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CRUDE OIL DEGRADATION POTENTIAL BY HYDROCARBON-UTILIZING MICROBES: A REVIEW

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ABSTRACT

Globally, environmental pollution by crude oil is one of the most frequently encountered problem faced by the world today as a result of industrial activities, oil spill, and accidental occurrence, among others. Primarily, crude oil are composed of hydrocarbons, which are molecules composed of only carbon and hydrogen atoms. This review aim to present the indispensable role played by hydrocarbon-utilizing microorganisms in the degradation of crude oil, thereby reducing their pollution in the environment. The degradation of hydrocarbon is a complex action primarily mediated by microorganisms that utilize hydrocarbons as carbon sources via employing series of enzymatic pathways to break down these otherwise persistent environmental pollutants. Beyond enzymatic actions, biofilm formation and biosurfactants production are among the mechanisms used in these crude oil degradation. Microorganisms, including Penicillium, Nocardia, Aspergillus, Corynebacterium, Pseudomonas and Bacillus species are among the most frequently reported microorganisms capable of degrading crude oil pollutants. Several factors which influences these microbial action such as pH, inhibitors, nutrients availability, moisture and temperature always limits these degradation process. As reported by many scholars, bioremediation of crude oil by utilizing hydrocarbon degrading microorganisms has now been employed due to their inexpensive and non-toxic nature. Thus, bioremediation of crude oil by the usage of hydrocarbon-utilizing microorganisms represents a wonderful approach for decreasing the environmental impact of crude oil. Therefore parameters such as temperature, nutrient levels and pH should be optimized to enhance biodegradation efficiency.

Keywords: Crude oil, Hydrocarbon-utilizing Microorganisms, Hydrocarbon, Enzyme, Degradation

INTRODUCTION

Crude oils are chemical substances containing a complex mixture of elements known as hydrocarbons (Aljamali and Salih, 2021; Bahzad and Rana, 2022). In many industrial aspects and our daily life activities, hydrocarbon-based products are among the major source of energy for normal functioning of these processes. One of the major source of soil and water pollution is the release or deposit of hydrocarbon containing substances such as crude oil into the soil and water bodies through human (anthropogenic) activities or by accident (Ossai *et al*., 2020). The spill of hydrocarbons including crude oil products (e.g., petroleum) frequently occurs through actions such as leak in tanks and accidents during the recovery, exploration, refining, production, storage, and transportation of these hydrocarbon products (Narayanan *et al*., 2023). Over hundreds of years ago, as documented by Elijah. (2022), these hydrocarbon based products are among the most commonly occurring environmental pollutants. Therefore, given the widespread awareness of environmental and health risks associated with crude oil and its byproducts, it is logical that public concerns about contamination have influenced the current perception of hydrocarbons. The accumulation of hydrocarbons in the soil environments has been known to cause extensive damage to the soil microbiomes, animals and also plants, which may lead to death or mutations of affected species (Mekonnen *et al*., 2024).

Some of the prominent technologies usually used for the remediation of hydrocarbon contaminated soils includes soil washing, filtration, dispersion, and evaporation among others. However, the expensive and non-friendly nature of these technologies has limited their applications (Ali, 2024). Therefore, bioremediation as an inexpensive and environmental friendly technological approach which involves the utilization of microorganisms to remove or detoxify pollutants from the environment has come to overtake those technologies (Sokal *et al*., 2022). As reported by Alkan *et al*. (2023), in the year 1946 AD, one of the most prominent scientists in the field of petroleum microbiology by the name Claude E. ZoBell examined the interactions between microorganisms and hydrocarbons. He then found out that, many microbes possess the potential to utilize hydrocarbons and other hydrocarbon containing products as their sole source of carbon and energy. Therefore, hydrocarbons which are present in the environment can be biodegraded primarily by microorganisms including fungi, bacteria, and yeasts (Gaur *et al*., 2022; Mahmud *et al*., 2022).

Many scholars reported the percentage efficacy of these microorganisms on the biodegradation of hydrocarbons. For example, soil bacteria were found to possess hydrocarbon biodegradation efficiency ranging from 0.13% to 50%. Also, for fungi, it was found to have the efficiency ranging from 6% to 82% (Mahmoud *et al*., 2019). Biodegradation by microorganisms represents one of the primary bioremediation method by which crude oil and other hydrocarbon pollutants can be removed or detoxify from the contaminated environment at a cheaper rate as compared to other remediation technologies (Amran *et al*., 2022). The biological and chemical influenced changes in the composition of hydrocarbons are generally referred to as weathering. Degradation processes by microorganisms plays a significant impact in this weathering process (Mutshow, 2023).

Microorganisms, namely *Acinetobacter, Alcaligens, Arthrobacter, Aspergillus, Bacillus, Burkholderia, Corynebacterium, Micrococcus, Penicillium, Pseudomonas,* and *Rhodococcus* species are among the most potent microorganisms having the potential of degrading crude oil and other hydrocarbon based products (Amran *et al*., 2022; Kumar *et al*., 2025). Hydrocarbons vary in their vulnerability to microbial degradation, with a general ranking from the most to least susceptible; Linear alkanes > Branched alkanes > small aromatics > Cyclic alkanes. This ranking reflects the relative ease with which microorganisms can break down different types of hydrocarbons (Oyediran, 2022). The degradation of hydrocarbon mixtures is majorly influenced by the type/nature of the oil, the composition of the microbial community, and various environmental factors that impact microbial activity. Furthermore, a key factor limiting the biodegradation of oil pollutants is the limited accessibility of nutrients by microorganisms (Kebede *et al*., 2021; Sun *et al*., 2021). This review aim to provide context and establish a factual foundation regarding the role of hydrocarbon-utilizing microorganisms in the biodegradation of crude oil pollutants in the environment.

MATERIALS AND METHODS

Crude Oil

Crude oil is a naturally occurring, unrefined petroleum product composed of hydrocarbon deposits and other organic materials (Aljamali and Salih, 2021; Hedgpeth *et al*., 2021). This oil is formed from the remains of ancient marine organisms such as plankton and algae, which were buried under layers of sediment and rock, and were subjected to intense heat and pressure over millions of years. This transformation results in a thick, dark liquid with a complex composition that varies depending on the geological conditions of its source (Qi *et al*., 2023). Crude oil serves as the raw material for a vast range of products. Through the process of fractional distillation in refineries, crude oil is separated into various components based on boiling points. These fractions include gasoline, diesel, jet fuel, lubricating oils, waxes, and petrochemical feedstocks used to produce plastics, fertilizers, and pharmaceuticals (Aljamali and Salih, 2021).

Oil-exporting countries, particularly in the Middle East, West Africa, South America, rely heavily on crude oil revenues to fund national budgets and development projects (Steadman *et al*., 2023). Countries like Nigeria, Saudi Arabia, and Venezuela have historically derived the majority of their foreign exchange earnings from crude oil exports. However, this dependence can be a double-edged sword; fluctuations in oil prices can lead to economic instability and budget deficits (Cai *et al*., 2024). Oil transportation through pipelines and tankers poses additional risks of leaks and spills, which can contaminate soil and water bodies for decades. Moreover, the socio-environmental consequences are particularly acute in regions where regulatory oversight is weak (Ossai *et al*., 2020). In the Niger Delta region of Nigeria, for instance, oil extraction has led to chronic pollution, loss of livelihoods, and health issues among local communities (Gbadamosi and Aldstadt, 2025). Soil as found to be one of the most endangered environment usually exposed to crude oil contamination is shown in figure 1.

Figure 1: Contaminated Soil Environment Due to Crude Oil Pollution
Source: Abioye. (2011)

Composition of Crude Oil

The primary constituents of crude oil are hydrocarbons, which are molecules composed solely of hydrogen and carbon atoms. These hydrocarbons can be classified into four main types: alkanes (paraffins), cycloalkanes (naphthenes), aromatics, and alkenes (olefins) (Bahzad and Rana, 2022). Alkanes are saturated hydrocarbons and represent the largest fraction in most crude oils, consisting of straight-chain or branched molecules. Naphthenes, a saturated cyclic hydrocarbons, are also a significant component and contribute to the stability and density of crude oil (Binhazzaa, 2024). Aromatics, such as benzene, toluene, and xylene, are unsaturated cyclic hydrocarbons known for their ring structures and are present in varying concentrations depending on the source of the crude oil. Although alkenes are generally unstable in crude oil, they can form during processing or degradation. These hydrocarbons vary in molecular weight and boiling point, contributing to the physical characteristics of different crude oils (Karishma et al., 2024).

In addition to hydrocarbons, crude oil contains a range of non-hydrocarbon compounds, which are typically found in smaller quantities but have significant implications for refining and environmental impact. These include sulfur, nitrogen, oxygen, and trace metals such as vanadium, nickel, iron, and copper (Dey et al., 2024). Furthermore, crude oil can also harbor volatile organic compounds (VOCs) such as benzene, toluene, ethylbenzene, and xylene (collectively known as BTEX). BTEX compounds are often released during oil spills, drilling operations, and refining activities, and they are rapidly absorbed in biological systems, where they affect the central nervous system, liver, and kidneys (Das et al., 2024). Regulatory bodies such as the U.S. Environmental Protection Agency (EPA) and the World Health Organization (WHO) have established stringent guidelines for BTEX levels in air and water due to their health implications.

Hydrocarbon Utilizing Microorganisms (HUMs)

Hydrocarbon-Utilizing Microorganisms (HUMs), also known as hydrocarbonoclastic microorganisms, are diverse group of bacteria, fungi, and yeasts which are capable of metabolizing hydrocarbons as their sole source of carbon and energy (Gouthami et al., 2023; Gyasi et al., 2024). These microorganisms play a crucial role in the natural attenuation and bioremediation of hydrocarbon-contaminated environments such as oil-polluted soils, aquatic systems, and sediments. The metabolic versatility of HUMs allows them to degrade a wide range of hydrocarbon compounds, including alkanes, cycloalkanes, aromatic hydrocarbons, and polycyclic aromatic hydrocarbons (PAHs) (Chunyan et al., 2023). Some of the most studied hydrocarbon-degrading bacteria include Pseudomonas, Alcanivorax, Acinetobacter, Rhodococcus, Mycobacterium, and Bacillus species. Fungi such as Aspergillus, Penicillium, and Candida also exhibit hydrocarbon-degrading capabilities (Kumar et al., 2025). These organisms produce enzymes like oxygenases and peroxidases that initiate the breakdown of complex hydrocarbons by introducing oxygen into the hydrocarbon structure, thereby, increasing their solubility and facilitating further degradation (Fouad et al., 2022).

HUMs are not only important for environmental remediation but also serve as model organisms for studying microbial adaptation to extreme environments and pollutant stress (Rahmati et al., 2022) The application of HUMs in bioremediation technologies has shown promising results in cleaning up oil spills and restoring polluted habitats. Advances in molecular biology and omics technologies have provided deeper insights into the genetic and functional diversity of HUMs, enabling the identification of novel hydrocarbon-degrading genes and regulatory pathways. Genetic engineering is also being explored to enhance the hydrocarbon-degrading capabilities of specific microbial strains (Mishra et al., 2021). As the demand for eco-friendly and cost-effective remediation strategies grows, HUMs remain at the forefront of environmental biotechnology, offering sustainable solutions to hydrocarbon pollution while contributing to our understanding of microbial ecology and metabolism. Hydrocarbon utilizing microorganisms (HUMs) represent a crucial group of microbes involved in the biodegradation and bioremediation of hydrocarbon-contaminated environments, with bacteria, fungi, and actinomycetes being the most prominent classes (Sui et al., 2021; Purmar et al., 2024).

Bacteria

Bacteria constitute the most diverse and metabolically active class of hydrocarbon utilizing microorganisms, playing a central role in the biodegradation of petroleum hydrocarbons and related pollutants in both terrestrial and aquatic ecosystems (Parmar et al., 2024). These microorganisms possess a remarkable ability to metabolize a wide range of hydrocarbon compounds, including alkanes, aromatics, cycloalkanes, and polycyclic aromatic hydrocarbons (PAHs), using them as sources of carbon and energy (Fouad et al., 2022). The most prominent bacterial classes involved in hydrocarbon degradation include Gammaproteobacteria, Alphaproteobacteria, Betaproteobacteria, and Actinobacteria. Genera such as Pseudomonas, Alcanivorax, Marinobacter, Acinetobacter, and Rhodococcus have been extensively studied for their potent hydrocarbon-degrading capabilities (Gidudu and Chirwa, 2022).

These bacteria utilize specialized enzymatic systems such as alkane monooxygenases, and aromatic ring-hydroxylating dioxygenases to catalyze the initial activation of inert hydrocarbon molecules, typically converting them into alcohols, aldehydes, and acids that can enter central metabolic pathways like the tricarboxylic acid (TCA) cycle (Kumari and Das, 2023). The degradation process is predominantly aerobic, as the terminal electron acceptor; however, some bacteria can also degrade hydrocarbons under anaerobic conditions using alternative electron acceptors such as nitrate, sulfate, or iron (Wartell et al., 2021).

Many hydrocarbon-degrading bacteria also produce biosurfactants, thereby, increasing the bioavailability of hydrophobic hydrocarbon substrates. For example, Pseudomonas aeruginosa produces rhamnolipids that enhance the emulsification and uptake of oil droplets (Sah et al., 2022). Additionally, bacterial consortia are often more effective than single strains in degrading complex mixtures of hydrocarbons, owing to their complementary metabolic pathways (Zhang and Zhang, 2022) The adaptability, metabolic diversity, and ecological resilience of hydrocarbon-degrading bacteria make them indispensable agents in natural and engineered bioremediation processes aimed at restoring polluted environments (Chicca et al., 2022; Alaidaroos, 2023).

Fungi

Fungi as an important agent, also play a crucial role as a class of hydrocarbon utilizing microorganisms, particularly in the biodegradation of complex and recalcitrant hydrocarbons such as polycyclic aromatic hydrocarbons (PAHs), heavy crude oil fractions, and other high-molecular-weight petroleum contaminants (Alao and Adebayo, 2022). Unlike bacteria, which primarily rely on intracellular enzymatic pathways for hydrocarbon metabolism, fungi employ a unique extracellular degradation mechanism facilitated by oxidative enzymes such as lignin peroxidase (LiP), manganese peroxidase (MnP), and laccase (Al-Zaban et al., 2021). These enzymes, secreted by fungi including Aspergillus, Penicillium, Fusarium, and Trichoderma enable them to break down highly persistent hydrocarbon pollutants that are otherwise resistant to bacterial degradation (Rezaei and Moghimi, 2024).

In addition to enzymatic degradation, fungi also exhibit a high affinity for hydrocarbon sorption due to their filamentous growth and hydrophobic cell wall components, which enhance hydrocarbon uptake and bioavailability (Wu et al., 2023). Hydrocarbon degradation by fungi is particularly advantageous in acidic or nutrient-deficient environments, where bacterial activity is often limited. Additionally, fungal mycelial networks allow for extensive colonization of hydrocarbon-contaminated soils and sediments, increasing the surface area for hydrocarbon metabolism and promoting bioaugmentation in bioremediation strategies (Yin et al., 2023). Due to their robust enzymatic capabilities, adaptability, and ability to thrive in harsh environmental conditions, fungi serve as vital agents in the bioremediation of petroleum-contaminated ecosystems, offering sustainable and effective solutions for the breakdown of persistent organic pollutants (Al-Zaban et al., 2021; Wu et al., 2023).

Actinomycetes

Actinomycetes represent a distinct and ecologically significant class of hydrocarbon utilizing microorganisms, characterized by their filamentous morphology, Gram-positive cell wall structure, high G+C content in their DNA, and remarkable metabolic versatility (Devanshi et al., 2021). Belonging primarily to the order Actinomycetales within the phylum Actinobacteria, these microorganisms bridge the morphological and functional traits of both bacteria and fungi, enabling them to thrive in a wide range of environmental conditions, including extreme and hydrocarbon-polluted habitats (Kumar et al., 2022). Notable genera such as Rhodococcus, Nocardia, Gordonia, and Streptomyces have demonstrated strong capabilities in degrading a variety of hydrocarbon compounds, including straight-chain alkanes, branched alkanes, aromatic hydrocarbons, and complex polycyclic aromatic hydrocarbons (PAHs) (Reineke and Schlömann, 2023).

Actinomycetes possess diverse catabolic enzymes such as alkane hydroxylases, cytochrome P450 monooxygenases, and ring-cleaving dioxygenases, which facilitate the oxidation and cleavage of hydrocarbon structures into less toxic and more biodegradable intermediates (Rusănescu et al., 2024). These enzymes enable actinomycetes to initiate and sustain the breakdown of persistent hydrocarbons under both aerobic and, in some cases, microaerophilic conditions. Their ability to form resistant spores and withstand environmental stress makes them particularly valuable in long-term bioremediation efforts, especially in arid or nutrient-limited environments where other microbial groups may not survive (Goswami et al., 2025). The unique metabolic and physiological attributes of actinomycetes not only make them efficient hydrocarbon degraders but also highlight their potential in developing innovative biotechnological applications for environmental cleanup, particularly in the bioremediation of complex and recalcitrant petroleum pollutants (Makarani and Kaushal, 2025).

Mechanisms of Hydrocarbon Degradation

Hydrocarbon degradation is a complex and dynamic process mediated primarily by microorganisms that utilize hydrocarbons as sources of carbon and energy, employing a series of enzymatic pathways to break down these otherwise persistent environmental pollutants (Fouad et al., 2022; Gyasi et al., 2024). Under aerobic conditions, the degradation of hydrocarbons is initiated by oxygenase enzymes (particularly monooxygenases and dioxygenases) which introduce molecular oxygen into the hydrocarbon structure, thereby, forming alcohols, aldehydes, and subsequently carboxylic acids that enter into the central metabolic pathways like the tricarboxylic acid (TCA) cycle (Dyes, 2023). In contrast, anaerobic degradation operates under anoxic conditions, relying on alternative electron acceptors such as nitrate, sulfate, iron (III), or carbon dioxide. Anaerobic pathways typically begin with the activation of hydrocarbons via fumarate addition or carboxylation, catalyzed by enzymes like benzylsuccinate synthase and methyl-coenzyme M reductase, leading to intermediate metabolites processed through reductive pathways (Boll et al., 2022).

Beyond enzymatic action, microbial colonization of hydrocarbon-contaminated environments often involves biofilm formation. Biofilms allow for close microbial interaction and more effective substrate utilization, particularly in recalcitrant hydrocarbon matrices (Sonawane et al., 2022). Moreover, many hydrocarbon-degrading microbes produce biosurfactants such as rhamnolipids, sophorolipids, and lipopeptides that significantly increase the bioavailability of hydrophobic hydrocarbon compounds (Ali and Wang, 2021). The synergistic interaction between these biochemical and physiological strategies collectively underpins the microbial efficacy in hydrocarbon bioremediation and highlights the versatility of microbial metabolism in adapting to diverse environmental constraints (Zainab et al., 2023).

Enzymatic Pathways

As stated by Saravanan et al. (2021), enzymatic pathways are central to the microbial degradation of hydrocarbons by enabling microorganisms to utilize hydrocarbons as carbon and energy sources in diverse environmental conditions. In the case of aliphatic hydrocarbons, enzymes like alkane monooxygenase and alkane dioxygenase play an indispensable role in the oxidation of straight-chain and branched alkanes. These enzymes catalyze the incorporation of one or two oxygen atoms into the carbon-hydrogen bonds of the alkane, producing alcohols or aldehydes, which are further metabolized through subsequent enzymatic steps to yield carboxylic acids, which then enter the microbial cell's central metabolic pathways (Redice, 2022). Aromatic hydrocarbons, which are more structurally complex and resistant to degradation, require a different set of enzymatic systems, primarily dioxygenases such as toluene dioxygenase. These enzymes initiate the cleavage of the aromatic ring, creating intermediates such as catecholate and methylcatechol, which are subsequently converted into intermediates that can enter the TCA cycle for further energy production (Dyes, 2023)

Additionally, microorganisms possess specialized enzymes like monooxygenases and dioxygenases capable of degrading halogenated hydrocarbons, commonly found in polluted environments (Bhandari et al., 2023). The degradation process typically involves a series of coordinated reactions, where enzymes such as hydrolases, reductases, dehydrogenases, and transferases act sequentially to further oxidize and break down hydrocarbon intermediates. The ability of microorganisms to degrade hydrocarbons through enzymatic pathways is enhanced by the presence of inducible enzyme systems that are activated when hydrocarbons are available in the environment (Saravanan et al., 2021). The synergy of these enzymatic pathways allows for the effective breakdown of a wide range of hydrocarbons, facilitating the conversion of these persistent pollutants into non-toxic byproducts, such as water and carbon dioxide (Alaidaroos, 2023).

Aerobic Degradation

Aerobic degradation of hydrocarbons is a highly efficient microbial process in which microorganisms utilize molecular oxygen to oxidize hydrocarbons, transforming them into less harmful products such as carbon dioxide and water (Salari et al., 2022). This process is central to the bioremediation of hydrocarbon pollutants in oxygen-rich environments like soils, waters, and sediments exposed to atmospheric oxygen (Kebede et al., 2021). The key to aerobic hydrocarbon degradation lies in the ability of microorganisms to possess or induce specific oxygenases, which are enzymes that catalyze the incorporation of oxygen atoms into hydrocarbon molecules, making them more reactive and easier to metabolize (Dyes, 2023).

One of the first enzymes involved in aerobic degradation is alkane monooxygenase, which activates aliphatic hydrocarbons such as alkanes by adding an oxygen atom to the carbon-hydrogen bonds (Schultes et al., 2024). This activation converts the alkane into a hydroxylated alcohol intermediate, which is subsequently oxidized to a corresponding aldehyde and carboxylic acid by aldehyde dehydrogenase and alcohol dehydrogenase enzymes. The energy derived from these catabolic processes supports microbial growth and sustains cellular activities (Chunyan et al., 2023). Oxygen availability is critical in aerobic degradation, and microbial systems have evolved mechanisms to optimize oxygen consumption, such as enhancing oxygen diffusion through the production of surfactants or through the formation of biofilms that concentrate microbial communities around the contaminant (Kebede et al., 2021). Aerobic mechanisms are fundamental to the microbial breakdown of hydrocarbons in polluted environments, contributing significantly to the natural attenuation of contaminants and supporting environmental cleanup efforts through bioremediation (Chunyan et al., 2023). Figure 2 illustrates the aerobic biodegradation pathway of crude oil hydrocarbon contaminants by microorganisms.

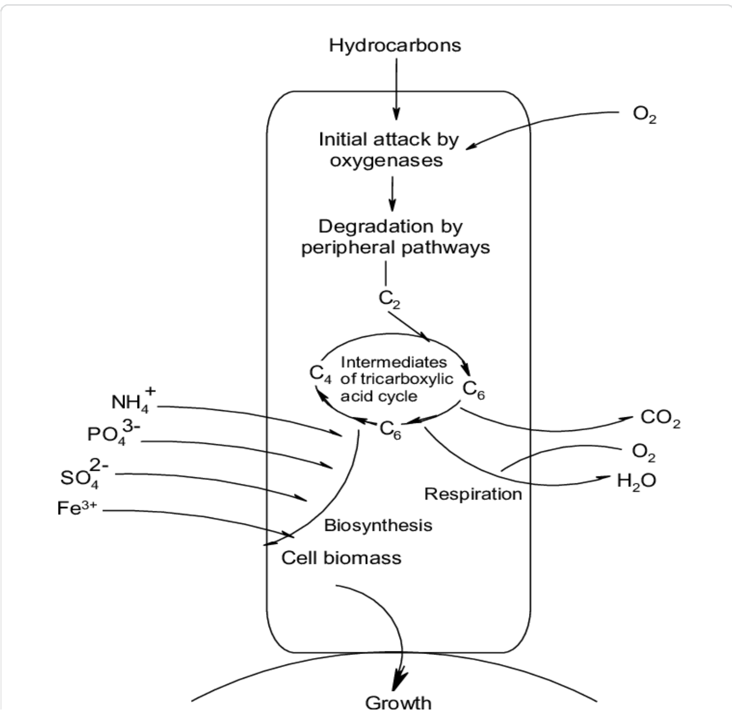

Figure 2: The Biodegradation of Crude Oil Hydrocarbon by Microorganisms under Aerobic Environment
Source: Olajire and Essien (2014)

Anaerobic Degradation

Anaerobic degradation of hydrocarbons is also an important mechanism for the microbial breakdown of hydrocarbons in oxygen-depleted environments, such as deep soils, marine sediments, and groundwater, where oxygen is either absent or present in minimal concentrations (Dhar *et al*., 2020). In contrast to aerobic degradation, which relies on molecular oxygen as the primary electron acceptor, anaerobic hydrocarbon degradation involves a range of alternative electron acceptors, such as nitrate, sulfate, carbon dioxide, and ferric iron (Boll *et al*., 2022).

The process of anaerobic degradation is initiated by the activation of hydrocarbons through various enzymatic reactions that do not require oxygen (Boll *et al*., 2020). For example, in the degradation of aliphatic hydrocarbons, microorganisms use enzymes like alkylsulfate reductases or fumarate addition reactions to activate the hydrocarbons (Koh and Khor, 2023). In this process, the alkyl group of the hydrocarbon is added to fumarate or another organic electron acceptor, forming products such as alkylsuccinate. These intermediates are subsequently metabolized through reductive pathways, such as the β-oxidation of fatty acids or other anaerobic pathways, ultimately leading to the generation of simpler compounds that enter central metabolic cycles, like the TCA cycle (Heker *et al*., 2025).

A key feature of anaerobic hydrocarbon degradation is the coupling of these biochemical reactions to the reduction of electron acceptors, such as sulfate or nitrate (Wartell *et al*., 2021). In sulfate-reducing environments, for example, sulfate-reducing bacteria (SRB) play a vital role by reducing sulfate to hydrogen sulfide, utilizing the energy from the hydrocarbon degradation to drive this reduction process (Gao and Fan, 2023). Furthermore, the degradation of hydrocarbons in anaerobic conditions is often slower than in aerobic conditions, due to the complexity of the metabolic pathways and the lower energy yield from electron acceptor reduction. Nonetheless, anaerobic hydrocarbon degradation is a key process in environments where oxygen is limited, enabling microorganisms to metabolize hydrocarbons in the absence of oxygen (Wartell *et al*., 2021). Anaerobic degradation pathways employed by microorganisms in biodegrading toluene (an essential component of crude oil) in anoxic environment is presented in figure 3 below.

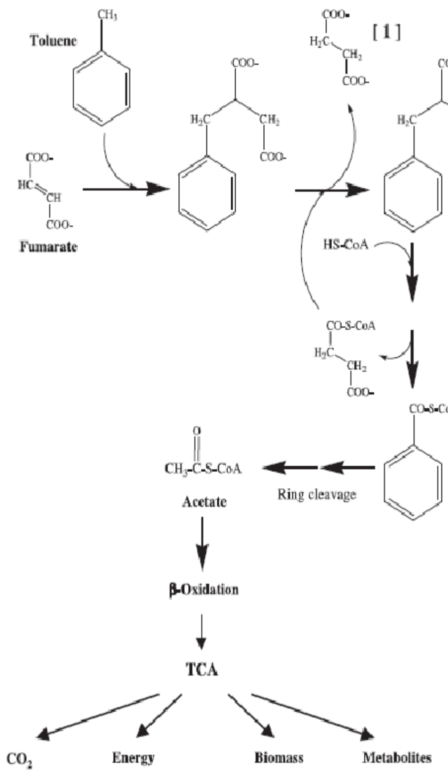

Figure 3: Biodegradation of Toluene in Crude Oil in an Oxygen Depleted Environment by Anaerobic Microorganisms
Source: Hassanshahian and Cappello (2013)

Biofilm Formation

A biofilm is a structured community of microorganisms embedded in a self-produced extracellular matrix of polysaccharides, proteins, lipids, and nucleic acids, which adheres to solid surfaces such as soil particles, rocks, sediments, or oil droplets in water (Saini *et al*., 2023). In the context of hydrocarbon degradation, biofilm formation provides several advantages that support microbial survival and enhance the efficiency of biodegradation processes. One of the key benefits of biofilm formation is the increased access to hydrocarbons (Kungwami *et al*., 2022).

In the case of aerobic hydrocarbon degradation, biofilms can create localized zones where oxygen diffusion is optimized, allowing oxygen-dependent organisms to metabolize hydrocarbons more effectively (Kumari and Das, 2023). On the other hand, in anaerobic conditions, biofilms can support the activity of sulfate-reducing bacteria, methanogens, or other anaerobes that degrade hydrocarbons using alternative electron acceptors, thus facilitating both aerobic and anaerobic degradation pathways within the same community (Castro *et al*., 2022). The synergistic relationships within biofilms are essential for the efficient degradation of complex hydrocarbons, such as those found in petroleum or crude oil spills. As a result, biofilm formation plays a vital role in natural attenuation processes and bioremediation strategies, promoting the breakdown of hydrocarbons in both aerobic and anaerobic environments (Gadkari *et al*., 2022). Figure 4 below illustrated the formation of biofilm by hydrocarbon-degrading bacteria in moist environments.

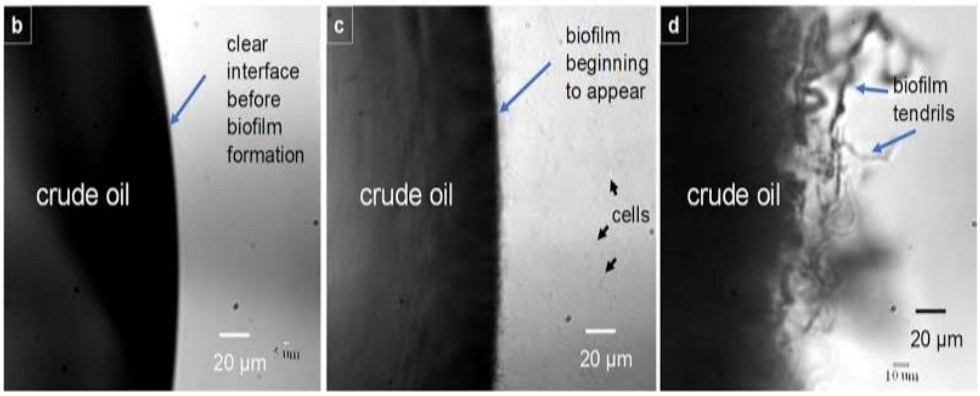

Figure 4: Formation of Biofilm by Hydrocarbon-utilizing Bacteria during the Biodegradation of Crude Oil Contaminants
Source: Omarova *et al.* (2019)

Biosurfactants Production

Biosurfactant production is a critical mechanism employed by microorganisms to enhance the degradation of hydrocarbons, particularly in environments where hydrocarbons are poorly soluble in water (Sah *et al*., 2022). Biosurfactants are surface-active compounds synthesized by microorganisms, such as bacteria, fungi, and yeasts, which possess both hydrophobic and hydrophilic properties, allowing them to lower surface and interfacial tension between water and hydrophobic substrates like hydrocarbons (Fardami *et al*., 2022). By reducing the surface tension, biosurfactants increase the bioavailability of hydrophobic compounds, making them more accessible to microbial cells for uptake and degradation. This is particularly important in the case of hydrocarbons, which are often present in a non-aqueous phase and are difficult for microorganisms to access due to their low solubility in water (Gidudu and Chirwa, 2022).

The production of biosurfactants is usually induced by the presence of hydrophobic substrates, such as oils, aliphatic hydrocarbons, or aromatic compounds, triggering the microbial synthesis of these compounds (Bhadra *et al*., 2023). The biosurfactants, which include glycolipids, lipopeptides, phospholipids, and polysaccharide-protein complexes, act by emulsifying the hydrocarbons, breaking them into smaller droplets and increasing the surface area available for microbial degradation (Chafale and Kapley, 2022). Biosurfactant production is an essential mechanism that enhances the biodegradation of hydrocarbons by increasing the accessibility of hydrophobic pollutants to microorganisms in the cleanup of hydrocarbon-contaminated environments (Selva Filho *et al*., 2023). The production of biosurfactants by crude oil degradation microbes during biodegradation of hydrocarbon is shown in figure 5.

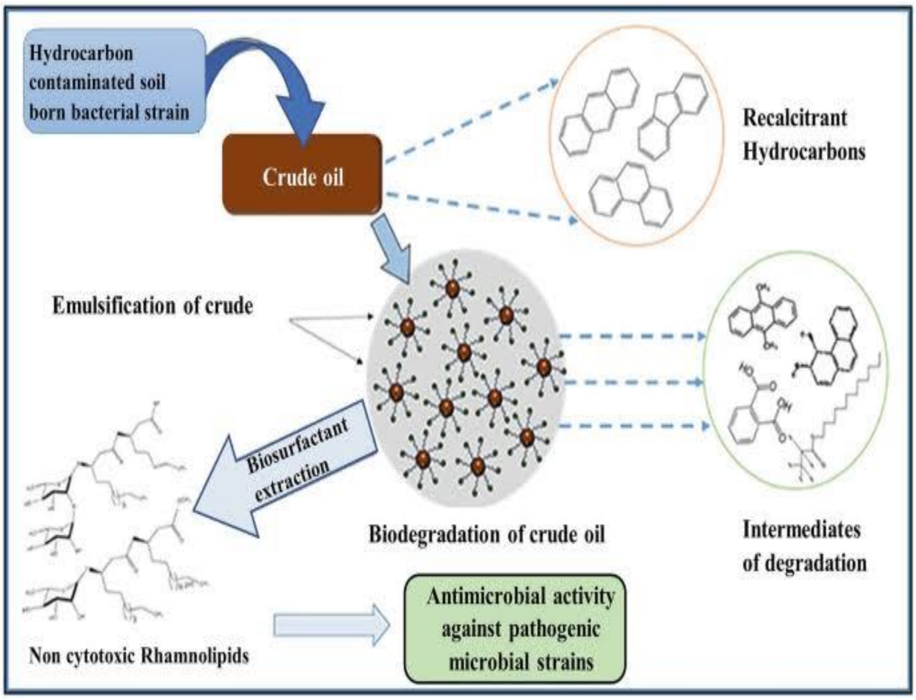

Figure 5: Production of Biosurfactants by Hydrocarbon-utilizing Microbes via Degradation of Crude Oil Pollutants
Source: Koh and Khor. (2023)

Factors Influencing Microbial Degradation

Several factors contribute to the degradation of crude oil by microorganisms. Temperature, pH, moisture content, nutrients availability, and inhibitors are one of the major contributors to the effectiveness of hydrocarbon-utilizing microbes in degrading crude oil pollutants (Kebede et al., 2021; Ganguly et al., 2023; Mekonnen et al., 2024; Strotmann et al., 2024)

pH

pH is a critical environmental factor that significantly influences the microbial degradation of hydrocarbons, with a direct impact on the activity, growth, and metabolism of microorganisms (Kebede *et al*., 2021). Most hydrocarbon-degrading bacteria and fungi thrive in neutral to slightly alkaline conditions (pH 7-8), where enzymatic systems like oxygenases, which are essential for initiating the breakdown of hydrocarbons, function optimally (Mekonnen *et al*., 2024). Acidic conditions (pH below 6) often hinder microbial activity due to the protonation of functional groups in enzymes, leading to a reduction in the efficiency of hydrocarbon degradation. In contrast, highly alkaline conditions (pH above 9) can denature microbial enzymes, impairing microbial growth and metabolism (Kebede *et al*., 2021). However, some specialized hydrocarbon-degrading microbes, such as alkaliphilic or acidophilic species, have evolved to survive and function effectively under extreme pH conditions, allowing them to participate in bioremediation processes in diverse environments (Chia *et al*., 2024).

Temperature

Microorganisms involved in hydrocarbon degradation exhibit a range of temperature optima, with mesophilic organisms typically thriving in moderate temperatures between 20°C and 40°C, where enzymatic processes are most efficient (Karishma *et al*., 2024). At these temperatures, microbial enzymes, such as oxygenases, which are crucial for the initial oxidation and breakdown of hydrocarbons, operate at optimal efficiency. However, as temperature increases beyond the optimal range, enzymatic denaturation and membrane fluidity disruption can occur, resulting in a decline in microbial activity and growth (Moon *et al*., 2023). Conversely, lower temperatures, such as those found in polar or temperate environments, can slow down microbial metabolism, thereby reducing the rate of hydrocarbon degradation (Murphy *et al*., 2021). Additionally, temperature fluctuations can lead to thermal stress, which may impact microbial community dynamics, favoring the growth of certain species over others (Sörenson *et al*., 2021).

Moisture

Microorganisms involved in the degradation of hydrocarbons require an aqueous medium for the transport of nutrients, enzymes, and electron acceptors, which are essential for metabolic processes such as hydrocarbon oxidation (Pandolfo *et al*., 2023). In environments with insufficient moisture, microbial activity is often limited due to desiccation and lack of water for enzymatic reactions. On the other hand, excessive moisture, particularly in flooded environments or waterlogged soils, can create anaerobic conditions, which can inhibit the activity of aerobic hydrocarbon-degrading microorganisms (Mishra *et al*., 2022). In such conditions, although some anaerobic bacteria are capable of degrading hydrocarbons through alternative metabolic pathways, their activity is generally less efficient, and degradation rates are slower (Wartell *et al*., 2021). The optimal moisture content varies depending on the type of hydrocarbon contamination and the microbial community involved. However, the presence of adequate water content ensures a favorable environment for microbial growth, biofilm formation, and the production of extracellular enzymes required for hydrocarbon breakdown (Chunyan *et al*., 2023).

Nutrients Availability

Nutrient availability is also one of the fundamental factor influencing the microbial degradation of hydrocarbons, as the breakdown of these complex organic compounds requires essential nutrients that support microbial growth, metabolism, and enzymatic activity (Kebede *et al*., 2021). Hydrocarbon-degrading microorganisms, like all bacteria and fungi, require a balanced supply of macronutrients such as nitrogen, phosphorus, sulfur, and trace elements like iron and magnesium to carry out their metabolic processes (Ganguly *et al*., 2023). Nitrogen and phosphorus, in particular, are often limiting factors in hydrocarbon degradation, as they are required for the synthesis of amino acids, nucleotides, and other cellular components essential for growth and enzyme production (Shabestary *et al*., 2024).

Inhibitors

Inhibitors can be either naturally occurring or anthropogenic compounds that interfere with various stages of microbial metabolisms for the degradation process (Strotmann *et al*., 2024). Heavy metals, such as mercury, cadmium, and lead, are among the most potent inhibitors of microbial hydrocarbon degradation. These metals can bind to cellular enzymes, disrupting their structure and function, thereby reducing the efficiency of degradation (Jomova *et al*., 2025). Additionally, organic pollutants like phenols, aldehydes, and other toxic by-products of hydrocarbon breakdown can accumulate in the environment and exert inhibitory effects on microbial communities. The presence of such inhibitory compounds may cause decrease in microbial populations, altered metabolic pathways, or even cell death, which decreases the rate of hydrocarbon degradation (Maqsood *et al*., 2023). In some cases, microorganisms may have evolved mechanisms to detoxify or sequester these inhibitors, such as the production of specific enzymes or the formation of biofilms that provide a protective barrier. Despite these adaptive strategies, the presence of inhibitors generally complicates bioremediation efforts, as it may require additional treatments, such as the addition of chelating agents or the application of nutrient amendments to outcompete the inhibitory compounds (Oyeyemi and Alaba, 2024).

Applications in Bioremediation

The application of microbial degradation in bioremediation includes the use of indigenous microorganisms or the introduction of engineered strains to accelerate the breakdown of toxic substances, thereby, reducing environmental hazards and restoring ecosystems. This method is cost-effective, environmentally friendly, and sustainable compared to traditional chemical cleanup techniques (Pande *et al*., 2020). Some of the applications of hydrocarbon utilizing microorganisms in the degradation of crude oil pollutants includes;

Bioaugmentation

Bioaugmentation is a critical bioremediation strategy employed to enhance the natural microbial degradation of hydrocarbons in contaminated environments (Chettri *et al*., 2024). It involves the deliberate introduction of specific microbial strains to improve the degradation rate of hydrocarbons, particularly in environments where indigenous microbial populations are insufficient or ineffective at degrading the contaminants. These microorganisms are typically selected for their ability to utilize hydrocarbons as a carbon and energy source, enabling them to break down complex organic compounds, which are prevalent in petroleum waste (Gao *et al*., 2022; Patel *et al*., 2022). The success of bioaugmentation depends on the compatibility of the introduced microbes with the environmental conditions, their ability to outcompete native microorganisms, and their persistence over time (Gao *et al*., 2022). Boaugmentation has been applied in the remediation of oil spills, thereby, offering an environmentally friendly and cost-effective solution compared to traditional physical or chemical methods (Chettri *et al*., 2024).

Biostimulation

Biostimulation process involves the addition of nutrients, such as nitrogen, phosphorus, oxygen, or trace elements, to the contaminated site, which stimulate the growth and proliferation of native microbial populations that can degrade hydrocarbons (Jabbar *et al*., 2022). The primary goal of biostimulation is to create an environment that supports and accelerates the microbial degradation of hydrocarbons, particularly in cases where natural microbial populations exist but are limited by nutrient availability or other growth factors (Karishma *et al*., 2024). For instance, in oil-contaminated environments where nitrogen and phosphorus are often the limiting factors, the addition of these nutrients can enhance microbial activity and promote the breakdown of many hydrocarbons (Sui *et al*., 2021).

Additionally, biostimulation can involve adjustments in parameters like pH, temperature, or oxygen levels to further optimize microbial growth and activity (Anekwe and Isa, 2024). This technique has been widely used in the bioremediation of soil, groundwater, and surface water contaminated with petroleum hydrocarbons, providing a cost-effective and environmentally sustainable alternative to chemical or physical cleanup methods (Jabbar *et al*., 2022). While biostimulation can significantly accelerate the biodegradation process, its success depends on careful monitoring and optimization of environmental conditions to ensure the desired microbial responses (Kuppan *et al*., 2024).

Surfactants-Enhanced Bioremediation

Surfactant-enhanced bioremediation is an important approach employed to improve the degradation of hydrophobic hydrocarbons in contaminated environments by using surfactants to increase the bioavailability of these pollutants to microorganisms (Tiwari and Tripathy, 2023). Surfactants, which are amphiphilic compounds that reduce the surface tension between water and hydrocarbons, can facilitate the emulsification of hydrophobic contaminants, thus improving their dispersion and increasing the surface area available for microbial attack (Sah *et al*., 2022). The application of surfactants in bioremediation works by altering the physicochemical properties of the contaminated site, such as increasing the bioavailability of hydrocarbons to microbial communities, thereby, accelerating microbial degradation processes (Kebede *et al*., 2021). Surfactant-enhanced bioremediation has been successfully applied to soil, water, and sediment contaminated with hydrocarbons which enhances the removal of contaminants and promoting faster recovery of ecosystems (Ling *et al*., 2023).

Case Study (Nigeria)

Nigeria, being one of Africa's largest oil-producing nations, has faced extensive crude oil pollution primarily in the Niger Delta region due to frequent oil spills, pipeline vandalism, and poor oil waste management (Babatunde, 2020). A notable real-world application of microbial crude oil degradation was documented in Ogoniland, Rivers State, where decades of oil exploration left the land severely polluted (Azuazu, 2023). A collaborative study between Nigerian research institutions and international environmental agencies (notably the United Nations Environment Programme, UNEP) identified native bacterial strains capable of degrading total petroleum hydrocarbons (TPHs) effectively. In situ bioremediation was applied using a combination of land farming and bioaugmentation techniques. Nutrients such as nitrogen and phosphorus were added to stimulate microbial activity. Over a period of some months, microbial counts of hydrocarbon-degrading bacteria increased significantly, and oil spill levels were reduced in the heavily polluted plot (Nwosu *et al*., 2024).

Furthermore, in the Bodo community, Gokana Local Government Area of Rivers State, microbial bioremediation was used after two major oil spills in 2008 and 2009 caused severe environmental damage (Badom *et al*., 2024). Also, in a report by Oyebamiji *et al*. (2024), in Delta, River and Imo states, there have been issues of oil spill which cause damage to several biotic and abiotic components of the environment.

Future Prospect

Crude oil bioremediation through the use of hydrocarbon-degrading microorganisms are increasingly promising, driven by advancements in microbiology, environmental biotechnology, and molecular biology (Mekonnen *et al*., 2024). Hydrocarbonoclastic microorganisms, including bacteria as well as certain fungi, have demonstrated significant potential in degrading various components of crude oil. The integration of genetic engineering and synthetic biology is enabling the development of genetically enhanced strains with improved metabolic efficiency, stress tolerance, and the ability to degrade a broader range of hydrocarbon compounds (Yaashikaa *et al*., 2022). Additionally, the use of bioaugmentation and biostimulation is gaining attention as effective remediation techniques. As global concerns over oil pollution intensify, the demand for green and cost-effective remediation methods is expected to grow (Abdulghani *et al*., 2024). Crude oil bioremediation using hydrocarbon-degrading microorganisms thus represents a sustainable and scalable approach for mitigating the environmental impact of petroleum hydrocarbons (Mekonnen *et al*., 2024; Vertrivel *et al*., 2025).

CONCLUSION

Hydrocarbon-utilizing microbes are important agents in the biodegradation of crude oil, because they offers a sustainable and eco-friendly approach to environmental remediation. Some of the microbes capable of degrading crude oil includes Aspergillus, Bacillus, Pseudomonas, Burkholderia, and Arthrobacter species. These microorganisms possess several mechanisms among which includes enzymatic systems capable of breaking down complex hydrocarbons into simpler, less toxic compounds. Their effectiveness in crude oil biodegradation is influenced by factors such as microbial species, environmental conditions, and nutrient availability. In conclusion, the metabolic potential of these microbes not only aids in cleaning up crude oil-contaminated environments but also contributes significantly to maintaining ecological balance and promoting the recovery of polluted ecosystems.

RECOMMENDATIONS

It can be recommended that;

i. Focusing on isolating and identifying native hydrocarbon-degrading microbes from contaminated sites, as they are often more adapted to local environmental conditions and crude oil composition should be given an emphasis for better understanding of bioremediation potential by hydrocarbon microbial utilizers.
ii. Several factors influencing the microbial degradation of hydrocarbon contaminants such as pH, temperature, oxygen availability, and nutrient levels should be optimized to enhance microbial activity and degradation efficiency in situ.
iii. Employing mixed microbial cultures with complementary metabolic capabilities can improve the degradation of a wider range of hydrocarbon components in crude oil.
iv. Advancing biotechnological approaches should be utilized to enhance the hydrocarbon-degrading pathways of microbes, thereby, improving their efficiency and resilience in harsh environmental conditions.
v. Controlling field studies are recommended to validate laboratory findings, assess the real-world effectiveness of microbial treatments, and refine strategies for large-scale application.

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