per g soil), environmental condition optimization (pH, temperature, moisture, aeration), and nutrient supply at C:N:P ratio = 120:10:1.

Biostimulation is effective for fresh light fraction contamination, characterized by low cost (\$15-40/m<sup>3</sup>) and suitable for large areas. Bioaugmentation ensures rapid degradation onset of specific pollutants but has high cost (\$40-80/m<sup>3</sup>) and introduced strain survival problems. Phytoremediation is most economical (\$10-25/m<sup>3</sup>) but requires long time (6-12 months) and is effective only in root zone.

Biological methods are 5-30 times cheaper than traditional physicochemical methods with comparable efficiency. For a 10,000 m<sup>3</sup> site: excavation and disposal costs \$1.5-3 million, biostimulation \$150-400 thousand, phytoremediation \$100-250 thousand.

Bioremediation is an effective and economically feasible alternative to traditional physicochemical methods for petroleum contaminated soil cleanup, achieving 50-95% petroleum hydrocarbon degradation at 5-30 times lower cost.

Microbial degradation is the main mechanism for petroleum hydrocarbon removal from soil. Key degraders are bacteria of genera *Pseudomonas*, *Rhodococcus*, *Mycobacterium*, *Arthrobacter* and fungi of genera *Aspergillus*, *Penicillium*.

Biodegradation efficiency is determined by a complex of factors: contaminant structure and concentration, hydrocarbon bioavailability, environmental conditions (pH 5.5-8.8, temperature 15-45°C, moisture 50-70%), C:N:P ratio = 120:10:1, and presence of adapted microbial communities.

Hydrocarbon biodegradation susceptibility decreases: n-alkanes (85-95% in 2-4 weeks) > monoaromatics (60-80% in 6-12 weeks) > 2-3 ring PAHs (70-90% in 2-4 months) > 4-6 ring PAHs (30-60% in 6-12 months) > asphaltenes (5-20% in 12-24 months).

Biostimulation with organic fertilizers is more effective (73-90% TPH degradation in 4-8 weeks) than mineral fertilizers (50-75%). Poultry manure is optimal for high contamination levels, pig waste for low levels.

Bioaugmentation with microbial consortia outperforms monocultures, achieving 72.7% heavy fraction degradation versus 45.7% under natural attenuation through complementary metabolic pathways.

Plant-microorganism rhizosphere interactions play a key role. Root exudates stimulate degrader growth, whose numbers in the rhizosphere are 10-1000 times higher than in unplanted soil.

Phytoremediation achieves degradation predominantly through rhizosphere microorganism stimulation (~99% of total cleanup). Most effective are grasses with fibrous root systems (50-85% TPH degradation in 3-6 months). Rhizoremediation demonstrates synergistic effect (synergy index 1.2-1.8), achieving 70-92% degradation, which is 20-40% higher than sum of individual component effects.

Combined plant-microorganism systems represent the most promising direction, ensuring optimal balance of effectiveness, cost, and environmental safety for petroleum contaminated soil cleanup.

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## МҰНАЙ КӨМІРСУТЕКТЕРІМЕН ЛАСТАНҒАН ТОПЫРАҚТАРДЫ БИОРЕМЕДИАЦИЯЛАУДА ӨСІМДІКТЕР МЕН МИКРООРГАНИЗМДЕРДІҢ РӨЛІ

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**Аннотация.** Топырақтың мұнай көмірсутектерімен ластануы ауыр жаһандық экологиялық мәселе болып табылады. Дәстүрлі физика-химиялық тазарту әдістері қымбат және жиі тиімсіз. Бұл шолу мұнай көмірсутектерімен ластанған топырақтарды биоремедиациялауда өсімдіктер мен микроорганизмдердің рөлі туралы қазіргі білімді жүйелейді. Ғылыми басылымдарды талдау микробтық ыдырату механизмдерін, ризосферадағы өсімдіктер мен микроорганизмдердің өзара әрекеттесуін және биостимуляция, биоаугментация, фиторемедиация және ризоремедиацияны қолдануды зерттеді. Биоыдырау қоршаған орта факторларымен (рН 5,5-8,8, температура 15-45°C, С: N:P қатынасы = 120:10:1) және *Pseudomonas*, *Rhodococcus*, *Mycobacterium* және *Arthrobacter* сияқты мамандандырылған микроорганизмдердің метаболикалық белсенділігімен анықталады. Көмірсутектердің ыдырауға сезімталдығы төмендейді: н-алкандар> тармақталған алкандар> моноароматтар> полиароматтар> асфальтендер. Органикалық тыңайтқыштармен биостимуляция 50-95% ыдырауға қол жеткізеді, микробтық консорциумдармен биоаугментация 63-84%, шөптерді пайдаланған фиторемедиация 99% дейін. Өсімдіктер мен микроорганизмдердің біріктірілген жүйелері ең тиімді және экономикалық тұрғыдан орынды тәсіл болып табылады. Табыс жергілікті микробтық қауымдастықтар үшін жағдайларды оңтайландыруға, дамыған тамыр жүйесі бар өсімдіктерді таңдауға және мамандандырылған көмірсутектерді ыдыратушы консорциумдарды пайдалануға байланысты.

**Түйін сөздер:** биоремедиация; мұнай көмірсутектері; микробтық ыдырау; фиторемедиация; ризосфера; биостимуляция; биоаугментация.

## РОЛЬ РАСТЕНИЙ И МИКРООРГАНИЗМОВ В БИОРЕМЕДИАЦИИ ПОЧВ, ЗАГРЯЗНЕННЫХ НЕФТЯНЫМИ УГЛЕВОДОРОДАМИ

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**Аннотация.** Загрязнение почвы нефтяными углеводородами представляет серьезную глобальную экологическую проблему. Традиционные физико-химические методы очистки дороги и часто неэффективны. Данный обзор систематизирует современные знания о роли растений и микроорганизмов в биоремедиации почв, загрязненных нефтяными углеводородами. Анализ научных публикаций исследовал механизмы микробной деградации, взаимодействие растений и микроорганизмов в ризосфере, а также применение биостимуляции, биоаугментации, фиторемедиации и ризоремедиации. Биodeградация определяется факторами окружающей среды (рН 5,5-8,8, температура 15-45°C, соотношение С:N:P = 120:10:1) и метаболической активностью специализированных микроорганизмов, включая *Pseudomonas*, *Rhodococcus*, *Mycobacterium* и *Arthrobacter*. Восприимчивость углеводородов к деградации снижается: н-алканы> разветвленные алканы> моноароматические> полиароматические> асфальтены. Биостимуляция с органическими

удобрениями достигает 50-95% деградации, биоаугментация с микробными консорциумами 63-84%, фиторемедиация с использованием трав до 99%. Комбинированные системы растение-микроорганизм представляют наиболее эффективный и экономически целесообразный подход. Успех зависит от оптимизации условий для местных микробных сообществ, выбора растений с развитой корневой системой и использования специализированных консорциумов, деградирующих углеводороды.

**Ключевые слова:** биоремедиация; нефтяные углеводороды; микробная деградация; фиторемедиация; ризосфера; биостимуляция; биоаугментация.