Microbial Degradation of Hydrocarbons in Marine Ecosystems: A Review of Recent Advances

[1]Gunamathy K, [2]Kumaresan S,[3]Bragadeeswaran S, [4]Celcia Gnanarathinam WV

[1]Researcher,[2]Assistant professor,[3]Professor, [4]Researcher

[1]CAS in Marine Biology,

[1]Annamalai University, Parangipettai,India

[1]gunamathy23590@gmail.com, [2]kskumaresan@yahoo.co.in, [3] dpragathi@gmail.com, [4]cellorathinam@gmail.com

Abstract- During the last decade, increasing attention has been directed toward environmental pollution caused by petroleum and petrochemical products. Oil contamination is a major contributor to soil and water pollution and poses serious risks to ecosystems and human health. Traditional treatment methods have been widely used to remove hydrocarbon contaminants; however, many of these approaches are expensive and environmentally harmful. Bioremediation has emerged as an eco-friendly and cost-effective alternative. This method uses naturally occurring microorganisms to reduce the toxicity and concentration of pollutants, including both aliphatic and aromatic hydrocarbons. Several bacterial strains are capable of degrading petroleum-derived compounds. Because of its affordability and potential for complete mineralization, bioremediation is considered a promising strategy for restoring contaminated environments.Biodegradation, the core process of bioremediation, involves the breakdown of organic pollutants into carbon dioxide, water, inorganic compounds, and microbial biomass, or their transformation into simpler organic molecules. Many naturally occurring microbes in soil and aquatic environments can degrade hydrocarbon pollutants. This review summarizes recent developments in microbial degradation of petroleum hydrocarbons in different environments.

KEYWORDS: Petroleum hydrocarbon, Biodegradation, Microbes, degradation.

INTRODUCTION

Biological activity enables enzymatic reactions that act on most organic substances and many inorganic compounds. Many of these substances are environmental pollutants generated by modern human activities, and their breakdown by enzymatic processes is known as biodegradation. Bioremediation refers to the practical application of biodegradation processes to remove or detoxify contaminants that threaten environmental and public health. Such pollutants are commonly present in soil, water, and sediment.

Oil contamination of soil is currently one of the most serious global environmental concerns. Petroleum-polluted soils pose significant risks to human health, restrict groundwater usage, cause economic losses, and reduce soil fertility and agricultural productivity. Human exposure may occur through direct contact with contaminated soil, inhalation of toxic vapors, or secondary contamination of surface and groundwater. Petroleum hydrocarbons are toxic to humans, animals, plants, and microorganisms. In as plants, hydrocarbons can act herbicidalagents by dissolving membrane lipids, which leads to leakage of cellular contents [Currier & Peoples, 1954]. Major sources of petroleum contamination include leakage from storage tanks, industrial discharges, refinery operations, and accidents during oil transport. Since major oil-producing countries are often not the primary consumers, large volumes of crude oil must be transported over long distances, increasing the likelihood of spills and environmental pollution.

Rapid industrial growth and intensified oil exploration have led to increased discharge of petroleum pollutants into the environment. Accidental leakage from petroleum industries is one of the primary causes of soil and groundwater contamination [Holliger et al., 1997]. Petrochemical contamination can severely disrupt soil stability and function, leading to ecological damage and decreased agricultural productivity. Crude oil is a complex mixture of hydrocarbons with molecular weights ranging from approximately 16 to

1800. These hydrocarbons are generally classified into four main groups: saturates, aromatics, resins, and asphaltenes. Biodegradation is considered an effective approach for treating such petroleum-derived contaminants.

Traditional remediation methods, including chemical treatments and physical techniques such as excavation and soil washing, are often expensive and may cause additional environmental harm [Kuiper et al., 2004]. Chemical methods, such as the use of strong oxidants or surfactants, can cost up to 300 USD per cubic yard of soil [US EPA, 2006]. Consequently, there is a growing demand for environmentally sustainable and cost-effective "green" remediation technologies.

The term Total Petroleum Hydrocarbons [TPH] refers to the concentration of petroleum-based hydrocarbons measured in environmental samples using specific analytical methods [Weisman et al. 1996]. TPH measurement techniques vary widely in their specificity, and results depend on the analytical method used. Therefore, understanding the methodology is essential for proper interpretation of TPH data. Differences in extraction efficiency can lead to variations in measured TPH concentrations for the same sample [ATSDR, 1999; Speight, 2014].

Bioremediation efficiency may be limited by low microbial diversity or the absence ofspecialized microorganisms capable of degrading the diverse hydrocarbons present at contaminated sites [Ron & Rosenberg, 2014]. Several studies have shown that mixed microbial cultures are more effective than pure cultures in utilizing petroleum hydrocarbons as a sole carbon source [Cerqueira et al. 2011; Das &Chandran, 2011; Varjani et al., 2014]. Laboratory experiments have also demonstrated that bacterial–fungal co-cultures enhance the degradation of diesel and various polycyclic aromatic hydrocarbons [PAHs][Li et al., 2008; Wang et al., 2023; Varjani&Upasani, 2016]. These findings highlight the importance of cooperative interactions among different microbial groups during biodegradation [Atlas, 1981; Varjani et al., 2015].

The present review aims to expand understanding of petroleum hydrocarbon bioremediation. It addresses the environmental fate and toxicity of petroleum hydrocarbons, available bioremediation technologies, microbial degradation pathways, metabolic mechanisms, and the key factors influencing the rate of hydrocarbon biodegradation.

ENVIRONMENTAL FATE OF PETROLEUM HYDROCARBONS

Understanding how hydrocarbons behave in the environment is essential for effective pollution control and management [Walker, 2018]. After release, petroleum undergoes various weathering processes, including spreading, evaporation, dispersion, sinking, dissolution, emulsification, photo-oxidation, resurfacing, formation of tar balls, and biodegradation. Among these processes, biodegradation naturally breaks down hydrocarbon components of crude oil [Al-Majedet al., 2012; Souza et al., 2016].

Photo-oxidation is limited in its overall impact because it occurs only when oil is exposed to sunlight [Widdel and Rabus, 2001]. Environmental factors such as temperature, ocean currents, and weather conditions strongly influence these weathering processes [Atlas, 1981; Widdel and Rabus, 2001]. Over long time periods, biodegradation—especially of polycyclic aromatic hydrocarbons [PAHs]—is considered the most important mechanism affecting hydrocarbon concentrations in the environment [Abbasian et al.2015].

The resistance of hydrocarbon pollutants to microbial degradation depends largely on their type, molecular weight, and, in the case of PAHs, the number of aromatic rings. Low-molecular-weight compounds such as naphthalene are usually degraded rapidly, whereas PAHs containing four to six rings break down much more slowly. Several studies have also shown that aerobic biodegradation generally occurs at a much faster rate than anaerobic degradation [Widdel and Rabus, 2001; Abbasian et al.2015; Meckenstock et al. 2016].

COMPOSITION OF CRUDE PETROLEUM OIL

Petroleum is formed over millions of years through the thermal decomposition of buried organic matter. After extraction from underground reservoirs, crude oil is transported to refineries, where it undergoes distillation to produce various petroleum products [Speight, 2007; Varjani, 2014]. The term petroleum, derived from Latin, means “rock oil,” and it is typically a black, sticky, and viscous liquid [Vieira et al., 2007].

Petroleum hydrocarbons are primarily composed of carbon and hydrogen in varying proportions, along with small amounts of oxygen, sulfur, and nitrogen [Chandra et al., 2013; Varjani et al., 2015]. Based on the proportion of heavy molecular components, crude oil is classified as light, medium, or heavy [Varjani, 2014]. Its composition varies depending on the location, age, and depth of the oil reservoir. More than 85% of crude oil constituents can generally be grouped into three categories: asphalt-base, paraffin-base, or mixed-base oils [Atlas, 1981; Varjani, 2014].

Aliphatics

Aliphatic hydrocarbons include n-alkanes, iso-alkanes, cycloalkanes [naphthenes], terpenes, and steranes. These compounds may be saturated or unsaturated and can occur as linear or branched chains [Rahman et al., 2003]. Based on molecular weight, n-alkanes are divided into four groups: gaseous alkanes, low-molecular-weight alkanes [C8–C16], medium-molecular-weight alkanes [C17–C28], and high-molecular-weight alkanes [>C28][Abbasian et al., 2015].

Aromatics

Aromatic hydrocarbons contain ring-shaped molecular structures and are mainly classified into two groups: polycyclic aromatic hydrocarbons [PAHs] and monocyclic aromatic hydrocarbons [MAHs], commonly known as BTEX [benzene, toluene, ethylbenzene, and xylenes][Chandra et al., 2013; Farhadian et al., 2008].
PAHs consist of multiple benzene rings. Low-molecular-weight PAHs contain two or three rings, such as naphthalene, phenanthrene, and anthracene [Wilkes et al., 2016]. High-molecular-weight PAHs have four or more rings, including compounds like pyrene, fluoranthene, and benzo[a]pyrene [Farhadian et al., 2008].

Resins

Resins are amorphous solids that contain numerous polar functional groups along with trace metals such as nickel, vanadium, and iron, as well as nitrogen, sulfur, and oxygen [Balba et al., 1998; Speight, 2019]. They are dissolved in crude oil and consist of long-chain aromatic compounds soluble in solvents like n-heptane and n-pentane [Jada and Salou, 2002; Parra-Barraza et al., 2003; Chandra et al., 2013]. Resins act as peptizing agents and share structural characteristics with surface-active compounds present in crude oil.

Asphaltenes

Asphaltenes, like resins, contain many polar functional groups. They are large, complex, dark-brown molecules that exist in colloidal form within the saturate and aromatic fractions of crude oil [Balba et al., 1998; Speight, 2007]. They are soluble in light aromatic solvents such as benzene and toluene [Parra-Barraza et al., 2003]. Asphaltenes are high-molecular-weight, viscous compounds composed of polycyclic structures that may be substituted with alkyl groups, which contributes to their resistance to biodegradation [Chandra et al., 2013]. Resins help maintain asphaltenes in suspension, thereby enhancing the stability of crude oil [Parra-Barraza et al., 2003; Chandra et al., 2013].

SOURCES OF PETROLEUM HYDROCARBONS IN THE MARINE ENVIRONMENT

Petroleum hydrocarbons in marine environments originate from both anthropogenic and natural sources [Wu et al., 2001]. Human-related inputs are typically described as petrogenic or pyrogenic, whereas natural inputs are classified as biogenic or diagenetic.

Biogenic hydrocarbons are produced by living organisms such as bacteria, algae, plankton, and terrestrial plants. These compounds arise from biological processes and include odd-numbered n-alkanes such as C15, C17, and C19, which are associated with marine biological activity, as well as C23–C33 aliphatic hydrocarbons derived mainly from plant debris on land. However, these biogenic hydrocarbons are generally present in relatively small concentrations [Sakari, 2012].

BIOREMEDIATION STRATEGIES

Biostimulation

Although microorganisms are usually present at contaminated sites, their activity often needs to be enhanced to achieve effective remediation. Biostimulation refers to the process of stimulating native microorganisms by supplying nutrients, oxygen, or electron acceptors to improve their ability to degrade pollutants. This approach focuses on modifying environmental conditions to support microbial growth and activity at the contaminated site.

Additives are commonly introduced into the subsurface through injection wells. When designing a biostimulation system, several subsurface factors must be considered, including groundwater flow rate, hydraulic conductivity, and soil or sediment characteristics [Vidali, 2001]. While native microorganisms carry out most of the degradation, the process can be further improved through bioaugmentation.

Bioaugmentation

Bioaugmentationinvolves the introduction of selected native or genetically modified microbial strains into contaminated soil or water. This method is particularly useful when indigenous microorganisms are absent or lack the metabolic capability required to degrade specific contaminants.

DEGRADATION OF PETROLEUM HYDROCARBONS BY MICROBIAL ACTIVITY

The degradation of petroleum hydrocarbons is a complex process that depends largely on both the quantity and the type of hydrocarbons present. Steliga[2012] categorized petroleum hydrocarbons into four main groups: aliphatics, aromatics, resins [including compounds such as carbazoles, sulfoxides, pyridines, quinolines, and amides], and asphaltenes[including phenols, ketones, esters, porphyrins, and fatty acids]. Numerous studies have demonstrated that environmental conditions significantly influence the biodegradation of these hydrocarbons [Cooney et al., 1985].

One of the main limitations in the biodegradation of oil pollutants is the insufficient availability or diversity of microorganisms capable of degrading them. In many contaminated sites, low microbial diversity or the absence of specialized microorganisms with the required metabolic capabilities restricts the efficiency of bioremediation.

Both bacteria and filamentous fungi play important roles in hydrocarbon biodegradation [Rahman et al., 2003]. In recent years, ligninolytic fungi have received considerable attention for their ability to degrade hydrocarbons. Key enzymes produced by these fungi include lignin peroxidases, manganese peroxidases, phenol oxidases such as laccases and tyrosinases, and hydrogen peroxide–producing enzymes, all of which are effective in degrading polycyclic aromatic hydrocarbons [PAHs][Lee et al., 2018].

Many fungal species have demonstrated strong hydrocarbon-degrading capabilities. These fungi can be cultivated in soil or solid matrices, where they multiply and contribute to pollutant removal. Since such fungi naturally occur in soil waste environments, they play an important role in the bioremediation of petroleum-contaminated sites [Lee et al., 2018].

FACTORS INFLUENCING THE DEGRADATION OF PETROLEUM HYDROCARBONS

Numerous studies and practical applications have demonstrated that contaminated soil and water can be effectively treated through bioremediation. Extensive research has been conducted on the environmental impact of petroleum hydrocarbons [PHs] and the techniques used for their remediation. Several environmental factors influence microbial activity, including temperature, oxygen availability, pH, and nutrient concentration.

For biodegradation to occur successfully, microorganisms must develop catabolic activity through specific mechanisms. These include the induction of particular enzymes, the development of new metabolic capabilities through genetic adaptation, and the selective enrichment of microbial populations capable of degrading contaminants. When environmental conditions are favorable, microorganisms can achieve maximum degradation of PHs. Among all factors, the chemical composition of the hydrocarbons is considered the most important determinant of their biodegradability.

Fedorak and Westlake [1981] reported that marine microbial communities degrade aromatic hydrocarbons more rapidly during crude oil breakdown. In another study, Rambeloarisoa et al. [1984] used a continuous culture fermenter with mixed marine bacteria and found that different fractions of crude oil degraded at similar rates. However, Jobson et al. [1972] observed significant differences in the degradation rates of asphaltenes, saturates, aromatics, and resins.

When petroleum hydrocarbons enter aquatic environments, they tend to spread over the water surface due to wind and wave action, sometimes forming emulsions such as water-in-oil or oil-in-water mixtures [Colwell et al., 1977]. The formation of such emulsions, either naturally or with the assistance of biosurfactants, is a key step that enhances the uptake of hydrocarbons by microorganisms.

Singh and Ward [2004] described the major differences between hydrocarbon biodegradation in soil and aquatic environments following an oil spill. Factors such as the movement, distribution, and particle content of oil influence its physical and chemical properties, which in turn affect the efficiency of microbial degradation.

TEMPERATURE

Temperature is a key factor controlling the biodegradation of petroleum hydrocarbons. According to Atlas, the viscosity of low-molecular-weight hydrocarbons is influenced by temperature: it increases at low temperatures and decreases at higher temperatures. Temperature therefore affects biodegradation by altering the physical and chemical properties of oil in soil and water. It also influences the metabolic activity of microorganisms responsible for hydrocarbon breakdown.

When temperatures rise above approximately 30–40 °C, the rate of petroleum hydrocarbon metabolism generally increases. Hydrocarbon degradation can occur over a wide temperature range, but metabolic activity typically slows as temperatures decrease. For example, compounds such as phenanthrene and naphthalene have been detected in seawater at 0 °C. In contrast, ligninolytic fungal enzymes such as manganese peroxidase and laccase function optimally at higher temperatures, often between 50 °C and over 75 °C, during the degradation of polycyclic aromatic hydrocarbons [PAHs]. Under optimal temperature conditions, more than 90% of PAHs may be degraded [Li et al., 2020].

Studies on Kuwaiti crude oil have shown that PAHs degrade at around 15 °C when oxygen is present at 4 ppm, whereas at temperatures of 40 °C or higher, oxygen levels may drop to zero [Muthal, 2017]. Microorganisms capable of degrading petroleum

hydrocarbons function within specific temperature ranges, including psychrophiles[below 20 °C], mesophiles[15–45 °C], and thermophiles [above 50 °C]. However, maximum degradation is typically achieved by mesophilic microorganisms at temperatures between 20 and 35 °C [Liu, 2020]. Overall, hydrocarbon degradation occurs more effectively in warmer climates than in colder regions, and mesophiles are often preferred because of their broader diversity and activity range.

NUTRIENTS

Biodegradation depends on the availability of essential nutrients such as nitrogen, phosphorus, iron, and oxygen. The addition of nutrients to contaminated environments is often necessary to stimulate microbial activity and initiate the biodegradation process [Alotaibi, 2021]. Previous studies indicate that adequate nutrient supply enhances microbial biomass, thereby improving hydrocarbon degradation.

When petroleum hydrocarbons enter the environment, the carbon content increases, while nitrogen and phosphorus often become limiting. Many freshwater and marine environments are naturally deficient in these nutrients, which restricts microbial growth. Therefore, an increase in nutrient availability is required to support effective degradation of oil pollutants.

Several researchers have examined the effect of nutrient levels on hydrocarbon degradation. Excessive concentrations of nutrients, particularly nitrogen, phosphorus, and potassium [NPK], may inhibit degradation, especially for aromatic hydrocarbons. Thus, both the type and concentration of nutrients play a critical role in the biodegradation process. In some cases, an overabundance of nutrients has been shown to slow down hydrocarbon breakdown.

During biodegradation, aerobic microorganisms utilize various nutrients, including nitrogen, sulphur, manganese, iron, and small amounts of phosphorus. Among these, nitrogen and phosphorus are especially important for natural hydrocarbon degradation, and their deficiency can significantly reduce the rate of biodegradation.

In seawater, these nutrients are typically present in low concentrations. For instance, phosphorus is often found as calcium phosphate, and the levels of nitrogen and phosphorus compounds vary with temperature. Their concentrations generally range from 0–0.7 mg/L for phosphorus and 0.1–1 mg/L for nitrogen. When nutrient levels are insufficient, fertilizers may be applied to support the biodegradation process [Goveaset al.2020].

OXYGEN

Oxygen is one of the most critical factors in the biodegradation of petroleum hydrocarbons. The initial stages of hydrocarbon degradation typically occur under aerobic conditions, where oxygen serves as an essential component of the process. Soil and water microorganisms use oxygen during respiration, and it is required throughout the degradation pathway.

Approximately 3–4 mL of oxygen are needed to break down 1 mL of hydrocarbon into carbon dioxide and water. Since petroleum is rich in carbon and hydrogen but low in oxygen, the biodegradation process requires a significant oxygen supply [Fragkou, 2021].

Surface waters such as lakes, oceans, and harbours usually contain high oxygen levels due to air–water interaction, wave action, and wind. However, oxygen concentrations decrease with depth. In deep aquatic environments, low oxygen levels lead to anaerobic degradation processes, which are generally slower.

When petroleum becomes buried in sediments, it disperses and sinks deeper, further reducing oxygen availability and slowing degradation. Additionally, oil films on the water surface can restrict oxygen exchange, preventing adequate re-oxygenation required for microbial activity [Ward and Overton, 2020].

The movement and degradation of oil are influenced by several factors, including oxygen concentration, soil type, moisture content, and the capacity of microorganisms to degrade hydrocarbons and promote re-aeration. These conditions are essential for effective biodegradation. Aerobic bacteria typically require about 3.1 mg of oxygen to degrade 1 mg of hydrocarbon [Moreno Ulloa, 2020].

DISPERSANTS

Petroleum is hydrophobic in nature, which limits its availability to microorganisms and slows down the degradation process. To enhance remediation, dispersants or detergents are often applied to oil-contaminated soils or water. These substances help desorb hydrocarbons and increase their accessibility to microbes.

Certain microorganisms naturally produce biosurfactants, such as rhamnolipids, which contain fatty acid and rhamnose components. These biosurfactants act as natural detergents and are widely used to improve the breakdown of petroleum hydrocarbons [Suryawanshi, 2021].

ANAEROBIC DECOMPOSITION

Most bioremediation approaches focus on increasing oxygen availability in contaminated environments, since aerobic respiration is the primary mechanism for hydrocarbon removal. However, in some situations—particularly where oil penetrates deeply into sediments—oxygen transfer may be insufficient to replace what is consumed by microbial metabolism. Under these conditions, anaerobic degradation of petroleum hydrocarbons becomes significant [Wartell et al., 2021].

In certain cases, biological processes such as ammonia-driven oxidation can increase the demand for nutrients like ammonia and urea, which are sometimes applied during oil spill remediation. When oxygen is limited, microorganisms capable of anaerobic metabolism play an important role in the breakdown of hydrocarbons.

SALINITY

Only a limited number of studies have examined the effect of salinity on microbial hydrocarbon degradation. Marine microorganisms generally tolerate a broad range of salinity levels, and there is little evidence that hypersaline conditions strongly inhibit microbial activity in petroleum-contaminated environments. Estuarine systems present unique conditions because their salinity fluctuates between freshwater and marine levels.

Microorganisms involved in hydrocarbon degradation often adapt to the salinity of their environment. For example, certain archaea can survive and function in highly saline conditions associated with crude oil deposits. Studies from the Kalamkass oil field in Kazakhstan reported the degradation of n-alkenes and isoprenoids in brine concentrations of 10–25%. Similarly, halophilic microorganisms such as Halococcus, Haloferax, and Halobacterium have been isolated from hypersaline environments in the Arabian Gulf, where salinity exceeds 26% NaCl and temperatures range between 40 and 45 °C. These microbes utilize both aliphatic and aromatic hydrocarbons as sources of carbon and energy [Cao, 2020].

Research also indicates that only a limited range of fungi contribute to hydrocarbon degradation under high-salinity conditions. Species such as Papulaspora, Fusarium lateritium, and Drechsler have been identified as active degraders in such environments. In salt marshes of Kuwait, where salinity ranges from 5–10%, crude oil is degraded as a carbon source by microorganisms.

Even in environments with salinity levels between 0 and 30%, bacteria, eukaryotes, and archaea are capable of degrading crude oil. However, natural attenuation tends to occur slowly in hypersaline conditions. Many archaea [e.g., Halobacterium, Haloferax] and eubacteria [e.g., Actinopolyspora, Streptomyces albiaxialis, Marinobacteraquaeolei] show optimal activity at salinity levels of 20–30% [Camacho Montealegre et al., 2021].

PH

Most heterotrophic bacteria and fungi function best within near-neutral pH conditions, although many fungi are capable of growing in more acidic environments. The optimal pH range for the mineralization of hydrocarbons in sediments is typically between 5.0 and 7.8, as reported by Bartha and Dibble [1979].

However, many hydrocarbon-contaminated sites do not naturally fall within this optimal pH range. For example, areas containing construction debris such as brick and concrete often exhibit elevated pH levels, which can create unfavorable conditions for microbial activity [Husnain, 2021]. In other cases, processes such as sulfide oxidation during coal leaching can produce highly acidic conditions.

Extreme pH levels—either highly acidic or highly alkaline—can inhibit microbial degradation of polycyclic aromatic hydrocarbons [PAHs]. Studies have shown that the degradation of aromatic compounds in contaminated soils is influenced by pH adjustments using substances such as sodium phosphate. Experimental results indicated that the breakdown of compounds like 2-methyl naphthalene was affected by pH levels between 2.0 and 4.0 [Idomeh, 2021].

pH adjustment at contaminated sites is commonly achieved through the application of lime. Certain bacteria, such as Burkholderiacocovenenans, can degrade phenanthrene effectively within a pH range of 5.5 to 7.5. Similarly, Sphingomonaspaucimobilis, a known PAH-degrading bacterium, operates optimally within a pH range of 5.2 to 7.0. Some microorganisms, including certain yeasts, bacteria, and fungi, can tolerate more extreme pH conditions, although their activity may be reduced.

In seawater, which typically has a pH between 7.5 and 10 and salinity levels of 1–2%, alkaliphilic microorganisms are present. Hydrocarbon degradation under such conditions has been observed at salt concentrations of 0.1–2 M NaCl, with optimal activity around 0.4 M [Lei et al., 2020].

PETROLEUM-DEGRADING MICROORGANISMS IN THE MARINE ENVIRONMENT: SPECIES AND DISTRIBUTION

The use of petroleum-degrading microorganisms for oil spill bioremediation has been widely documented since the mid-20th century. Research has shown that a diverse range of such microorganisms is naturally distributed throughout marine environments. Following oil contamination, some microbial groups are suppressed, while hydrocarbon-degrading bacteria rapidly multiply and often become the dominant species.More than 200 genera and species of petroleum-degrading microorganisms—including bacteria, fungi, algae, and cyanobacteria—have been identified in marine ecosystems. These include numerous genera across different microbial groups.Among bacteria, important hydrocarbon degraders include Achromobacter, Acinetobacter, Alcaligenes, Arthrobacter, Bacillus, Flavobacterium, Coryneform bacteria, Microbacterium, Micrococcus, Pseudomonas, Actinomycetes, and Nocardia. Yeasts such as Aureobasidium, Candida, Rhodotorula, and Sporobolomyces also contribute to petroleum degradation.Fungal genera such as Aspergillus, Fusarium, and Penicillium are known to degrade hydrocarbons as well. In addition, the genus Gordonia is widely distributed in coastal, marine, and terrestrial habitats. It is capable of degrading a broad range of environmental pollutants, including alkanes, polycyclic aromatic hydrocarbons, benzothiophene, and dibenzothiophene.

PARTICULARITIES OF BIODEGRADATION

Marine hydrocarbon-degrading bacteria are capable of utilizing either alkanes or aromatic hydrocarbons as energy sources. Common genera include Alcanivorax, Cycloclasticus, Marinobacter, Neptunomonas, and Oleiphilus[Ojuederie and Babalola, 2017]. Different bacterial groups exhibit substrate preferences. For example, Alcanivorax species mainly degrade n-alkanes and branched alkanes, whereas Cycloclasticus specializes in the degradation of aromatic hydrocarbons.Bacterial strains such as Pseudomonas, Corynebacterium, and Bacillus, isolated from residual oil in the Liaohe oil field, have demonstrated partial degradation of petroleum components. In these cases, degradation efficiencies varied among fractions, with approximately 80% reduction in aromatic

hydrocarbons, 53% in bitumen, 37% in aliphatic hydrocarbons, and 30% in non-hydrocarbon compounds.Certain specialized microorganisms also show the ability to degrade specific polycyclic aromatic hydrocarbons [PAHs]. For instance, *Tropicibacternaphthalenivorans* can degrade compounds such as naphthalene, phenanthrene, and alkylated naphthalenes, although it shows limited activity toward some benzothiophenes, alkyl phenanthrenes, and alkyl fluorenes.

RATE OF DEGRADATION EFFICIENCY

In principle, hydrocarbon-degrading microorganisms can convert petroleum components into inorganic end products through metabolic processes [Sharma, 2022]. However, the efficiency of degradation varies widely depending on the complexity of the hydrocarbons, including their molecular weight and structural characteristics. External environmental factors such as temperature, oxygen availability, salinity, pressure, and nutrient concentration also significantly influence degradation rates.

TOXIC IMPACT OF PETROLEUM HYDROCARBONS

Oil pollution is widely recognized for its harmful effects on the environment [Sikkema et al., 1995]. Major incidents, such as the Deepwater Horizon oil spill in the Gulf of Mexico, have caused severe ecological and economic damage, raising public concern [Xue et al., 2015]. While the effects on humans and animals are often emphasized, the toxic impacts on microbial communities are sometimes overlooked [Díez et al., 2007; Mason et al., 2012; Rivers et al., 2013; Overholt et al., 2016].

Studies have shown that petroleum hydrocarbons can reduce microbial biomass. For example, gasoline-contaminated sandy soils exhibited particularly severe effects [Labud et al., 2007]. Diesel exposure has also been linked to reductions in species richness, evenness, and phylogenetic diversity, with microbial communities becoming dominated by a few species, especially Pseudomonas. Such changes were also associated with disruptions in the nitrogen cycle, including declines in nitrifying species and related functional genes [van Dorst et al., 2014].

Research on specific compounds has produced varying results. Cerniglia[1983] reported that naphthalene and its methyl derivatives did not significantly inhibit the growth of *Agmenellumquadruplicatum*. However, phenolic and quinonic derivatives showed inhibitory effects, likely because their higher solubility increased their transfer into microbial cells. Some intermediate metabolites formed during hydrocarbon degradation may be more toxic than the original compounds, further affecting microbial populations [Hou et al., 2019].

Despite these toxic effects, native microbial communities can adapt by forming complex consortia in which different species perform specific roles. Hydrocarbon-degrading bacteria and those capable of utilizing toxic intermediates may proliferate, while sensitive species decline. However, relying solely on natural microbial activity may lead to slow remediation, highlighting the need for intervention strategies to accelerate the cleanup process.

PHYSICOCHEMICAL PROPERTIES

Boiling Points

The boiling point of hydrocarbons generally increases with the number of carbon atoms. In n-alkanes, each additional carbon atom typically raises the boiling point by about 20 °C. Polycyclic aromatic hydrocarbons [PAHs] usually have higher melting and boiling points than comparable n-alkanes, and many exist as solids under normal conditions [WHO].

Solubility, Volatility, and Persistence

The interaction of hydrocarbons with water depends largely on their polarity. Aliphatic hydrocarbons are less polar and therefore less soluble in water than aromatic hydrocarbons. For example, aliphatic hydrocarbons in the C5–C6 range have a solubility of about 36 mg/L, while aromatic hydrocarbons of similar size can reach solubilities of up to 220 mg/L. Among aromatics, lower-molecular-weight compounds are more soluble, while solubility decreases as the number of rings and molecular weight increase.

Aliphatic hydrocarbons are generally more volatile than aromatic hydrocarbons with similar carbon numbers. After an oil spill, most alkanes with fewer than 15 carbon atoms are rapidly lost through volatilization, whereas heavier compounds with more than 20 carbon atoms may persist for several weeks [ATSDR; Scally, 2005]. In general, persistence in the environment increases with molecular weight and boiling point [WHO].

Toxicity and Microbial Degradation

Aromatic hydrocarbons are typically more toxic and more resistant to microbial degradation than aliphatic hydrocarbons, including normal alkanes, isoalkanes, cycloalkanes, and unsaturated aliphatics[Ahmed et al., 2018]. The toxicity of hydrocarbons is strongly influenced by their solubility in water [WHO].The rate of microbial degradation depends on environmental factors such as pH, dissolved oxygen, and the abundance of degrading microorganisms. In unpolluted environments, the population of hydrocarbon-degrading microbes may be low, but it often increases rapidly after oil contamination [Okoh, 2003; Williams et al., 2006].Different hydrocarbon classes degrade at different rates. Under favorable conditions, microorganisms degrade low- to moderate-molecular-weight aliphatic and aromatic hydrocarbons relatively quickly. However, biodegradation slows as molecular weight and structural complexity increase [Wiedemeier et al., 1995]. The general order of biodegradability is n-alkanes > branched alkanes > cyclic alkanes > high-molecular-weight aromatics. Overall, aromatic hydrocarbons tend to be less biodegradable than their aliphatic counterparts [Fusey and Oudot, 1984; Leahy and Colwell, 1990].

Biochemical Pathways of Degradation

Alkanes are typically oxidized by oxygenase enzymes to form alcohols. These alcohols are further oxidized into aldehydes and fatty acids, which then enter the β-oxidation pathway. Cycloalkanes are converted into cyclic alcohols and subsequently dehydrogenated to ketones.

Aromatic hydrocarbons undergo oxidation to form epoxides, which are hydrated to produce trans-dihydrodiols and then oxidized into catechols. These intermediates are further metabolized into compounds such as muconic acid or 2-hydroxymuconic semialdehyde. Ultimately, these products are converted into organic acids that microorganisms use for energy production and cell growth [Cerniglia, 1993; Kothari et al., 2013].

SURFACTANTS IN DEGRADATION

The initial step in the interaction between microorganisms and oil pollutants involves direct contact between the microbial cell and the hydrocarbon substrate [Uadet al., 2010]. This interaction is largely determined by the characteristics of the cell wall, particularly its surface hydrophobicity. Through direct contact, hydrocarbons can enter the microbial cell in the form of very small droplets [Varjani et al. 2014].

Surfactants and cell surface hydrophobicity help facilitate this interaction by overcoming diffusion limitations during the transport of insoluble substrates to microbial cells [Kavitha et al. 2014; Varjani and Upasani, 2016a]. In anoxic environments, such as oil reservoirs, microorganisms capable of both hydrocarbon degradation and biosurfactant production are especially effective, as they enhance in situ methanogenesis[Peixoto et al., 2011; Zhao et al., 2016].

Hydrocarbon-degrading microorganisms produce various biosurfactants, which may either be released into the surrounding environment as extracellular compounds or remain attached to the cell surface [Van Hamme et al., 2003; Sajna et al., 2015; Varjani and Upasani, 2017]. These biosurfactants significantly reduce oil viscosity and lower the interfacial tension between oil and water under in situ conditions [Varjani et al., 2017]. According to Waigi et al. [2019], the production of biosurfactants is an important ecological adaptation that enhances hydrocarbon bioavailability, improves interactions between microbial cells and substrates, and promotes mass transfer processes.

CONCLUSION

Approximately eight million tonnes of petroleum are released into the environment each year worldwide. As a result, the remediation of petroleum-contaminated sites has become a major concern in urban areas, industrial regions, and locations involved in crude oil and natural gas extraction.Bioremediation has gained popularity as a treatment method for petroleum-contaminated soils because it is generally more cost-effective than conventional techniques. This approach offers several advantages, including environmental compatibility and the use of naturally occurring microorganisms. Research indicates that various bacteria and fungi present in soil and sludge are capable of degrading petroleum hydrocarbons. Many of these microorganisms adhere to oil surfaces and break down hydrocarbons through biological processes. Furthermore, hydrocarbon-degrading bacteria can often be found in extreme environments, highlighting their adaptability and potential for use in diverse remediation conditions.

REFERENCE

[1] Abbasian, F., Lockington, R., Mallavarapu, M. and Naidu, R., 2015. A comprehensive review of aliphatic hydrocarbon biodegradation by bacteria. *Applied biochemistry and biotechnology*, *176*(3), pp.670-699.

[2] Ahmed, F. and Fakhruddin, A.N.M., 2018. A review on environmental contamination of petroleum hydrocarbons and its biodegradation. *International Journal of Environmental Sciences & Natural Resources*, *11*(3), pp.1-7.

[3] Ahmed, F., Fakhruddin, A.N.M. and Kabir, M.M., 2018. Degradation of diesel and phenol using bacteria isolated from petroleum hydrocarbon contaminated soil. *Bangladesh Journal of Scientific and Industrial Research*, *53*(1), pp.53-62.

[4] Al-Majed, A.A., Adebayo, A.R. and Hossain, M.E., 2012. A sustainable approach to controlling oil spills. *Journal of environmental management*, *113*, pp.213-227.

[5] Alotaibi, F.S., Alrajhi, A. and Alharbi, S., 2024. Bioremediation of High Molecular Weight Polycyclic Aromatic Hydrocarbons. *Microbes Based Approaches for the Management of Hazardous Contaminants*, pp.378-389.

[6] Atlas, R.M., 1981. Microbial degradation of petroleum hydrocarbons: an environmental perspective. *Microbiological reviews*, *45*(1), pp.180-209.

[7] Balba, M.T., Al-Daher, R., Al-Awadhi, N., Chino, H. and Tsuji, H., 1998. Bioremediation of oil-contaminated desert soil: the Kuwaiti experience. *Environment International*, *24*(1-2), pp.163-173.

[8] Camacho-Montealegre, C.M., Rodrigues, E.M., Morais, D.K. and Tótola, M.R., 2021. Prokaryotic community diversity during bioremediation of crude oil contaminated oilfield soil: effects of hydrocarbon concentration and salinity. *Brazilian Journal of Microbiology*, *52*(2), pp.787-800.

[9] Cao, Y., Lin, C., Zhang, X., Liu, X., He, M. and Ouyang, W., 2020. Distribution, source, and ecological risks of polycyclic aromatic hydrocarbons in Lake Qinghai, China. *Environmental Pollution*, *266*, p.115401.

[10] Cerniglia, C.E., 1993. Biodegradation of polycyclic aromatic hydrocarbons. *Current opinion in biotechnology*, *4*(3), pp.331-338.

[11] Cerqueira, V.S., Hollenbach, E.B., Maboni, F., Vainstein, M.H., Camargo, F.A., Peralba, M.D.C.R. and Bento, F.M., 2011. Biodegradation potential of oily sludge by pure and mixed bacterial cultures. *Bioresource technology*, *102*(23), pp.11003-11010.

[12] Chandra, S., Sharma, R., Singh, K. and Sharma, A., 2013. Application of bioremediation technology in the environment contaminated with petroleum hydrocarbon. *Annals of microbiology*, *63*(2), pp.417-431.

[13] Colwell, R.R., Walker, J.D. and Cooney, J.J., 1977. Ecological aspects of microbial degradation of petroleum in the marine environment. *CRC critical reviews in microbiology*, *5*(4), pp.423-445.

[14] Cooney, J.J., Silver, S.A. and Beck, E.A., 1985. Factors influencing hydrocarbon degradation in three freshwater lakes. *Microbial Ecology*, *11*(2), pp.127-137.

[15] Currier, H.B. and Peoples, S.A., 1954. Phytotoxicity of hydrocarbons. *Hilgardia*, *23*(6), pp.155-173.

[16] Das, N. and Chandran, P., 2011. Microbial degradation of petroleum hydrocarbon contaminants: an overview. *Biotechnology research international*, *2011*(1), p.941810.

[17] de Souza, C.V. and Corrêa, S.M., 2016. Polycyclic aromatic hydrocarbons in diesel emission, diesel fuel and lubricant oil. *Fuel*, *185*, pp.925-931.

[18] Dibble, J.T. and Bartha, R., 1979. Leaching Aspects of Oil Sludge Biodegradation in SOIL1. *Soil Science*, *127*(6), pp.365-370.

[19] Díez, S., Jover, E., Bayona, J.M. and Albaigés, J., 2007. Prestige oil spill. III. Fate of a heavy oil in the marine environment. *Environmental science & technology*, *41*(9), pp.3075-3082.

[20] Farhadian, M., Vachelard, C., Duchez, D. and Larroche, C., 2008. In situ bioremediation of monoaromatic pollutants in groundwater: a review. *Bioresource technology*, *99*(13), pp.5296-5308.

[21] Fedorak, P.M. and Westlake, D.W.S., 1981. Microbial degradation of aromatics and saturates in Prudhoe Bay crude oil as determined by glass capillary gas chromatography. *Canadian Journal of Microbiology*, *27*(4), pp.432-443.

[22] Fragkou, E., Antoniou, E., Daliakopoulos, I., Manios, T., Theodorakopoulou, M. and Kalogerakis, N., 2021. In situ aerobic bioremediation of sediments polluted with petroleum hydrocarbons: a critical review. *Journal of Marine Science and Engineering*, *9*(9), p.1003.

[23] Fusey, P. and Oudot, J., 1984. Relative influence of physical removal and biodegradation in the depuration of petroleum-contaminated seashore sediments. *Marine Pollution Bulletin*, *15*(4), pp.136-141.

[24] Goveas, Louella Concepta, and Shyama Prasad Sajankila. "Effect of yeast extract supplementation on halotolerant biosurfactant production kinetics coupled with degradation of petroleum crude oil by Acinetobacter baumannii OCB1 in marine environment." *Bioresource Technology Reports* 11 (2020): 100447.

[25] Holliger, C., Gaspard, S., Glod, G., Heijman, C., Schumacher, W., Schwarzenbach, R.P. and Vazquez, F., 1997. Contaminated environments in the subsurface and bioremediation: organic contaminants. *FEMS Microbiology Reviews*, *20*(3-4), pp.517-523.

[26] Hou, L., Liu, R., Li, N., Dai, Y. and Yan, J., 2019. Study on the efficiency of phytoremediation of soils heavily polluted with PAHs in petroleum-contaminated sites by microorganism. *Environmental Science and Pollution Research*, *26*(30), pp.31401-31413.

[27] Husnain, A., Farooq, Q., Sohail, S., Shasang, S., Toor, D., Zafar, A. and Rehman, B., 2021. Adaptability of soil pH through innovative microbial approach. *Current Research in Agricultural Sciences*, *8*(2), pp.71-79.

[28] Idomeh, J.E., Shittu, O.B., Oyedepo, J.A., Bada, B.S., Balogun, S.A., Idomeh, F.A. and Ezenweani, R.S., 2021. Petroleum hydrocarbon impacted aquatic ecosystem reveals Methylotenera as the dominant genera in the Niger Delta Region of Nigeria. *Geomicrobiology Journal*, *38*(10), pp.879-894.

[29] Iovanna, R. and Griffiths, C., 2006. Clean water, ecological benefits, and benefits transfer: a work in progress at the US EPA. *Ecological Economics*, *60*(2), pp.473-482.

[30] Jada, A. and Salou, M., 2002. Effects of the asphaltene and resin contents of the bitumens on the water–bitumen interface properties. *Journal of Petroleum Science and Engineering*, *33*(1-3), pp.185-193.

[31] Jobson, A., Cook, F.D. and Westlake, D.W.S., 1972. Microbial utilization of crude oil. *Applied Microbiology*, *23*(6), pp.1082-1089.

[32] Kavitha, S., Jayashree, C., Kumar, S.A., Yeom, I.T. and Banu, J.R., 2014. The enhancement of anaerobic biodegradability of waste activated sludge by surfactant mediated biological pretreatment. *Bioresource technology*, *168*, pp.159-166.

[33] Kothari, V., Panchal, M. and Srivastava, N., 2013. Microbial degradation of hydrocarbons.

[34] Kuiper, I., Lagendijk, E.L., Bloemberg, G.V. and Lugtenberg, B.J., 2004. Rhizoremediation: a beneficial plant-microbe interaction. *Molecular plant-microbe interactions*, *17*(1), pp.6-15.

[35] Labud, V., Garcia, C. and Hernandez, T., 2007. Effect of hydrocarbon pollution on the microbial properties of a sandy and a clay soil. *Chemosphere*, *66*(10), pp.1863-1871.

[36] Leahy, J.G. and Colwell, R.R., 1990. Microbial degradation of hydrocarbons in the environment. *Microbiological reviews*, *54*(3), pp.305-315.

[37] Lee, D.W., Lee, H., Kwon, B.O., Khim, J.S., Yim, U.H., Kim, B.S. and Kim, J.J., 2018. Biosurfactant-assisted bioremediation of crude oil by indigenous bacteria isolated from Taean beach sediment. *Environmental pollution*, *241*, pp.254-264.

[38] Lei, Y.J., Zhang, J., Tian, Y., Yao, J., Duan, Q.S. and Zuo, W., 2020. Enhanced degradation of total petroleum hydrocarbons in real soil by dual-frequency ultrasound-activated persulfate. *Science of the Total Environment*, *748*, p.141414.

[39] Li, Q., Liu, J. and Gadd, G.M., 2020. Fungal bioremediation of soil co-contaminated with petroleum hydrocarbons and toxic metals. *Applied Microbiology and Biotechnology*, *104*(21), pp.8999-9008.

[40] Li, X., Li, P., Lin, X., Zhang, C., Li, Q. and Gong, Z., 2008. Biodegradation of aged polycyclic aromatic hydrocarbons (PAHs) by microbial consortia in soil and slurry phases. *Journal of hazardous materials*, *150*(1), pp.21-26.

[41] Mason, O.U., Hazen, T.C., Borglin, S., Chain, P.S., Dubinsky, E.A., Fortney, J.L., Han, J., Holman, H.Y.N., Hultman, J., Lamendella, R. and Mackelprang, R., 2012. Metagenome, metatranscriptome and single-cell sequencing reveal microbial response to Deepwater Horizon oil spill. *The ISME journal*, *6*(9), pp.1715-1727.

[42] Meckenstock, R.U., Boll, M., Mouttaki, H., Koelschbach, J.S., Cunha Tarouco, P., Weyrauch, P., Dong, X. and Himmelberg, A.M., 2016. Anaerobic degradation of benzene and polycyclic aromatic hydrocarbons. *Journal of molecular microbiology and biotechnology*, *26*(1-3), pp.92-118.

[43] Moreno-Ulloa, A., Sicairos Diaz, V., Tejeda-Mora, J.A., Macias Contreras, M.I., Castillo, F.D., Guerrero, A., Gonzalez Sanchez, R., Mendoza-Porras, O., Vazquez Duhalt, R. and Licea-Navarro, A., 2020. Chemical profiling provides insights into the metabolic machinery of hydrocarbon-degrading deep-sea microbes. *Msystems*, *5*(6), pp.10-1128.

[44] Muthal, A.P., 2017. *Study of Selectivity in Extraction, Separation, and Detection on Drugs Using Gas Chromatography*. Seton Hall University.

[45] Ojuederie, O.B. and Babalola, O.O., 2017. Microbial and plant-assisted bioremediation of heavy metal polluted environments: a review. *International journal of environmental research and public health*, *14*(12), p.1504.

[46] Okoh, A.I., 2003. Biodegradation of Bonny light crude oil in soil microcosm by some bacterial strains isolated from crude oil flow stations saver pits in Nigeria. *African journal of biotechnology*, *2*(5), pp.104-108.

[47] Overholt, W.A., Marks, K.P., Romero, I.C., Hollander, D.J., Snell, T.W. and Kostka, J.E., 2016. Hydrocarbon-degrading bacteria exhibit a species-specific response to dispersed oil while moderating ecotoxicity. *Applied and Environmental Microbiology*, *82*(2), pp.518-527.

[48] Parra-Barraza, H., Hernández-Montiel, D., Lizardi, J., Hernández, J., Urbina, R.H. and Valdez, M.A., 2003. The zeta potential and surface properties of asphaltenes obtained with different crude oil/n-heptane proportions☆. *Fuel*, *82*(8), pp.869-874.

[49] Peixoto, R., Chaer, G.M., Carmo, F.L., Araújo, F.V., Paes, J.E., Volpon, A., Santiago, G.A. and Rosado, A.S., 2011. Bacterial communities reflect the spatial variation in pollutant levels in Brazilian mangrove sediment. *Antonie Van Leeuwenhoek*, *99*(2), pp.341-354.

[50] Rahman, K.S., Rahman, T.J., Kourkoutas, Y., Petsas, I., Marchant, R. and Banat, I.M., 2003. Enhanced bioremediation of n-alkane in petroleum sludge using bacterial consortium amended with rhamnolipid and micronutrients. *Bioresource technology*, *90*(2), pp.159-168.

[51] Rambeloarisoa, E., Rontani, J.F., Giusti, G., Duvnjak, Z. and Bertrand, J.C., 1984. Degradation of crude oil by a mixed population of bacteria isolated from sea-surface foams. *Marine Biology*, *83*(1), pp.69-81.

[52] Rivers, A.R., Sharma, S., Tringe, S.G., Martin, J., Joye, S.B. and Moran, M.A., 2013. Transcriptional response of bathypelagic marine bacterioplankton to the Deepwater Horizon oil spill. *The ISME journal*, *7*(12), pp.2315-2329.

[53] Ron, E.Z. and Rosenberg, E., 2014. Enhanced bioremediation of oil spills in the sea. *Current Opinion in biotechnology*, *27*, pp.191-194.

[54] Sajna, K.V., Sukumaran, R.K., Gottumukkala, L.D. and Pandey, A., 2015. Retracted: Crude oil biodegradation aided by biosurfactants from Pseudozyma sp. NII 08165 or its culture broth.

[55] Sakari, M., 2012. *Depositional history of polycyclic aromatic hydrocarbons: reconstruction of petroleum pollution record in Peninsular Malaysia*. IntechOpen.

[56] Scally, K., 2005. The use of forensic polycyclic aromatic hydrocarbon signatures and Compound Ratio Analysis Techniques (CORAT) for the source characterisation of petrogenic/pyrogenic environmental releases.

[57] Sharma, P., 2022. Microbial communication during bioremediation of polyaromatic hydrocarbons. *Systems Microbiology and Biomanufacturing*, *2*(3), pp.430-444.

[58] Sikkema, J.A.N., de Bont, J.A. and Poolman, B., 1995. Mechanisms of membrane toxicity of hydrocarbons. *Microbiological reviews*, *59*(2), pp.201-222.

[59] Singh, A. and Ward, O.P. eds., 2004. *Applied bioremediation and phytoremediation* (Vol. 1). Springer Science & Business Media.

[60] Speight, J.G., 2014. *Handbook of offshore oil and gas operations*. Elsevier.

[61] Speight, J.G., 2019. *Handbook of industrial hydrocarbon processes*. Gulf Professional Publishing.

[62] Speight, S.L., 2007. Internalized racism: One more piece of the puzzle. *The Counseling Psychologist*, *35*(1), pp.126-134.

[63] Steliga, T., 2012. Role of Fungi in biodegradation of petroleum hydrocarbons in drill waste. *Polish Journal of Environmental Studies*, *21*(2).

[64] Suryawanshi, T., Yelmar, R., Peter, S., Sequiera, C., Johnson, S., Dutt, G., Babu, B. and Martina, P., 2021. Utilisation of oil-based waste for biosurfactant production. *International Journal of Environment and Sustainable Development*, *20*(1), pp.89-104.

[65] Uad, I., Silva-Castro, G.A., Pozo, C., González-López, J. and Calvo, C., 2010. Biodegradative potential and characterization of bioemulsifiers of marine bacteria isolated from samples of seawater, sediment and fuel extracted at 4000 m of depth (Prestige wreck). *International Biodeterioration& Biodegradation*, *64*(6), pp.511-518.

[66] US Department of Health and Human Services, 1999. Agency for Toxic Substances and Disease Registry-ATSDR.

[67] Van Hamme, J.D., Singh, A. and Ward, O.P., 2003. Recent advances in petroleum microbiology. *Microbiology and molecular biology reviews*, *67*(4), pp.503-549.

[68] Varjani, S.J. and Upasani, V.N., 2016. Biodegradation of petroleum hydrocarbons by oleophilic strain of Pseudomonas aeruginosa NCIM 5514. *Bioresource technology*, *222*, pp.195-201.

[69] Varjani, S.J. and Upasani, V.N., 2017. Crude oil degradation by Pseudomonas aeruginosa NCIM 5514: Influence of process parameters. *Indian Journal of Experimental Biology*, *55*(7), pp.493-497.

[70] Varjani, S.J., Joshi, R.R., Senthil Kumar, P., Srivastava, V.K., Kumar, V., Banerjee, C. and Praveen Kumar, R., 2017. Polycyclic aromatic hydrocarbons from petroleum oil industry activities: effect on human health and their biodegradation. In *Waste bioremediation* (pp. 185-199). Singapore: Springer Singapore.

[71] Varjani, S.J., Rana, D.P., Bateja, S., Sharma, M.C. and Upasani, V.N., 2014. Screening and identification of biosurfactant (bioemulsifier) producing bacteria from crude oil contaminated sites of Gujarat, India. *Int J Inno Res SciEngTechnol*, *3*(2).

[72] Varjani, S.J., Rana, D.P., Jain, A.K., Bateja, S. and Upasani, V.N., 2015. Synergistic ex-situ biodegradation of crude oil by halotolerant bacterial consortium of indigenous strains isolated from on shore sites of Gujarat, India. *International Biodeterioration& Biodegradation*, *103*, pp.116-124.

[73] Vidali, M., 2001. Bioremediation an overview. *Pure and applied chemistry*, *73*(7), pp.1163-1172.

[74] Vieira, P.A., Vieira, R.B., De França, F.P. and Cardoso, V., 2007. Biodegradation of effluent contaminated with diesel fuel and gasoline. *Journal of Hazardous Materials*, *140*(1-2), pp.52-59.

[75] Waigi, M.G., Wang, J., Yang, B., Gudda, F.O., Ling, W., Liu, J. and Gao, Y., 2019. Endophytic bacteria in in planta organopollutant detoxification in crops. *Reviews of Environmental Contamination and Toxicology Volume 252*, pp.1-50.

[76] Walker, T.R., 2018. Effectiveness of the national pollutant release inventory as a policy tool to curb atmospheric industrial emissions in Canada. *PeerJ Preprints*, *6*, p.e27372v1.

[77] Wang, S., Cheng, F. and Guo, S., 2023. Highly efficient screening and optimal combination of functional isolates for bioremediation of hydrocarbon-polluted soil. *Environmental Research*, *219*, p.115064.

[78] Ward, C.P. and Overton, E.B., 2020. How the 2010 Deepwater Horizon spill reshaped our understanding of crude oil photochemical weathering at sea: a past, present, and future perspective. *Environmental Science: Processes & Impacts*, *22*(5), pp.1125-1138.

[79] Wartell, B., Boufadel, M. and Rodriguez-Freire, L., 2021. An effort to understand and improve the anaerobic biodegradation of petroleum hydrocarbons: A literature review. *International Biodeterioration& Biodegradation*, *157*, p.105156.

[80] Weissman, J.G., Kessler, R.V., Sawicki, R.A., Belgrave, J.D.M., Laureshen, C.J., Mehta, S.A., Moore, R.G. and Ursenbach, M.G., 1996. Down-hole catalytic upgrading of heavy crude oil. *Energy & fuels*, *10*(4), pp.883-889.

[81] Widdel, F. and Rabus, R., 2001. Anaerobic biodegradation of saturated and aromatic hydrocarbons. *Current opinion in biotechnology*, *12*(3), pp.259-276.

[82] Wiedemeier, T.H., Wilson, J.T., Kampbell, D.H., Miller, R.N. and Hansen, J.E., 1995. Technical Protocol for Implementing Intrinsic Remediation with Long-Term Monitoring for Natural Attenuation of Fuel Contamination Dissolved in Groundwater. Volume II.

[83] Wilkes, H., Buckel, W., Golding, B.T. and Rabus, R., 2016. Metabolism of hydrocarbons in n-alkane-utilizing anaerobic bacteria. *Journal of molecular microbiology and biotechnology*, *26*(1-3), pp.138-151.

[84] Williams, S.D., Ladd, D.E. and Farmer, J.J., 2006. *Fate and transport of petroleum hydrocarbons in soil and ground water at Big South Fork National River and Recreation Area, Tennessee and Kentucky, 2002-2003* (pp. 2005-5104). Washington, DC, USA: US Department of the Interior, US Geological Survey.

[85] Wu, Y., Zhang, J., Mi, T.Z. and Li, B., 2001. Occurrence of n-alkanes and polycyclic aromatic hydrocarbons in the core sediments of the Yellow Sea. *Marine Chemistry*, *76*(1-2), pp.1-15.

[86] Xue, J., Yu, Y., Bai, Y., Wang, L. and Wu, Y., 2015. Marine oil-degrading microorganisms and biodegradation process of petroleum hydrocarbon in marine environments: a review. *Current microbiology*, *71*(2), pp.220-228.

[87] Zhao, J., Li, Y., Yang, G., Jiang, K., Lin, H., Ade, H., Ma, W. and Yan, H., 2016. Efficient organic solar cells processed from hydrocarbon solvents. *Nature Energy*, *1*(2), pp.1-7.