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REVIEW ARTICLE

Advances in Biodegradation of petroleum hydrocarbons based pollutants by Microbes

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Abstract: Petroleum hydrocarbons are the organic contaminants that accumulate in different ecosystems due to their hydrophobic nature and limited bioavailability, which have raised concerns about their release into the environment. Due to their carcinogenic and neurotoxic nature a serious threat has been posed to human and environmental health. But the removal of these pollutants from the environment is a challenging task. Conventional treatment techniques like mechanical and chemical approaches are expensive and inefficient for eliminating hydrocarbons from contaminated areas. Bioremediation is a significant approach for the remediation of petroleum hydrocarbon-contaminated environments, using the natural biodegradation activity of microorganisms. Microorganisms that utilize petroleum hydrocarbons are prevalent in the environment. They naturally degrade pollutants and remove them from the environment. Biosurfactants lower surface tension, encourage emulsification, micelle formation, and make hydrocarbons bioavailable for microbial breakdown. So, utilising biosurfactant-producing bacteria can increase the effectiveness of bioremediation (Zhuang et al., 2022). This article provides an overview of bioremediation of petroleum hydrocarbon pollutants. Some crucial, but often overlooked factors which play a key role in the bioremediation are also elucidated. It also provides information about hydrocarbon metabolism in microorganisms with emphasis on new insights gained during the past couple of years.

The main aim of this review is to provide a thorough understanding of the distinctive features of hydrocarbon microbiology that could be helpful in organizing further biodegradation studies. It also serves as a springboard for a broader discussion about the shortcomings and potential enhance ments of the bioremediation techniques now in use.

Keywords: Bioremediation, petroleum hydrocarbons, oil-contaminated soil, hydrocarbon-degrading bacteria, biosurfactants, microbial degradation, environmental pollution

Introduction

Nowadays everyone is interested in examining the environmental pollution represented by the presence of oil-derived hydrocarbons because oil pollution is one of the major issues of today, particularly in light of the major disasters to which the soil is exposed and caused by oil spills or leaks. Oil pollution is one of the most significant causes of environmental pollution that is currently recognized due to its wide-ranging effects on all facets of life and its difficulty in controlling, particularly in the soil. Mainly the branched twenty carbon atoms or more was thought to be the primary cause of petroleum hydrocarbon contamination (Aziz et al., 2024). The discharge of potentially toxic petroleum hydrocarbons into the environment has been a matter of concern, as these organic pollutants accumulate in many ecosystems due to their hydrophobicity and low bioavailability. Petroleum hydrocarbons are neurotoxic and carcinogenic organic pollutants, extremely harmful to human and environmental health (Sah et al., 2022). The objectives regarding petroleum hydrocarbon contamination and bioremediation through biological means should prioritize the reduction of petroleum hydrocarbons at the source by conserving resources and optimizing oil utilisation and processing. Additionally, research should focus on enhancing the efficiency and augmenting the population of bacterial species involved in the bioremediation process through genetic engineering (Pant et al., 2020; Aziz et al., 2024). Petroleum hydrocarbon are vital raw energy sources for many industries, but they also contribute significantly to environmental degradation worldwide. Due to their extreme toxicity and resistance, petroleum hydrocarbon pollutants are hazardous and long-lasting in an environment. However, microbes that can use petroleum compounds and hydrocarbons for their growth, nourishment and metallic processes are abundant in oil-contaminated soil (Yegon et al., 2026).

PETROLEUM HYDROCARBONS:

Petroleum are the hydrocarbons with an average composition of 30% alkanes with 5 or more carbon atoms, 49% cycloalkanes, 15% aromatics, and 6% asphalt. A significant portion of atmospheric volatile organic compounds (VOCs) are light hydrocarbons found in petroleum, such as alkanes and aromatic hydrocarbons with ≤C15, which tend to volatilize into their high vapour due to pressure and low boiling point. VOCs significantly affect the ecosystem by producing dangerous oxidants such photochemical ozone (O3) (Fetisov et al., 2023). The majority of the hydrocarbons (aliphatic, cycloaliphatic, and aromatic) and non-hydrocarbons (resins and asphaltenes) that make up crude oil have poor water solubility. The processing of oil which is done to obtain the useful products leads to formation of many unsaturated hydrocarbons and non-hydrocarbons such as nitrogen, sulphur, oxygen or metal containing organic compounds (Liu et al., 2023).

Due to oil pollution an alteration in the physical and chemical characteristics of soil occurs to varying extents. Whenever the petroleum leach into the soil, its compounds react with inorganic nitrogen and phosphorus, thus inhibiting soil nitrification and dephosphorization and hence leads to a decrease in readily available nitrogen and phosphorus. Also, a rise in organic carbon content in soil occurs due to the organic matter present in petroleum, thus altering the carbon-to-nitrogen ratio of the soil, and influences soil fertility. Currently, the economic growth and ecological conditions of oil-producing regions worldwide are severely impacted by the oil-contamination of soil. So, addressing contaminated soil has emerged as a key concern in current environmental research and stands as one of the main environmental challenges. To address this issue, we need to fully understand how oil pollution affects soil (Li et al., 2022).

OIL- DEGRADING BACTERIA:

Certain bioremediation strategies have been developed to remove petroleum hydrocarbons from soil which enhances the microbial efficiency in degrading petro-pollutants through the availability of nutrients, moisture and air. In order to biologically degrade the hydrocarbons, a variety of microorganisms were examined and identified.

Rhodococcus jostii, *Ochrobactrum intermedium*, *Achromobacter spanius*, *Citrobacter amalonaticus*., *Lysinibacillus boronitolerans*, *Acinetobacter junii, Flavobacterium*, *Bacillus* sp., *Aeromonas* sp., *Micrococcus* sp., *Staphylococcus* sp., *Vibrio Xanthomonas*, and *Pseudomonas* sp. are the most significant bacterial species that have been obtained from oil-contaminated soil and demonstrated petroleum biodegradation activity in different reports (Rache-Arce et al ., 2022; Oudah, 2024; Medic et al ., 2020; Aziz et al., 2024 ; Chen et al ., 2025 ; Shokranian et al., 2025).

MECHANISM OF OIL DEGRADATION:

While petroleum hydrocarbons fill soil pores, they can decrease soil aeration and water permeability, which can have toxicological and ecological consequences on plants and destroy the oilfield's natural condition. Furthermore, because of their biological toxicity, carcinogenicity and mutagenicity crude oil chemicals have the potential to produce lethal genetic alterations even at low pollution levels. As a result, they have received attention, particularly due to their hydrophobicity and structural complexity. Although carbon and hydrogen make up the majority of crude oil, it also contains sulfur, nitrogen, oxygen, and a variety of metals (Shishkova et al., 2022). Saturated hydrocarbon, aromatic hydrocarbon, asphaltene and colloid are its four primary constituents (Yu, et al., 2020).

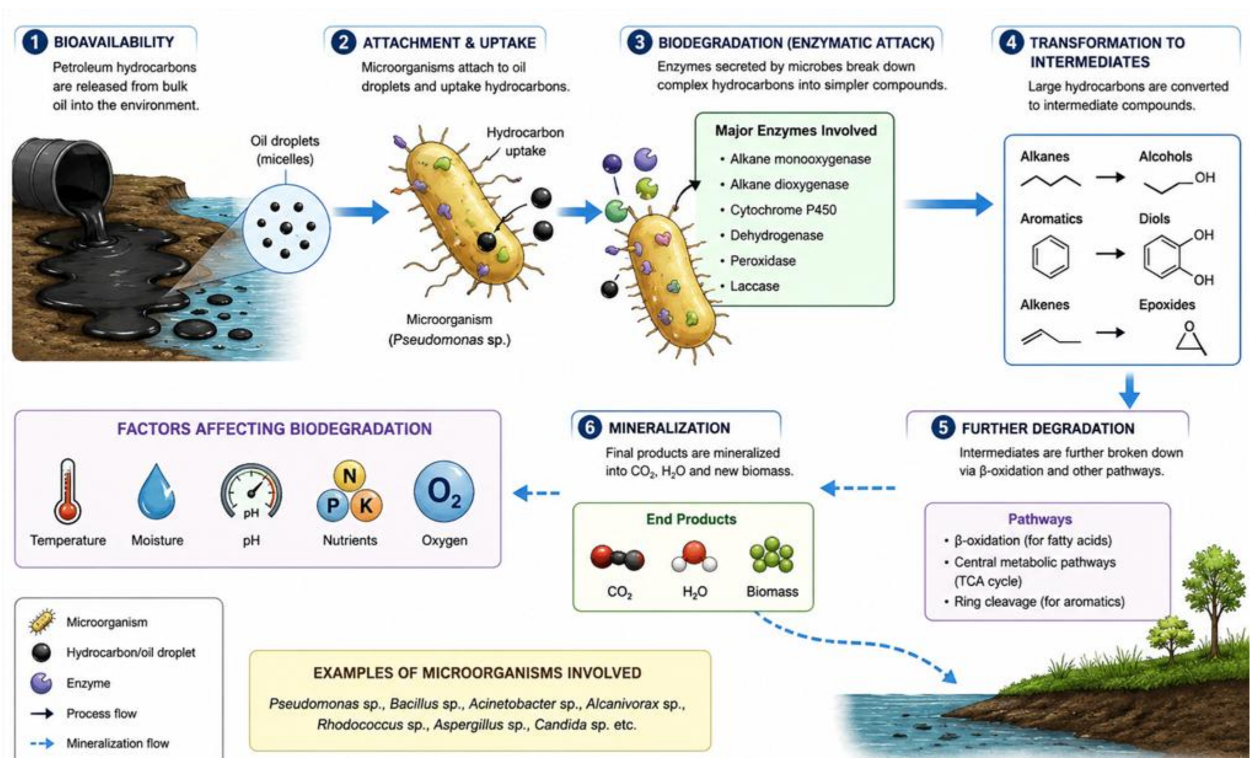

Figure 1. Mechanism of microbial biodegradation of petroleum hydrocarbons.

Microbial degradation is considered as one of the most effective, eco-friendly, and cost- effective approach for remediation of oil polluted environments. Different steps are involved in the degradation of oil.

Hydrocarbon bioavailability: Bioavailability is the part of a chemical in soil that is available for uptake or transformation by living organisms. The hydrocarbon availability is the key factor in the access and degradation of petroleum hydrocarbons by the oil-metabolizing microorganisms.

Petroleum hydrocarbons exhibit low bioavailability and are known as hydrophobic organic pollutants (Al Hawash et al ,. 2018). The bioavailability and biodegradation rates of hydrophobic pollutants are influenced by surfactants. Biosurfactants function as emulsifiers by lowering surface tension and creating micelles. The microdroplets, trapped within the hydrophobic microbial cell surface, are internalized and broken down (Das and Chandran 2011).

Microbial attachment and uptake: Following the physical interaction between bacterial cells and hydrocarbons, the subsequent phase involves the trans-membrane transport of these hydrocarbons. The movement of substrates across the cell membrane occurs through three primary mechanisms: (1) passive diffusion (2) passive facilitated diffusion (3) energy-dependent, active transport (Hua and Wang 2014).

Enzymatic oxidation and degradation: Organic pollutants get break down completely and rapidly under aerobic conditions. The main intracellular effect on the hydrocarbons involve activation, which is an oxidative process that incorporates oxygen and is catalyzed enzymatically by peroxidases and oxygenases (Adedeji et al., 2022). Enzymes like monooxygenases and dioxygenases add oxygen to hydrocarbon chains, causing them to break down into fatty acids, alcohols, and aldehydes (Laczi et al., 2020). The enzymes are frequently released outside the cell or linked to the cell membrane, helping to initiate the activation of otherwise inactive hydrocarbon molecules. Major classes of enzymes involved in microbial degradation of petroleum hydrocarbons are: Monooxygenases, Dioxygenases, Peroxidases, Cytochrome P450, Alkane hydroxylases etc (De Sousa et al., 2025).

Formation of intermediate metabolites: In most degradation pathways, the substrate n-alkane is transformed into its corresponding alcohol by substrate-specific terminal monooxygenases or hydroxylases. This alcohol is then oxidized to the corresponding aldehyde, which is subsequently converted into a fatty acid and then subjected to β-oxidation (Sierra and Oliveira 2013).

Complete mineralization into carbon dioxide, water, and biomass: Hydrocarbons in the soil can be converted by numerous biological pathways. Under optimal conditions, hydrocarbons are fully changed into carbon dioxide and water, accompanied by some biomass generation. In some cases, biodegradation does not fully occur. The microbial breakdown of hydrocarbons into partially oxidized compounds also helps in cleaning up of polluted soil by immobilizing and stabilizing hazardous compounds. The degraded hydrocarbons may undergo integration into soil organic content or humification. Microbial consortia are more effective in oil biodegradation than the single since different microorganisms break down distinct petroleum hydrocarbon fractions (Chikere et al., 2011).

Biodegradation efficiency is highly influenced by environmental factors such as temperature, moisture, pH, nutrient and oxygen availability. Recently the role of hydrocarbon-degrading genes and biosurfactants in improving the effectiveness of bioremediation has been highlighted (Elshafei & Mansour, 2024).

Table 1. Some bacterial species involved along with their mode of action for degradation of petroleum hydrocarbons

S. No	**Bacterial species**	**Mode of action**	**Reference**
1	*Rhodococcus indonesiensis* strain SARSHI1, *Pseudomons aeruginosa* strain SARSHI2, *Pseudomons argentinensis* strain SARSHI3, *Acinetobacter*	Produce biosurfactants and some species displayed efficiency upto 90%	Zaman et al., 2025

	baumannii strain SARSHI4, *and Rhodococcus qingshengii* strain SARSHI5		
2	*Alcanivorax borkumensis*	Use Alkane hydroxylase enzyme for degradation of oil hydrocarbons	Prasad et al., 2023; Schneiker et al., 2006
3	*Dietzia* strain	*Dietzia* isolated from petroleum-contaminated sediment, efficiently degraded a wide range of hydrocarbons, including C14–C31 alkanes, aromatic compounds, and crude oil. maintained its biodegradation activity even under high salinity (up to 85 g/L NaCl), indicating excellent salt tolerance. CYP153 and alkB alkane hydroxylase genes were induced during alkane degradation	Chen et al., 2017
4	Bacillus licheniformis and Pseudomonas aeruginosa	Degrades petroleum compounds via aerobic pathway	Ravi et al., 2022
5	*Bacillus licheniformis, Pseudomonas putida* and *Paenibacillus glucanolyticus*	Degradation due to alkane hydroxylase complex. Species having bigger cell size displayed more degradation capacity.	Costa and Millan ., 2024
6	*Ochrobactrum intermedium* and *Bacillus paramycoides*	Lipase and dehydrogenase enzyme are involved	Elhamrouni et al., 2025
7	*Pseudomonas*, *Marinobacter*, *Alcanivorax*, *Pseudomonas*, *Ochrobactrum*, and *Sphingomonas*.	These species are mainly n-hexadecane and phenanthrene degraders. PAH dioxygenase genes, *alkB* genes, phthalate and salicylate-related pathways are involved in degradation	Bird et al.,2022; Halfadji 2021; Li et al., 2024
8	*Pseudomonas aeruginosa*	*Alkanes and jet fuel degraders with alkane monooxygenases.*	Gunasekera et al., 2025
9	*Sphingomonas*	*Degrades polycyclic hydrocarbons with* Ring-hydroxylating dioxygenases	Jakoncic et al., 2007
10	*Methyloirubrum populi*	*Degrades alkanes in crude oil with enzymes* alkane monooxygenase, cytochrome P450 (CYP450), and lipase	Parsa and Nazeri., 2025

FACTORS AFFECTING BIODEGRADATION:

Microorganisms' ability to biodegrade oil is influenced numerous factors. Temperature is a significant factor affecting the microbial growth, enzyme activity, and oil viscosity. Moderate temperature normally promotes biodegradation, whereas extreme temperatures decrease microbial activity. Since most oil-degrading bacteria prefer to thrive in neutral or slightly alkaline environments, so pH is also crucial. As oxygen is needed by majority of the bacteria in effectively breaking hydrocarbons so, oxygen availability is crucial for aerobic degradation. Minerals specially nitrogen and phosphorus influence microbial growth and metabolism and hence their concentration impact the biodegradation. Since bacteria require water for metabolic processes, moisture content is another important component. However, too much moisture could hinder the diffusion of oxygen in soil.

Normally lighter hydrocarbons break down more easily than complex aromatic molecules, the nature of the hydrocarbon also affects its degradation. In marine ecosystem, microbial survival is impacted by salinity. The efficacy of biodegradation is also greatly influenced by the number and variety of microorganisms that are transforming the hydrocarbons. As the oil compounds that are firmly bonded to soil particles become less accessible to bacteria so bioavailability of hydrocarbons is equally essential influencing the degradation process (Mekonnen et al., 2024). Another important crucial factor is sunlight influencing the oil degradation as the UV light causes photooxidation which leads to susceptibility of oil for biodegradation. In some reports it was observed that increasing oil concentration leads to decrease in degradation rate (Bacosa et al., 2022). Biosurfactants if present are known to enhance the degradation of petroleum contamination (Zhu et al., 2025).

BIOREMEDIATION TECHNIQUES:

Bioremediation is more cost-effective and environmentally sustainable method than physical methods like incineration and chemical methods like chemical oxidation and hence can be chosen for oil removal. Physical and chemical procedures work well for removing oil, but they have dangerous side effects. Oil is broken down into safe products (CO2 and water) by microorganisms using bioremediation technology since they may use oil as their only source of carbon and energy. This technology uses two strategies: biostimulation, which increases the activity of native oil-degrading microorganisms by adding nutrients like nitrogen and phosphorous, and bioaugmentation, which suggests introducing effective oil-degrading microorganisms into polluted sites. The ability of native soil microorganisms to eliminate oil on their own is implied by the term "self-cleaning (Ali et al., 2022).

Bioremediation techniques have several benefits, such as lower on-site operating costs, no secondary pollution, and increased public acceptance. Some of the biological methods that can be used for bioremediation includes: (1) the use of microorganisms (fungi/bacteria) to degrade carbon-based chemicals; (2) the use of plants, particularly fast-growing plants with high biomass; (3) storage or stabilization by soil microbes (4) the combined use of plants and bacteria, known as microbe-assisted phytoremediation. In the past, crude oil pollution has been remedied using plants (Yu et al., 2020). Microbial degradation is a crucial method for petroleum bioremediation as the soil petroleum pollution is on rise (Huo K.et al., 2025).

RECENT ADVANCES:

Environmental contamination from petroleum production and processing processes is getting worse due to the growing demand for petroleum and petroleum products from all sectors. Petroleum-induced soil pollution has a negative impact not only on human lives and productivity but also on the quality of the environment. Currently, biological processes are the primary means of degrading petroleum in soil. When petroleum pollutants enter the soil, native bacteria in the soil naturally break them down. However, as pollution levels rise, the rates of degradation slow down, necessitating the addition of nutrients, dissolved oxygen. Microbial immobilization technologies, microbial fuel cell technologies, and exogenous petroleum-degrading microorganisms can all improve the degradation process (Wang, et al., 2021).

ENVIRONMENTAL SIGNIFICANCE:

A natural and sustainable way to restore soil contaminated by crude oil is through bioremediation, which uses microorganisms and plants (Yu et al., 2020).

One sustainable and environmentally friendly way to address the pressing problem of environmental contamination is through microbial bioremediation. Pollutants include heavy metals, hydrocarbons, oils, pesticides, and dyes undergo microbial biodegradation and transformation primarily through enzymatic mechanisms. Compared to direct chemical or physical treatment, this microbial transformation approach is more practical and preferred. Hazardous chemicals in the environment can be detoxified and broken down into less dangerous byproducts by using live microorganisms like bacteria, fungus, and algae (Elshafei et al., 2024).

By creating biosurfactants that function as emulsifiers, microorganisms can use petroleum hydrocarbons as a source of energy, mineralizing or changing hydrocarbons into safe substitutes. One emerging method for the removal and degradation of petroleum hydrocarbons and other environmental toxins is the use of microbes to detoxify or eliminate pollutants because of their broad metabolic capacity. Furthermore, it is believed that bioremediation or biodegradation by natural populations of microorganisms, is economical and non-invasive. Compared to traditional physico-chemical treatments, the biodegradation of xenobiotic pollutants (such oil) by natural populations of microorganisms is more economical, efficient and environmentally friendly. As a result of its natural approach, bioremediation has acquired a lot of recognition in recent decades and is probably going to be used in conjunction with physico-chemical procedures as part of an integrated treatment process to remove pollutants (Kalia et al., 2022; Sah et al., 2022).

CONCLUSION:

It is evident that bacteria and hydrocarbons have evolved over millions of years of interaction. As a result, many microbial communities possess the capacity to break down hydrocarbons. When environmental conditions permit, the biodegradation processes will naturally begin. Therefore, it appears that the safest way to enhance hydrocarbon elimination is by biostimulation. The bioremediation processes are likely to succeed only if the introduced stimulant's compatibility with the local bacteria is verified and appropriate nutritional dosages are added to maintain an ideal C:N:P ratio. To increase the likelihood of its successful implementation, bioaugmentation still needs more research. An alternative that appears to be more practical is autochthonous bioaugmentation.

Future research should concentrate on developing guidelines for the introduction of non-native strains and techniques for choosing the best strains based on the environmental conditions at the contaminated site. The application of immobilized pollutant degraders appears to be promising in this area.

Many parameters need to be taken into account, particularly in soil systems, in order to successfully deploy (bio)surfactant-assisted biodegradation. According to the examined data, it appears that when there is a high total petroleum hydrocarbons content in the early stages of the biodegradation process, administering lower dosages of (bio)surfactants leads to increased efficiency. In this instance, further testing concerning toxicity, contaminant mobility, and surfactant preferred degradation should be done before beginning any treatment procedures. Overall, it appears that there is still much to learn about hydrocarbons, even though they have been investigated as environmental pollutants for many years.

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Author s' Contributions

N.M., R.A and S.M. wrote the first draft of the manuscript. The final draft was read and edited by P.G and G.G. All authors have made a substantial, direct and intellectual contribution to the work and approved it for publication. All authors have read and agreed to the published version of the manuscript.

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