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Polymeric Nanocomposite Aided Bioaugmentation for Marine Oil Spills – A Review

A. Sheela Devi[1], V. Chithambaram[2,*], M. Mary Jaculine[3], N Saravanan[4], A. Lokeshbabu[5], J. Balakrishnan[6]

Abstract

Bioaugmentation is a promising, cost-effective bioremediation technique that enhances the degradation of marine pollutants by introducing hydrocarbon-degrading microorganisms. This review explores recent advancements in the use of bioaugmentation for petroleum biodegradation in marine environments, emphasizing the integration of microbial systems with polymeric and composite materials. Innovative methods, such as the immobilization of microbial cells within biodegradable polymeric matrices (e.g., alginate, chitosan, polyvinyl alcohol), have significantly improved microbial viability, metabolic efficiency, and environmental resilience. These biopolymer carriers serve as support matrices, forming bio-functional composites that facilitate sustained and targeted biodegradation in harsh marine conditions. Nanotechnology-based enhancements, including the use of polymer-supported magnetic nanoparticles, Pickering emulsions, and responsive polymer nanofibers, have further increased oil dispersion and microbial interaction. Such materials mimic nanocomposite behavior, where the polymeric matrix acts as a delivery platform and mechanical support, improving pollutant interaction and biodegradative performance. These hybrid systems combine the selectivity of microorganisms with the structural and functional advantages of polymers, yielding advanced bio-nanocomposites for efficient oil spill remediation. The review also discusses future perspectives, such as the development of smart polymer composites for real-time sensing, controlled microbial release, and environmentally responsive degradation. By bridging microbiology, materials science, and environmental engineering, polymer-based bioaugmentation platforms offer a scalable and sustainable solution to the complex challenge of oil contamination in marine systems. This review aligns with the journal's scope by emphasizing composite technologies in bioremediation, showcasing polymer-microbe synergies in tackling environmental pollution.

Keywords: bioaugmentation, biodegradation, hydrocarbons**,** microorganisms, life below water, oil spills

***Author for Correspondence**
V. Chithambaram

[1]Associate Professor, Department of Biotechnology, Karpaga Vinayaka College of Engineering and Technology, Karpaga Vinayaka Educational Lore for Learning (Deemed to be University), Tamil Nadu, India
[2]Professor, Department of Physics, Rajalakshmi Engineering College (Autonomous), Thandalam, Chennai, Tamil Nadu, India
[3]Professor, Department of Physics, Loyala-ICAM College of Engineering and Technology, Nungambakkalam, Chennai, Tamil Nadu, India
[4]Associate Professor, Department of Physics, Adhiparasakthi College of Engineering, kalavai, Tamil Nadu, India
[5]Tutor, Department of Pharmacology, Sree Balaji Medical college and Hospital Chrompet, Chennai, Tamil Nadu, India
[6]Professor, Department of Chemistry, Sri Muthukumaran Institute of Technology, Chikkarayapuram, Mangadu, Chennai, Tamil Nadu, India

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INTRODUCTION

Petroleum oil is an important resource for all countries, particularly where economic and industrial demands are rapidly expanding [64]. Covering approximately 71% of the Earth's surface, oceans contribute 96% of the total water volume and serve as major extraction zones for petroleum through anthropogenic activities. Petroleum-based products such as gasoline, kerosene, and diesel are central to the transportation sector, facilitating rapid mobility and global trade [28]. Additionally, petrochemical industries rely on crude oil as a key raw material for the production of plastics, synthetic fibers, fertilizers, pharmaceuticals, and lubricants essential in modern manufacturing processes [11].

However, this heavy reliance on petroleum products brings with it the persistent threat of oil spills. These spills commonly occur during offshore drilling, transportation, or accidental discharges from tankers and pipelines. The environmental and socioeconomic consequences are far-reaching. Local livelihoods especially those dependent on fishing, suffer substantial disruptions. For example, the Deepwater Horizon disaster led to billions of dollars in losses for Gulf Coast fisheries and tourism sectors [58]. Property values plummet in affected coastal areas, and cleanup operations burden governments and industries with significant financial strain.

Moreover, oil spills contribute to the long-term degradation of marine ecosystems. The accumulation of petroleum hydrocarbons, including carcinogenic compounds such as benzene and toluene, poses a serious threat to both marine biodiversity and human health [53]. These hydrocarbons persist in the environment, affecting plankton, fish, seabirds, and even entering the human food chain. Bioremediation, particularly through bioaugmentation, has emerged as a highly promising and eco-friendly strategy for the remediation of oil-contaminated environments. The process typically employs hydrocarbon-degrading microorganisms, such as deep-sea bacteria and genetically modified strains, capable of breaking down complex hydrocarbon chains through aerobic or anaerobic metabolic pathways [49]. These microbes have demonstrated high efficacy in controlled lab environments and are now being tested in large-scale field applications.

Recent research has introduced polymer-based composites and nanostructured carriers to enhance microbial stability and pollutant interaction. For instance, encapsulating bacterial strains in biodegradable polymers such as alginate, chitosan, or synthetic polymeric beads enables prolonged microbial viability and targeted pollutant degradation. These composite systems serve as controlled release biocarriers, reducing microbial loss in turbulent marine environments and increasing the efficiency of oil biodegradation.

Nanotechnology-based tools including magnetic nanocomposites, emulsifiers, and polymer-nanoparticle hybrids are being developed to aid bioaugmentation processes. These materials help in dispersing oil more uniformly and in creating a favorable microenvironment for microbial activity. Surface-modified polymers with hydrophilic/hydrophobic balance have also been reported to enhance microbial adhesion and degradation potential. Environmental pollution from industrialization also adds to the problem. Toxic aromatic compounds, including halogenated aromatics and polycyclic aromatic hydrocarbons (PAHs), frequently enter marine ecosystems as industrial effluents [41]. These compounds are not only persistent but also mutagenic and carcinogenic, causing severe ecological imbalance. The United States Environmental Protection Agency (USEPA) endorses bioremediation as a preferred remediation technology, recognizing its ability to detoxify complex contaminants while promoting ecosystem sustainability [33].

To technological advancement, there are various biodegradation techniques having their own pros and cons on efficiency, cost-effectiveness, and environmental impact. Some of them are listed below:

- *Natural attenuation:* Relies on indigenous microbial populations to degrade contaminants without any human involvement. It is cost-effective but can be slow and less effective for extensive contamination [6].
- *Bio-stimulation:* It involves the addition of nutrients to enhance the activity of native microbes. It increases degradation rates but may lead to unintended ecological effects like algal blooms as an effect if not managed properly [38].
- *Bioaugmentation:* Introduction of specific microorganisms with known metabolic pathways. Having potentially high effectiveness in degrading compounds, they are costly and may pose ecological risks if non-native species alter the local microbial community structure [33].

- *Phytoremediation:* Utilizing plants to absorb, collect, or break down pollutants is known as phytoremediation. Although it is slower and only works in places where plants can grow, it is far less expensive and more ecologically friendly [59]. The selection of the process depends on site-specific conditins, the nature of the contaminants, regulatory requirements, and cost considerations. Often, integrating multiple techniques can enhance remediation effectiveness. The soil consists of indigenous native microorganisms isolated and genetically modified to treat the soil contaminants. This review aims to provide a comprehensive analysis of recent advancements in bioaugmentation strategies for the biodegradation of oil spills in marine environments using genetically engineered microorganisms, an environmentally friendly method, and challenges associated with implementing these biotechnological solutions, and practical applications and implications for future research.

Polymeric and Composite Matrices in Microbial Immobilization

Immobilization of microbial cells in polymer-based matrices has emerged as a critical advancement in bioaugmentation for marine oil spill remediation. Natural and synthetic polymers such as alginate, chitosan, polyacrylamide, and polyvinyl alcohol (PVA) have been used to entrap microbes, forming stable bio-functional composites. These matrices protect microorganisms from environmental stress, enhance their survival and activity, and allow controlled pollutant degradation.

Biopolymer composites act as both mechanical supports and diffusion barriers, enabling sustained microbial performance. Nanostructured carriers such as hydrogel-biochar blends, sponge-NaCl-PEG composites, and PVA - nanoclay hybrids serve as bio-compatible scaffolds, mimicking conventional polymer nanocomposites. These materials provide high surface area, tunable porosity, and biocompatibility - ideal for marine environments with fluctuating salinity and temperature.

Furthermore, the functionalization of polymer surfaces has enabled selective microbial adhesion and enhanced hydrocarbon interaction. Smart composites with stimuli-responsive behavior are under exploration for real-time activation and pollutant targeting. Thus, polymer-composite-based immobilization is a key innovation aligning bioremediation with material science.

COMPOSITION OF PETROLEUM HYDROCARBON

Petroleum, or crude oil, is a complex mixture of hydrocarbons and other chemicals. Finding a solution for a problem always starts with understanding the problem, so it is necessary to understand the composition of petroleum hydrocarbons for selecting appropriate bioremediation strategies based on the complexity and variability of petroleum components. Hydrocarbons such as aliphatic and aromatic compounds and asphaltenes have unique chemical compositions determining the time taken for microbial degradation.

Aliphatic hydrocarbons like n-alkanes are more biodegradable due to their simpler structure [62]. On the other hand, polycyclic aromatic hydrocarbons (PAHs) with complex structures having aromatic rings show resistance to degradation because of their structural stability and lower solubility [43]. Some hydrocarbons can cause biomagnification in the aquatic food chain, which leads to long-term ecological and health effects, including carcinogenicity, mutagenicity, and endocrine disruption in wildlife and humans [1].

Prior knowledge about the metabolic pathways of microbes to be used is necessary to degrade specific hydrocarbons. It also acts as a bio stimulant by providing the appropriate nutrients or environmental conditions to enhance microbial activity against the target compounds, thereby increasing the efficiency of the bioremediation process [55]. The hydrocarbon mainly consists of alkanes, cycloalkanes, and aromatic hydrocarbons [26]. It also contains many different hetero compounds with rare metals like nickel and vanadium present in trace amounts. The elemental composition of petroleum hydrocarbons (oil spills) is given in Table 1.

Table 1. The elemental and composition of petroleum hydrocarbon (oil spills).

S.N.	Elements	Percentage	Reference
1	Carbon	85–90%	[53]
2	Hydrogen	10–14%	
3	Sulfur	0.3–3%	
4	Oxygen	0.05–1.5%	[26]
5	Nitrogen	0.1–2%	
6	Metals	< 0.1%	

Table 2. Types of hydrocarbons present in crude oil.

S.N.	Hydrocarbon	Percentage	Reference
1	Paraffins	15–60%	[26]
2	Naphthene	30–60%	
3	Aromatic	3–30%	
4	Aliphatic	Trace amount	

The most common metals are iron, nickel, copper, vanadium, mercury, potassium, and many other metals (Li, Se, Rb, Ag, Ba, Pb, As, Cd). There are four main types of hydrocarbons that are present in crude oil, as given in Table 2 [13].

PETROLEUM HYDROCARBON BIOAUGMENTING MICROORGANISMS IN MARINE (BIODEGRADATION)

Most of the petroleum hydrocarbons encountered in the water ecosystem are metabolized by the indigenous or native bacteria because of their energetic and physiological activities. The scientific studies revealed that a large number of hydrocarbon-degrading bacteria are present in the oil spill environment, and this bacterium is isolated from such an environment to identify its biodegrading ability by oxidizing the oil spills [20]. The microbes can metabolize hydrocarbons either by anaerobic or aerobic processes, depending on the strains of bacteria. These anaerobic processes have been demonstrated in surface sedimentation and laboratory condition which plays a potential role of oil biodegradation in anoxic petroleum reservoirs [56].

Due to various explosions taking place over the last 10 years, the marine microbes dramatically increased their diversity and adapted themselves for oil biodegradation. Some 400,000 to 1,000,000 barrels of oil spills go into the Gulf of Mexico every year on the seafloor, which has a huge impact on the ocean ecosystem. The Deepwater Horizon oil is degraded by the bacterial communities like Gamma probacteria, which are dominant in degrading the oil spills beneath the surface of the sea surface. Pseudo alteromonas, Pseudomonas, Vibrio, Acinetobacter, and Aeromonas: these strains of bacteria are predominantly metabolizing the oil spills in the warm surface of the sea and also in the deep sea at 4°C [23]. In 2022, the oil spill off the coast of Peru caused by the volcanic eruption in Tonga generated abnormal waves, which caused the release of approximately 6,000 barrels of oil into the environment, disturbing the balance of marine life and local livelihoods [40].

The spill contaminated over 20 beaches, leading to the death of marine animals and impacting fishing and tourism industries. The Mauritius oil spill in 2020 studies investigated the use of indigenous microbial strains enhanced through bioaugmentation to degrade stranded oil on shorelines. Results demonstrated accelerated degradation rates of alkanes and PAHs based on environmental factors like temperature and nutrient availability [24]. In the Niger Delta region, bioaugmentation was done using locally isolated hydrocarbon-degrading bacteria. This study reported significant reductions in total petroleum hydrocarbons and emphasized the importance of using indigenous microbes to minimize ecological disruption with the challenge of ensuring the survival and activity of introduced microbes in the competitive natural environment and the need for continuous monitoring [30].

Table 3. Microbes used to treat the oil spills or petroleum hydrocarbon present in the top surface oF sea (marine ecosystem).

S.N.	Microorganisms	Class of organism	Biodegrading components	Reference
1	Methylococcus Methylomonas	Methylococcuscapsulatusstr	C1-C8 alkanes, alkenes and cycloalkanes	[14]
2	Pseudomonas Burkholderia Rhodococcus	Gammaproteobacteria Betaproteobacteria Actinomycetia	C5-C16 alkanes , fatty acids , alkyl benzene, hydrocarbon	
3	Desulfacinuminfernum	Deltaproteobacteria	Sulfate reducer	[56]
4	Halanaerobiumcongolense	Firmicutes , Bacteria	Thiosulfate and sulfur reducing bacteria	
5	Pseudomonas stutzeri	Gammaproteobacteria	Nitrate reducer	
6	Methanococcus	Archaea ,Euryarchaeota	Methanogen	
7	Gordonia Marinobacter	Actinomycetia	n-alkanes (C14−C30) and resins	[31, 46]
8	Anabaena Oscillatoria	Cyanophyceae Cyanophyceae	n-alkanes aromatics	[46]
9	Alkanindiges Alteromonas Arthrobactor	Gammaproteobacteria Gammaproteobacteria Actinomycetia	petroleum hydrocarbon	[64]
10	Achromobacter xylosoxidans DN002	Betaproteobacteria	monoaromatic and polyaromatic hydrocarbons	
11	Stenotrophomonas maltophilia Pseudomonas aeruginosa	Gammaproteobacteria Gammaproteobacteria	crude oil upto 83.49%	
12	Bacillusceres Bacillus sphaericus	Bacilli Bacilli	Polycyclic Aromatic Hydrocarbon	[47]
13	Raoultella sp.	Gammaproteobacteria	Degrade aromatic compounds, crude oil	[49]

Genetically modified strains and normal strains were used in the treatment of oil spills or petroleum hydrocarbons present in the top surface of the sea (marine ecosystem), and were listed in Table 3. Some species are used in wastewater treatment plants to degrade the harmful substances by biological methods without using chemicals, which is eco-friendly and does not cause any negative effects on marine organisms [23].

The utilization of Genetically Modified Microorganisms (GMMs) in biodegradation results in effective treatment but also has some limitations and ethical considerations. It causes potential ecological risk associated with introducing GMMs into marine environments. These organisms may outcompete native microbial populations, leading to disruptions in the natural microbial ecosystem and unforeseen ecological consequences [36].

There's also the risk of indigenous species mutation creating new pathogenic strains by altering native species' functions [15]. Releasing GMMs into the environment raises concerns about long-term ecological impacts and risks under assessments and regulatory oversight. Public perception and acceptance of GMMs are additional factors to be considered, as societal concerns about genetic modification have influenced regulatory policies and the deployment of such technologies [50].

Comparatively, leveraging natural microorganisms like bacteria, fungi, and enzymes can enhance biodegradation while minimizing ecological risks. Recent studies have highlighted the effective role of marine fungi in degrading hydrocarbons due to their diverse enzymatic capabilities [22]. Enzymes, such as oxidoreductases and hydrolases, can be applied directly to contaminated sites, which provide controlled degradation without introducing microbes, thereby reducing potential ecological disturbances [38].

DIFFERENT METHODS FOR OIL SPILL BIODEGRADATION (BIOAUGMENTATION TECHNIQUES)

Many traditional processes are used to treat the oil spills, which are sediment on the top layer of the sea. Mechanical methods include quick recovery of oil with different thicknesses of film and viscosities using skimmers (booms). The chemical method uses different agents to prevent the spreading and minimize the oil's impact on the marine ecosystem. For example, surface-active agents like surfactants, which emulsify and degrade the fatty acid chain present in oil [9]. Natural methods play an important role in maintaining the ecosystem and help to prevent the deleterious effects on the aquatic organisms. This technique utilizes microbes to disintegrate the oil contaminants, which is an eco-friendly and sustainable strategy for bioaugmentation [68]. Some examples of such microbes are:

- *Alcanivorax borkumensis:* A marine bacterium known for its capacity to degrade linear and branched alkanes using alkane monooxygenases by the initiation of terminal oxidation of alkanes to fatty acids [19].
- *Pseudomonas aeruginosa:* Can degrade aromatic hydrocarbons by employing enzymes like catechol 2,3-dioxygenase to cleave aromatic rings via the ortho or meta pathways [29].
- *Rhodococcus erythropolis:* Exhibits broad substrate specificity to degrade a range of hydrocarbons, including alkanes, aromatics, and heterocyclic compounds, through diverse catabolic genes [39].

These microorganisms metabolize hydrocarbons into less toxic intermediate forms, which are further processed through central metabolic pathways for energy and biomass production. Identification of specific enzymes involved in alkane degradation, such as alkane hydroxylases, allows the engineering of microbial strains with enhanced degradation [61]. This knowledge allows for the design of bioaugmentation strategies using microbes with over expressed or modified enzymes to increase efficiency

Table 4. Application of micro-organisms utilized for bioaugmentation of contaminants and pollutants present in water resources.

Bacteria	Immobilizing material	Degrading pollutants	Reference
Pseudomonas putida	Silica and Alginate	Lignin	[33]
Brevibacillus agri	Laccase polyurethane	Reduces COD, degrade color and lignin	
Pseudomonas sp.	Alginate	Removes chlorinated compound	[12]
Bacillus megatrium	Polyvinyl alcohol	Degrade black liquor	[42]
Rhodococcus pyridinivorans	Ca-alginate	Degrades phenol	[8]
Ochrobacterium sp.	PVA-alginate	Dimethylformamide	[37]
Agrobacterium radiobacter	Phosphorylated-polyvinyl alcohol (PPVA)	Atrazine and Petroleum	
Bacillus sp., Pseudomonas sp., Serratia sp.	Polyacrylamide, Alginate	Chromium, Mercury and Nickel	[45]
Burkholderia sp.	Alginate	Quinoline	[45]
Rhodococcus sp., Gordonia rubripectinota, Rhodococcus equi	Polyvinyl alcohol and Lentikats	TPH present in the crude oil and petroleum	[4]
Pseudomonas aeruginosa, Bacillus subtitlis	Agarose gel	TPH from spent motor oil spills	[2]
Klebsiella pneumoniae	Microcapsules of agar	Degrades kraft lignin	[65]
Halomonas alkaliphile	Agarose gel	Reduces COD and phenol	[3]
Aeromonas hydrophila	PVA	Phenanthrene	[44]
Streptomyces sp.	Alginate	Xylene	[37]
Selenastrum capricornutum	Alginate	Pyrene, copper, chromium	[45]
Sphingomonas sp.	Alginate	Naphthalene and pyrene	

Additionally, enzymes can be immobilized and applied directly to contaminated sites, offering a controlled and efficient remediation method [34]. Recent advanced methods have been discovered for the biodegradation of petroleum oil, which include immobilized microbial cells and modified microbial cells (surface modification).

IMMOBILIZED MICROBIAL CELL

Immobilization is the process of entrapping or restricting the movement of a cell within a solid matrix. By this process, a whole cell or microbes of interest can be encapsulated for biocatalytic reactions.

Recently the microorganisms are used for cleaning up oil spill contaminants present in aquatic environments. The immobilized microbial cells have the great advantage that they are recycled and can be used for a longer period of time [9]. It can reduce the competition among various indigenous organisms; they increase the ability of tolerance of cells that is present in the matrix (immobilized cells). This immobilized cell can directly dump in affected areas to degrade the contaminants, which is an effective and sustainable method [60]. Some of the microorganisms are listed in Table 4.

Immobilized microbial cells are used in bioreactors for treating oily wastewater, where immobilization enhances microbial density and stability leads to increased degradation rates [67]. Scalability is achievable in controlled environments but presents challenges in open marine settings due to difficulties in distribution and maintenance of immobilized cells in vast and dynamic ecosystems. Advances in materials science including the development of buoyant and biodegradable carriers are being explored to overcome these challenges [5]. While genetically engineered microbes can be tailored for enhanced degradation of specific hydrocarbons, practical application is limited by stringent regulations, potential ecological risks, and public concern over environmental release. Research is ongoing to develop biosafety mechanisms including synthetic gene circuits that control microbial survival in the environment [66].

MODIFIED MICROBIAL CELL (SURFACE MODIFICATION)

Surfactants play a major role in the biodegradation process of oil spills and other petroleum hydrocarbons present in water resources. Surfactants reduce the adhesion between oil and water, which tends to decrease the surface area of oil, which helps in the wipeout of oil spills. By reducing the droplet size of oil, microbes can easily degrade contaminants [35]. This increases the bioavailability of oil to the microbes, which increases oil-water interaction; thus, pollutants are destroyed quickly. The outer surface of microbes is modified according to the surroundings, which helps to withstand the chemicals and other harmful pollutants present in water

The surface modifier acts on the petroleum hydrocarbon, converting it to oxygen (O_2) and carbon dioxide (CO_2). These molecules are let into the atmosphere, which is safe and does not cause any other type of pollution [18]. The process of microbial bioremediation of oil spills is given in Figure 1 [7].

IMPACT ON HUMANS AND AQUATIC ECOSYSTEM

The harmful impact depends on the chemical nature and toxic compounds present in oil spills. The petroleum and other forms of oil pollutants are released into the marine environment due to human activity [51]. More than 3 million metric tonnes of oil contaminants are found in the sea every year. These spills can happen due to pipelines bursting, oil tankers sinking, and drilling of underground petroleum that goes wrong. One of the largest accidents in history was in the Gulf of Mexico during this group; the well cap was installed in Deepwater Horizon. Due to some technical issues, the caps burst, which caused nearly 134 million gallons of oil to spill into the marine area. The people who depend on this sea for trading got affected, and fishing people are unable to do their work. The marine life present in the gulf was severely affected, which caused them to be unable to survive in seawater. This was the case in 2010 [17].

The National Oceanic and Atmospheric Department of the US lists out threats that are caused by oil spills on marine life [17]:

1. The insulating capacity of otters gets destroyed, and sea mammals get hyperthermia, which causes the death of sea creatures v, and plankton (phytoplankton and zooplankton) consume small droplets of oil spills, which eventually cause death. These microscopic organisms are the main food source for all small fishes and other organisms [10]. By the death of this creature, the food chain is affected.
2. Sea turtles get trapped in oil and ingest it as food by mistake, which causes indigestion problems for them, which results in the death of endangered species [32].
3. Dolphins and whales, which are mammalian creatures, inhale oil spills that get deposited in their gills and affect the lungs, which cause harmful impacts on the respiratory system [25].
4. The wings of birds have water-repelling capacity in nature because of oil spill deposition on wings; birds cannot migrate and cause death due to starvation [27]. These are all the serious effects of oil spills on marine ecosystems and organisms.

The impact of oil spills on humans may be direct or indirect. The health effects, which include respiratory problems, irritations (eye, skin, some sensitive organs, etc.), neurological effects, and traumatic symptoms, are due to the direct exposure of humans to oil contaminants. Due to the intake of oil-contaminated water, there will be an increased risk of cancer, reproductive damage, and low count of immune cells, which results in decreased immunity and also causes liver damage. The oil spills also enter the human food chain by the process of biomagnification [63].

When non-degradable substances enter the food chain, they do not get metabolized or broken down by organisms; rather, they get transferred up to the trophic levels of the food chain. During this process, they show an increase in concentration, which is referred to as biomagnification. For example, the hydrocarbons present in oil spills and petroleum get deposited on the tissues or cells of marine organisms like fish, and at the next trophic level, they are taken by primary consumers (big fish); at last, this fish is consumed by humans. At each stage, as the tropic level increased, the amount of hydrocarbon concentration also increased. This results in the deposition of hydrocarbons in the tissues and cells of the human body and causes serious health effects that cause various diseases [63]. This process is given in Figure 2.

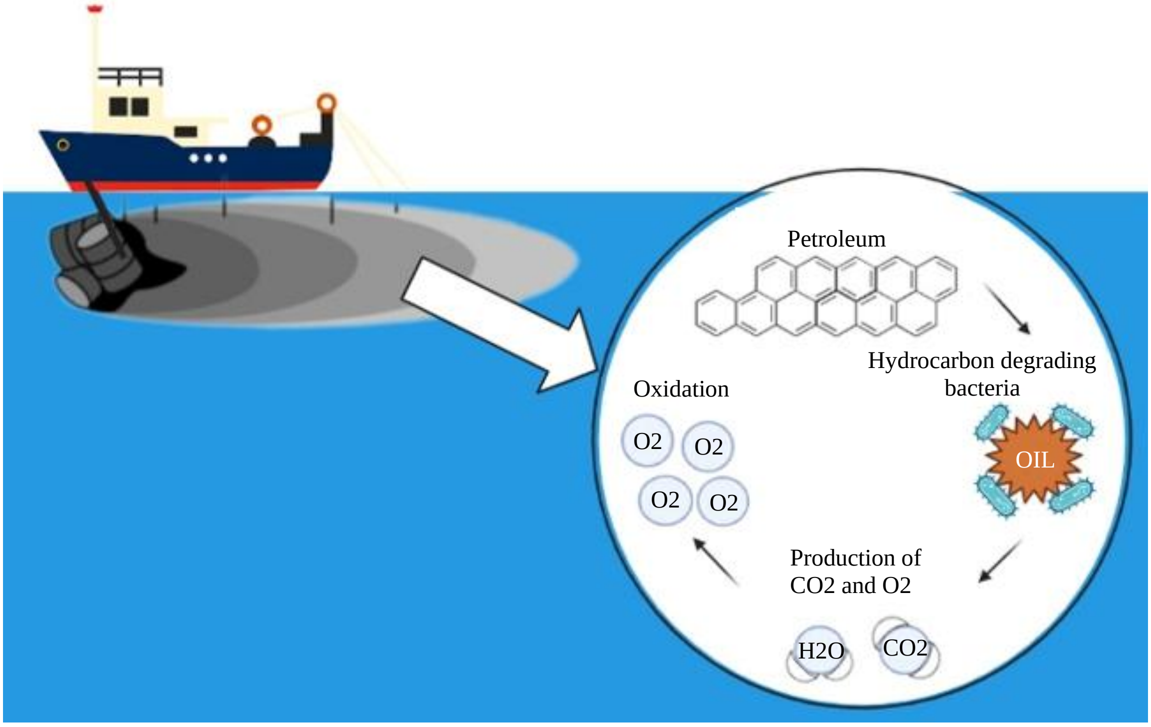

Figure 1. Microbial bioremediation of oil spills.

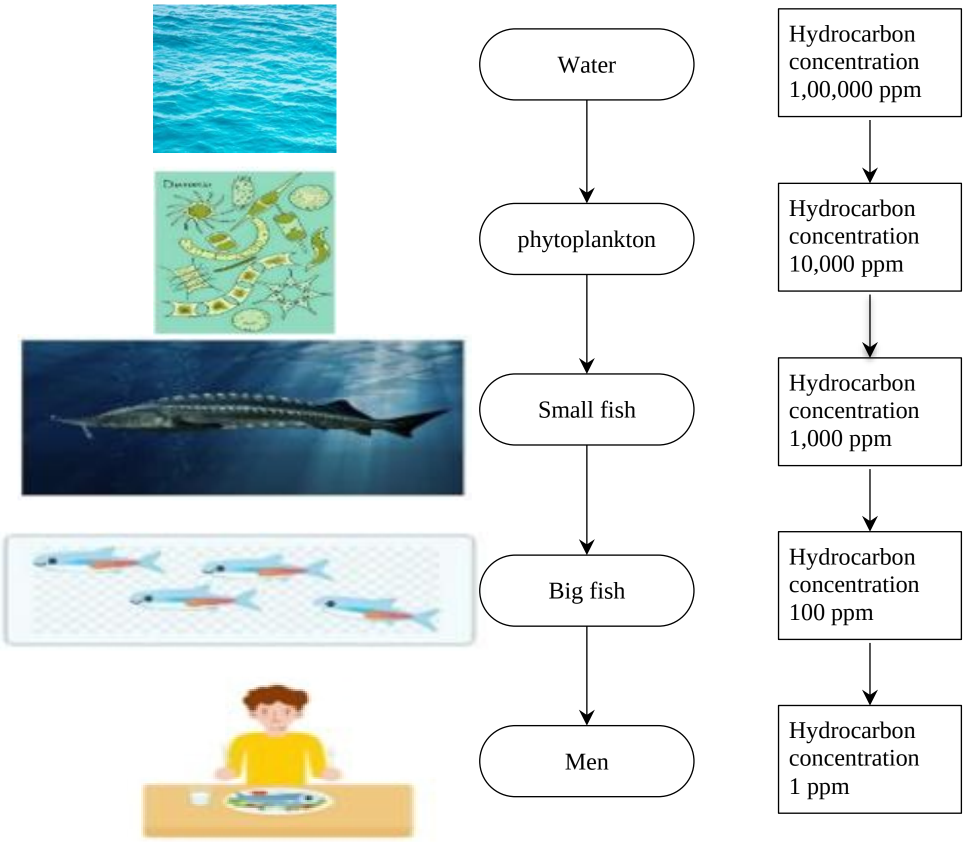

Figure 2. Biomagnification

FUTURE ASPECTS AND ADVANCEMENT

Recent advancements in environmental cleanup have demonstrated the promising potential of nanomaterials and nano-enabled bioremediation technologies for addressing oil contamination in aquatic ecosystems. One such development is nano-remediation, where nanoparticles are combined with hydrocarbon-degrading bacteria to enhance the biodegradation process. This hybrid technique, referred to as nano-enhanced bioremediation, improves microbial performance by increasing surface interactions and providing catalytic support [52]. Pickering emulsifiers are gaining traction in oil spill cleanup due to their ability to stabilize oil–water emulsions without synthetic surfactants. These emulsifiers, made from solid particles such as silica, polymer microspheres, or nanoclays, help prevent the collapse of emulsions and maintain consistent interaction between microbes and oil droplets, enhancing the degradation rate [46, 48]

In addition, magnetic nanosorbents, such as iron oxide-based nanocomposites, have been utilized for their excellent oil absorption properties and magnetic retrievability [57]. Unlike traditional organic sorbents, these nanosorbents offer reusability over multiple cycles, thereby improving economic feasibility [16]. Furthermore, polymeric nanofiber mats and magnetically modified biopolymer composites are now being tested as efficient, eco-friendly materials for rapid oil adsorption and biodegradation.

Another growing area involves immobilization techniques, which anchor microbial cells onto solid carriers. This approach enhances microbial stability, prolongs cell activity, and allows reuse across treatment cycles. Recently developed biodegradable matrices such as sponge-NaCl-PEG, hydrogel-biochar-zero-valent iron composites, and polycaprolactone-based sponges have shown promise due to their water-insolubility, mechanical strength, and biocompatibility [54]. Such matrices not only support microbial activity but also withstand fluctuations in marine environmental conditions.

Despite these advancements, certain limitations remain:

- Salinity, pH, and temperature variations in marine systems hinder microbial degradation efficiency.
- Post-treatment separation of nanoparticles from water is challenging due to their ultrafine size.
- Sustaining microbial viability over extended periods requires constant nutrient supplementation or enrichment strategies.

Future directions should focus on developing cost-effective immobilization matrices with stable physicochemical properties and non-toxic characteristics. For example, natural coconut fiber, a biodegradable and abundant support material, has been used to immobilize Pseudomonas aeruginosa for efficient degradation of n-hexadecane, significantly reducing its environmental half-life [21].

Furthermore, genetic engineering approaches for designing tailored microbial strains with enhanced metabolic pathways hold significant potential. Coupled with smart polymeric supports, biosensing nanomaterials, and responsive composites, these methods will form the backbone of next-generation oil spill response systems. The strategic integration of native marine microbes with nutrient-enriched nanocarriers also offers a sustainable and scalable approach for future bioaugmentation.

CONCLUSION

This review highlights the critical role of bioaugmentation in the degradation of oil spills and petroleum hydrocarbons, particularly within sensitive marine ecosystems. It underscores the effectiveness of hydrocarbon-degrading microorganisms, including native and genetically engineered strains, and the importance of selecting appropriate species based on the molecular structure and complexity of hydrocarbon pollutants. A thorough understanding of microbial metabolic pathways remains essential for designing targeted and efficient remediation strategies. However, real-world scalability poses challenges, including microbial survivability, competitive inhibition in diverse ecosystems, and environmental fluctuations such as salinity, temperature, and nutrient availability. To overcome these limitations, recent advancements in polymer and composite technologies have shown remarkable potential. The integration of microbial systems with biodegradable and stimuli-responsive polymer matrices such as alginate, chitosan, polyvinyl alcohol (PVA), and polycaprolactone has improved microbial stability, activity, and reusability. These polymeric scaffolds function as immobilization platforms, creating bio-nanocomposite systems that offer enhanced mechanical strength, surface area for microbial adhesion, and controlled release of nutrients or microbes. Hybrid materials, such as magnetic nanocomposites and Pickering emulsions, further improve dispersion, target specificity, and ease of recovery from marine environments.

- Moving forward, future research must focus on:
- Designing microbial strains with enhanced degradation kinetics and broad substrate specificity.
- Developing smart polymer systems that respond to environmental stimuli for real-time control of bioremediation.

Assessing long-term ecological safety, especially for genetically engineered organisms and synthetic nanocomposite materials needs estimating environmental persistence, trophic transfer risks, and unintended genetic or chemical interactions. Establishing integrated monitoring platforms using biosensors and remote sensing to evaluate remediation progress and ecosystem recovery. Innovating post-treatment separation and purification techniques to recover residual nanoparticles and byproducts without secondary contamination. Another emerging challenge is the environmental retrieval of nano-adsorbents and polymeric composites post-biodegradation. Research into eco-safe recovery and recycling mechanisms such as magnetically retrievable materials and biodegradable supports is essential for developing a closed-loop remediation system.

In conclusion, the convergence of microbiology, polymer science, and nanotechnology offers a transformative path for marine oil spill remediation. Bioaugmentation, when combined with smart, biocompatible composite systems, provides a scalable, sustainable, and eco-friendly strategy to tackle complex oil contamination challenges. This integrative approach not only advances environmental restoration technologies but also aligns with the global drive toward cleaner oceans and sustainable development. As such, it falls well within the thematic and scientific scope of the Journal of Polymer and Composite, demonstrating the potential of multifunctional bio-polymer systems in real-world marine applications.

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