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Marine Bioremediation of Oil Spills Using Indigenous Bacteria of the Persian Gulf and Oman Sea

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Key words

Oil-degrading bacteria
Hydrocarbons
Biostimulation
Bioaugmentation

Abstract

Oil pollution is one of the most significant threats to marine ecosystems. Its destructive impact on aquatic organisms, food chains, and the quality of coastal environments makes it essential to develop sustainable and cost-effective solutions. Oil-degrading bacteria are a group of microorganisms capable of breaking down petroleum hydrocarbons. These bacteria, naturally present in the environment or applied through biotechnological approaches, play a vital role in cleaning up contaminated areas. This article discusses the processes of identifying and isolating effective bacterial strains, laboratory techniques for their cultivation and enhancement, and field application strategies including biostimulation (promoting the growth of native bacteria) and bioaugmentation (introducing selected strains). It also presents examples of successful projects worldwide from the coasts of Alaska and the Mediterranean to the Persian Gulf, to compare efficacy and environmental adaptability. Findings indicate that the targeted use of native bacterial strains with high tolerance to salinity and temperature can significantly accelerate and improve the efficiency of marine bioremediation, thereby helping reduce environmental damage caused by oil spills.

Problem Statement

Oil pollution represents one of the most serious environmental threats to marine ecosystems, with far-reaching consequences for aquatic life, fisheries productivity, and the health of coastal communities. Oil spills originating from drilling platforms, vessels, pipelines, and industrial maritime activities release toxic and persistent hydrocarbons into aquatic environments (Figure 1). These compounds not only degrade water and sediment quality but also destroy habitats, reduce biodiversity, and cause massive mortality among marine organisms (Li et al., 2022). Conventional cleanup approaches—such as mechanical containment or the use of chemical dispersants—are often costly, inefficient, and prone to adverse side effects (Rahman et al., 2022). Furthermore, technical and economic constraints in many countries, particularly those in developing regions, limit the large-scale implementation of such methods, often resulting in unsustainable environmental outcomes. In recent years, growing scientific attention has turned toward *biological remediation processes*, which harness the intrinsic ability of microorganisms to degrade hydrocarbons in an environmentally safe and sustainable manner. Oil-degrading bacteria, especially indigenous species, are capable of converting a large fraction of alkanes, aromatics, and complex petroleum compounds into less harmful or non-toxic substances (Al-Naamani et al., 2024).

Despite proven efficiency in laboratory tests and selected field projects, practical and large-scale application of this approach in marine environments still faces several challenges. These include identifying potent native strains, optimizing conditions for their growth and activity at scale, ensuring adaptability to dynamic coastal and

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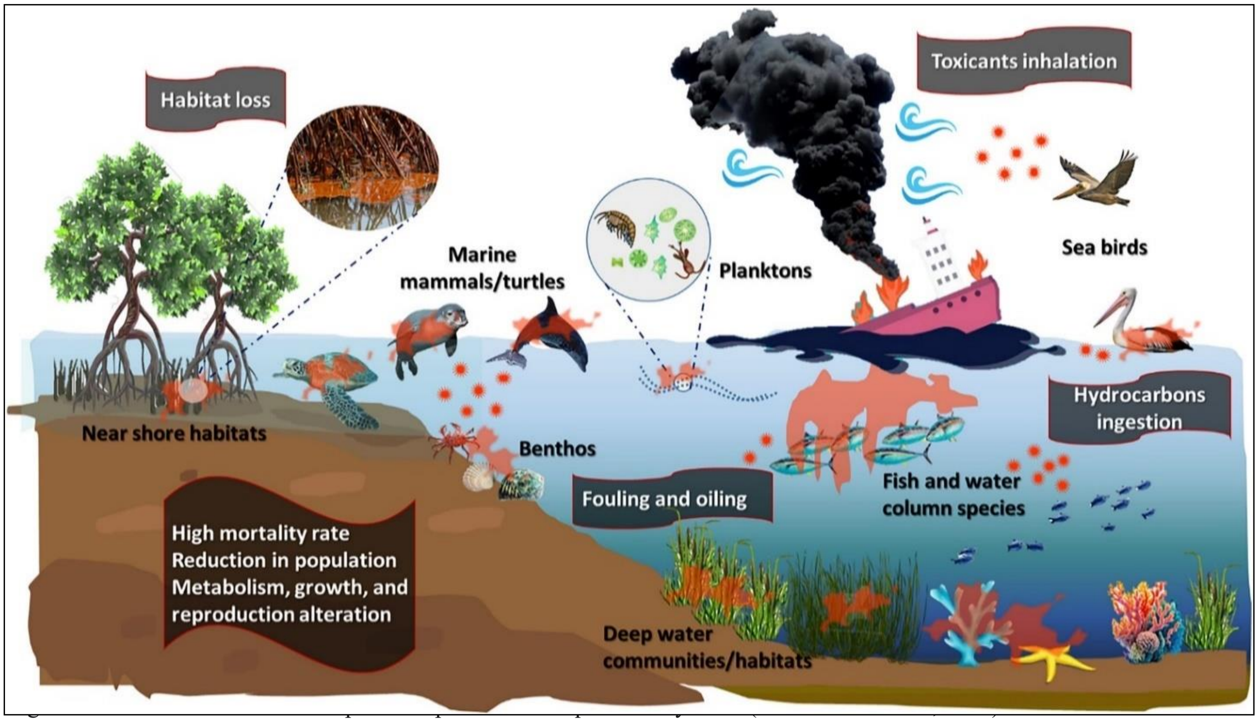
offshore environments, and establishing appropriate infrastructure for monitoring and performance assessment (Tavanaei et al., 2023).

Persian Gulf situated in a highly sensitive region where dense tanker traffic and continuous oil extraction and transportation occur. Oil pollution poses not only an environmental concern but also a substantial threat to food security, fisheries economy, and the livelihoods of coastal populations. Therefore, the identification, cultivation, and application of oil-degrading bacteria adapted to local marine conditions could serve as an effective and low-cost solution aligned with the goals of sustainable development and marine resource protection (Mujaini et al., 2023).



Key achievements and practical solutions

Recent research in marine bioremediation shows that using oil-degrading microorganisms—especially native bacterial strains—can provide a sustainable alternative to traditional chemical or mechanical cleanup methods. This biological strategy not only lowers operational costs but also helps prevent the secondary environmental impacts often caused by conventional cleanup approaches (Al-Harbi et al., 2023).

Overall, the key achievements and technological advancements in this area can be summarized in five main axes:

1. Isolation and identification of effective bacterial strains
2. Mass cultivation and optimization of growth conditions
3. Design of applicable systems for real-world marine environments
4. Monitoring and Control Systems
5. Doing test runs in the sea and recording the results

1. Isolation and identification of effective bacterial strains

In many marine regions, including the Persian Gulf and the Sea of Oman, native oil-degrading bacterial species have been isolated from contaminated water and sediment. Strains belonging to genera such as *Alcanivorax, Marinobacter, Pseudomonas*, and *Rhodococcus* have demonstrated the greatest capacity for degrading alkanes and aromatic hydrocarbons (Hashem et al., 2023). These bacteria often possess key enzymes such as alkB and nahA, which activate the metabolic pathways required for hydrocarbon degradation.

Research conducted in Iran by Tavanaei et al. (2023) emphasized the critical importance of proper isolation and identification of native bacterial species under the hot, saline conditions of the Persian Gulf. Strains capable of tolerating salinities above 40 ppt and temperatures exceeding 30 °C exhibited significantly higher efficiency in degrading heavy alkanes.

2. Mass cultivation and optimization of growth conditions

A key step in the practical application of these bacteria is the development of large-scale cultivation systems that ensure high survival and activity. Nutrient-rich media containing nitrogen and phosphorus, supplemented with natural emulsifiers such as lecithin or gum arabic, have been shown to enhance both growth and hydrocarbon-degrading capacity (Fernández-Álvarez et al., 2022). The use of immobilized matrices, such as biofilms or natural polymers, further improves resistance to environmental fluctuations and prolongs bacterial persistence in open-water systems. Under laboratory conditions, *Alcanivorax borkumensis* was capable of degrading up to 80 % of crude oil within 10 days; when supplemented with specific nutrients in natural seawater, the efficiency reached 95 % (Zhang et al., 2024).

3. Design of applicable systems for real-world marine environments

Field-scale application of oil-degrading bacteria generally, relies on three main approaches:

1.Biostimulation – enhancing nutrient availability to stimulate native microbial populations (Figure 2);
2.Bioaugmentation –injecting selected, pre-cultivated bacterial strains;
3. Combined Strategy – sequential application of both methods in contaminated coastal or offshore zones.

Pilot projects conducted in Oman and Qatar reported that combined strategies reduced total hydrocarbon concentrations by 65–80 % within three weeks (Al-Naamani et al., 2024). Similarly, a field experiment in the Persian Gulf (Asaluyeh region) by Marzban et al. (2023) showed that injection of 10^8 cells mL^{-1} resulted in significant reduction of dissolved oil and measurable improvement in water quality and ecological indicators.

4. Monitoring and Control Systems

Quantitative and qualitative monitoring of bioremediation is achieved through measurements such as Total Petroleum Hydrocarbon (TPH), Biochemical Oxygen Demand (BOD), and analysis of microbial community composition. Biosensor technologies based on fluorescence or infrared spectroscopy now enable rapid pollutant detection (Singh et al., 2023). In Iran, academic research collaborations have proposed microbial-level monitoring systems employing 16S rRNA gene sequencing, offering a robust framework for long-term environmental surveillance (Marzban et al., 2023).

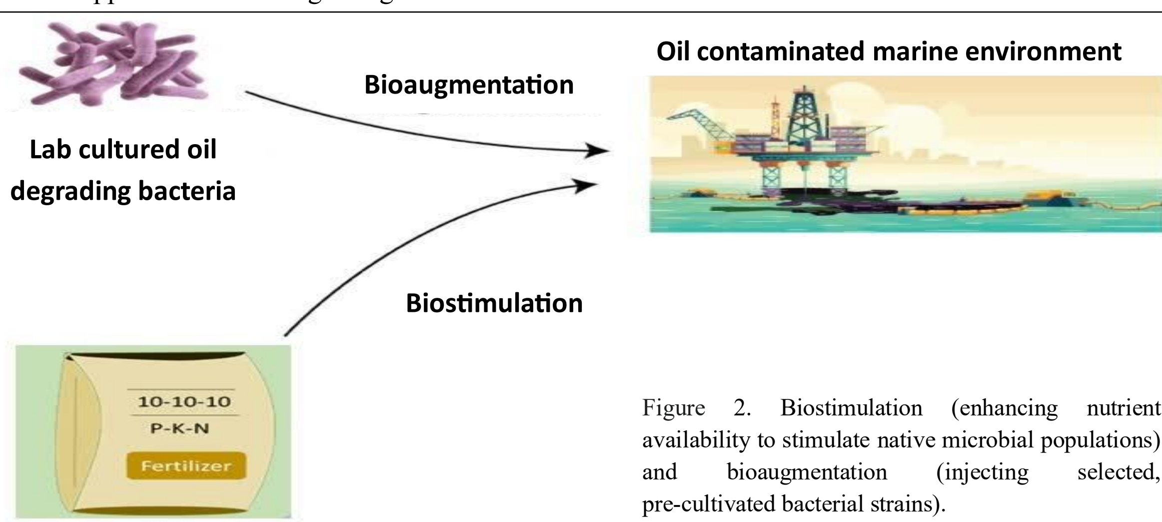


Figure 2. Biostimulation (enhancing nutrient availability to stimulate native microbial populations) and bioaugmentation (injecting selected, pre-cultivated bacterial strains).

5. Doing test runs in the sea and recording the results

Coastal nations such as Japan, Canada, and India have reported successful applications of oil-degrading bacteria in shoreline recovery efforts. Results consistently highlight that ecological stability and the adaptability of native microbial species are decisive in determining the rate and permanence of hydrocarbon breakdown (Yadav et al., 2024). In Iran, pilot applications utilizing indigenous bacterial strains collected from Bandar Abbas and Chabahar sediments have achieved up to 70 % reduction of coastal oil contamination. These findings underscore the strong potential of locally adapted microorganisms for deployment in marine environments of southern Iran. It is therefore recommended that a National Indigenous Oil-Degrading Bacterial Bank be established to catalog native strains, characterize their genetic properties, and support coordinated marine bioremediation programs. Such a resource would serve as a foundation for future research, capacity-building, and the design of practical large-scale cleanup systems.

Practical recommendation and conclusion

This paper demonstrates that the use of oil-degrading bacteria is not only an effective method for pollution cleanup but also contributes to ecological restoration and lower operational costs compared with traditional physical and chemical approaches. For coastal countries with environmentally sensitive shorelines—such as Iran—targeted investment in the identification of indigenous bacterial strains, as well as the development of injection and monitoring systems, can establish a strong regional model for the environmental management of oil pollution. This integrated strategy aligns with the principles of sustainable development and marine ecosystem conservation in the Persian Gulf and the Sea of Oman.

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زیست پالایی دریایی لکه‌های نفتی با استفاده از باکتری‌های بومی خلیج فارس و دریای عمان

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واژگان کلیدی
باکتری‌های نفت‌خوار
هیدروکربن‌ها
زیست تحریکی
زیست افزایی

چکیده
آلودگی نفتی یکی از مهم‌ترین تهدیدها برای اکوسیستم‌های دریایی است که اثرات مخرب آن بر آبزیان، زنجیره غذایی و کیفیت محیط زیست ساحلی، نیاز به راهکارهای پایدار و کم‌هزینه را ضروری می‌سازد. باکتری‌های نفت‌خوار، گروهی از میکروارگانیسم‌ها هستند که توانایی تجزیه هیدروکربن‌های نفتی را داشته و به طور طبیعی یا با کمک فناوری‌های زیستی، در پاکسازی محیط‌های آلوده نقش‌آفرینی می‌کنند. در این مقاله، فرآیند شناسایی و جداسازی سویه‌های مؤثر، روش‌های آزمایشگاهی برای تکثیر و تقویت آن‌ها، و راهکارهای استفاده میدانی شامل زیست تحریکی و زیست افزایی بررسی شده است. همچنین نمونه‌هایی از طرح‌های موفق در جهان، از سواحل آلاسکا و مدیترانه تا خلیج فارس، با هدف مقایسه کارایی و تطبیق شرایط اقلیمی ارائه شده است. نتایج نشان می‌دهد استفاده هدفمند از سویه‌های بومی با وجود مقاومت بالا به شوری و دما، می‌تواند سرعت و اثربخشی زیست‌پالایی دریایی را به شکل چشمگیری افزایش دهد و به کاهش خسارات زیست‌محیطی ناشی از نشت نفت در دریا کمک کند.