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Opinion Article

Microbial Strategies for Enhanced Oil Spill Degradation in Marine and Terrestrial Environments

Yuan Xiangyu*

Department of Civil and Environmental Engineering (DICA), Milan, Italy

DESCRIPTION

Oil spills represent one of the most severe forms of environmental pollution, posing significant threats to marine and terrestrial ecosystems, human health, and economic activities. Petroleum hydrocarbons released during accidental spills or operational discharges are complex mixtures of alkanes, aromatics, resins, and asphaltenes, which are toxic, persistent, and challenging to remove from contaminated environments. Traditional physicochemical remediation techniques, including skimming, chemical dispersants, and incineration, often prove costly, inefficient, or environmentally disruptive. In contrast, oil spill degradation through bioremediation offers a sustainable and leveraging the natural capacity of microorganisms to metabolize hydrocarbons and restore contaminated sites.

Microorganisms, particularly bacteria and fungi, play a central role in oil spill degradation. Hydrocarbon-degrading bacteria such as *Alcanivorax, Pseudomonas, Rhodococcus,* and *Mycobacterium* have evolved enzymatic pathways capable of breaking down alkanes, aromatics, and other petroleum constituents. Fungi, including species of *Phanerochaete* and *Aspergillus,* also contribute by secreting extracellular enzymes like lignin peroxidases and laccases, which degrade complex hydrocarbon structures. The degradation process typically involves enzymatic oxidation, converting hydrocarbons into intermediate metabolites and ultimately into carbon dioxide, water, and biomass. Aerobic degradation is generally faster, as oxygen serves as an electron acceptor in catabolic reactions, whereas anaerobic pathways, relying on sulfate, nitrate, or iron reduction, proceed more slowly but are critical in oxygen-limited environments such as sediments or deep-sea spills.

Several environmental factors determine the efficiency of microbial hydrocarbon degradation. Temperature, pH, salinity, nutrient availability, and oxygen concentration critically affect microbial activity and growth. Low nutrient conditions, particularly nitrogen and phosphorus deficiencies, can limit biodegradation rates. Strategies such as biostimulation, which involves the addition of limiting nutrients, can significantly enhance microbial activity and accelerate oil removal. Similarly, bioaugmentation, the introduction of specialized hydrocarbon-degrading strains, can improve degradation efficiency in sites with low indigenous microbial activity. The chemical composition and physical state of the spilled oil volatile fractions versus heavy resins and asphaltenes also influence degradation kinetics, with lighter fractions typically degraded more rapidly.

Biosurfactants surface-active compounds produced by microorganisms plays an important role in oil spill degradation by increasing the bioavailability of hydrophobic hydrocarbons. They emulsify oil droplets, facilitating microbial access and accelerating breakdown. Phytoremediation provides another complementary strategy, where plants and their rhizospheric microbial communities enhance hydrocarbon degradation in soils and coastal environments. Root exudates stimulate microbial growth, oxygenate the rhizosphere, and stabilize contaminated sediments, resulting in improved long-term remediation outcomes.

Recent advances in molecular biology, metagenomics, and synthetic biology are transforming oil spill degradation strategies. Omics-based approaches enable detailed profiling of microbial communities, identifying key degraders and functional genes involved in hydrocarbon metabolism. Synthetic biology allows the engineering of microorganisms with enhanced tolerance to toxic compounds and improved degradation efficiency, including the ability to metabolize recalcitrant compounds such as Polycyclic Aromatic Hydrocarbons (PAHs). Integrating these technologies with traditional bioremediation approaches promises higher efficiency, predictability, and scalability for oil spill cleanup.

In conclusion, oil spill degradation represents a vital, sustainable solution for mitigating petroleum contamination in aquatic and terrestrial ecosystems. Microbial and plant-based strategies, supported by advances in biotechnology, offer cost-effective,Understanding the interactions between hydrocarbons, microbial communities, and environmental factors is essential

Corresponding to: Yuan Xiangyu, Department of Civil and Environmental Engineering (DICA), Milan, Italy, E-mail: yuanxiangyu@156788.it

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for optimizing degradation efficiency. Continued research and the integration of innovative biotechnological tools will further enhance the effectiveness of oil spill remediation, protecting ecosystems and reducing the long-term ecological and economic impacts of petroleum pollution.