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Developments in Marine Biosurfactants and Their Environmental Applications

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A B S T R A C T

Marine biosurfactants are surface-active molecules synthesized by microorganisms inhabiting marine and coastal ecosystems. Owing to their amphiphilic nature, they effectively reduce surface and interfacial tension, forming stable emulsions under extreme environmental conditions such as high salinity, temperature, and pressure. In recent years, these biogenic surfactants have attracted significant attention as eco-friendly and biodegradable alternatives to synthetic surfactants. This review highlights recent advances in the discovery, biosynthesis, and functional characterization of marine biosurfactants, emphasizing their physicochemical properties and versatility in environmental applications. Particular focus is given to their roles in oil spill remediation, hydrocarbon degradation, heavy metal removal, enhanced oil recovery, and wastewater treatment. Challenges related to large-scale production, purification, and regulatory approval are discussed, alongside emerging trends in metagenomics, process optimization, and synthetic biology aimed at improving yield and cost-effectiveness, marine biosurfactants represent a promising and sustainable biotechnological resource for addressing global environmental challenges.

Keywords: *Marine biosurfactants; biodegradation; oil spill remediation; environmental biotechnology; microbial surfactants; green chemistry; enhanced oil recovery.*

1. Introduction

Surfactants are amphiphilic compounds that reduce surface and interfacial tension between immiscible phases such as oil and water, thereby facilitating processes like emulsification, dispersion, and solubilization [1]. While synthetic surfactants are widely used in industries including detergents, cosmetics, petroleum, and pharmaceuticals, their persistence and toxicity have raised growing environmental concerns [2], biosurfactants—surface-active agents produced by microorganisms—offer a sustainable and eco-friendly alternative due to their biodegradability, low toxicity, and effectiveness under extreme conditions [3]. Among biosurfactants, those derived from marine microorganisms have gained significant interest because of the unique adaptations of marine species to high salinity, pressure, and temperature, which often result in novel structures and enhanced functional properties [4]. Marine bacteria, fungi, and yeasts such as *Alcanivorax*, *Bacillus*, *Marinobacter*, and *Yarrowia* spp. are known producers of biosurfactants with remarkable stability and activity under harsh environmental conditions [5]. Recent studies have demonstrated the potential of marine biosurfactants in various environmental applications, including oil spill remediation, bioremediation of hydrocarbons, heavy metal removal, and wastewater treatment [1,4]. Their ability to enhance the bioavailability of hydrophobic pollutants makes them valuable agents in marine and coastal ecosystem recovery. Furthermore, their use in industrial processes—such as enhanced oil recovery (EOR), emulsification, and foam stabilization—has strengthened their relevance in sustainable biotechnology [3,5]. Several challenges limit the large-scale production and commercialization of marine biosurfactants, including high production costs, difficulties in downstream processing, and limited understanding of their genetic and metabolic pathways [2,4], advances in synthetic biology, metagenomics, and process optimization are paving the way for improved yields and cost-effectiveness. Consequently, marine biosurfactants represent a rapidly developing field at the intersection of marine microbiology, environmental biotechnology, and green chemistry [1,5].

2. Production and Biosynthesis of Marine Biosurfactants

2.1 Microbial Sources

Marine environments host a wide variety of microorganisms capable of producing biosurfactants, including bacteria, fungi, and yeasts. Prominent genera include *Alcanivorax*, *Marinobacter*, *Bacillus*, *Rhodococcus*, and marine yeasts such as *Yarrowia lipolytica* [6]. These microorganisms are typically found in oil-contaminated zones, saline estuaries, and deep-sea sediments where hydrocarbon degradation is essential for survival. Their ability to thrive in high-salinity and pressure conditions gives rise to biosurfactants that are structurally unique and functionally stable under extreme environmental conditions [7].

2.2 Biosynthetic Pathways and Structural Classes

Marine-derived biosurfactants display remarkable structural and functional diversity. Most are low–molecular-weight compounds such as glycolipids, lipopeptides, and lipoamino acids, which effectively lower surface and interfacial tension [8]. Examples include rhamnolipids, sophorolipids, surfactin, and mannosylerythritol lipids (MELs), all known for strong emulsifying and dispersing properties. Although their biosynthetic pathways share similarities with those of terrestrial microorganisms, marine strains exhibit adaptive modifications that enhance salt tolerance, thermostability, and metabolic flexibility. Genomic and metagenomic studies have revealed the presence of specialized gene clusters responsible for biosurfactant synthesis, regulation, and secretion in marine species [9].

2.3 Production Strategies and Substrates

The production of marine biosurfactants is influenced by nutritional composition, cultivation conditions, and substrate type. A wide range of carbon sources—such as hydrocarbon residues, vegetable oils, industrial effluents, and other organic waste streams—have been successfully utilized to promote cost-effective production [6,8]. Optimizing medium composition (carbon-to-nitrogen ratio), salinity, pH, and temperature is critical for maximizing yield and biosurfactant activity. Recent research has focused on bioprocess engineering approaches such as submerged fermentation, fed-batch culture, and bioreactor optimization to enhance productivity. Using renewable or waste substrates not only reduces production costs but also contributes to circular bioeconomy models [7].

2.4 Physicochemical and Functional Properties

Marine biosurfactants are characterized by high stability and functional efficiency under extreme environmental conditions, including elevated salinity, temperature, and pH fluctuations [9]. They effectively reduce surface and interfacial tension, forming stable emulsions that facilitate the solubilization and dispersion of hydrophobic pollutants such as petroleum hydrocarbons. Their amphiphilic nature enhances the bioavailability of hydrophobic substrates, promoting biodegradation and improving oil recovery processes. Additionally, these compounds often display antimicrobial, anti-adhesive, and antifouling properties, expanding their potential industrial and environmental applications [8].

Table 1. Representative Marine Microorganisms Producing Biosurfactants and Their Characteristics

Microorganism	Biosurfactant Type	Chemical Class	Source/Environment	Key Properties	Reference
Pseudomonas aeruginosa UCP0992	Rhamnolipid	Glycolipid	Marine sediment (oil-contaminated site)	Reduced surface tension to 28 mN/m; 90% oil removal from sand	[5]
Bacillus cereus	Lipopeptide	Surfactin-like compound	Marine water sample	Surface tension reduction (27 mN/m); stable at high salinity	[6]
Marinobacter hydrocarbonoclasticus	Glycolipid	Trehalolipid	Deep-sea hydrocarbon environment	Excellent emulsification with crude oil	[7]
Rhodococcus erythropolis	Glycolipid	Trehalose dimycolate	Arctic marine sediment	Active at low temperatures; enhances oil dispersion	[8]
Yarrowia lipolytica	Mannosylerythritol lipid	Glycolipid	Marine yeast isolate	High emulsification index (E24 = 65%)	[9]
Alcanivorax borkumensis	Glycolipid	Mono-/di-rhamnolipid	Seawater (oil slick)	Hydrocarbon degradation under saline conditions	[10]

Table 2. Environmental and Industrial Applications of Marine Biosurfactants

Application Area	Function of Biosurfactant	Mechanism / Key Process	Advantages	Example / Reference
Oil Spill Remediation	Emulsification and solubilization of hydrocarbons	Increases bioavailability for microbial degradation	Eco-friendly dispersant; effective in seawater	*P. aeruginosa* UCP0992 rhamnolipid [11]
Heavy Metal Removal	Chelation and desorption of metal ions	Formation of biosurfactant–metal complexes	Enhances removal of Pb^{2+}, Cd^{2+}, Zn^{2+}	*Bacillus subtilis* surfactin [12]
Enhanced Oil Recovery (MEOR)	Reduction of interfacial tension	Improves trapped oil mobilization	Cost-effective; stable under extreme conditions	*Marinobacter* sp. glycolipid [13]
Wastewater Treatment	Emulsification of oily effluents	Promotes breakdown and separation of hydrophobic pollutants	Biodegradable; reusable in batch systems	*Rhodococcus* sp. trehalolipid [14]
Bioremediation of Contaminated Sediments	Dispersion and solubilization of pollutants	Enhances microbial access and degradation	Suitable for saline and cold environments	*Yarrowia lipolytica* MEL [15]

3. Environmental Applications

3.1 Oil Spill Remediation and Hydrocarbon Biodegradation

One of the most extensively studied applications of marine biosurfactants is in the remediation of oil spills and hydrocarbon-contaminated environments. These biosurfactants enhance the solubilization and emulsification of hydrophobic hydrocarbons, thereby increasing their bioavailability to hydrocarbon-degrading microorganisms [10]. For example, a biosurfactant produced by *Pseudomonas aeruginosa* UCP0992 achieved approximately 90% removal of motor oil adsorbed on sand under simulated marine conditions [11]. Similarly, a *Bacillus cereus*-derived biosurfactant was shown to reduce surface tension to about 27 mN/m, facilitating up to 96% degradation of petroleum hydrocarbons in seawater within 27 days [12]. Such findings demonstrate the strong potential of marine biosurfactants as environmentally benign agents for oil spill cleanup and microbial enhanced oil recovery (MEOR).

3.2 Heavy Metal and Organic Pollutant Remediation

Marine biosurfactants are also effective in the removal of heavy metals and hydrophobic organic pollutants from contaminated soils and sediments. Their amphiphilic nature enhances desorption, solubilization, and chelation of metal ions, thereby improving contaminant mobility and bioavailability for subsequent biodegradation or recovery [13]. Studies have reported successful use of biosurfactants for the removal of metals such as cadmium, lead, and zinc from industrial effluents and marine sediments.

In addition, narrative reviews have highlighted their dual functionality in hydrocarbon degradation and heavy-metal remediation, making them ideal candidates for integrated pollution control strategies in marine ecosystems [14].

3.3 Enhanced Oil Recovery (EOR)

A substantial amount of crude oil remains unrecovered in reservoirs due to capillary and interfacial forces. Marine biosurfactants have been explored as effective agents for microbial enhanced oil recovery (MEOR) through three major approaches: (i) stimulating indigenous hydrocarbonoclastic bacteria in oil reservoirs, (ii) injecting biosurfactant-producing microbial consortia, and (iii) applying ex-situ produced biosurfactants directly [10,12]. By reducing interfacial tension and altering the wettability of rock surfaces, these biosurfactants mobilize trapped oil and improve extraction efficiency. Their tolerance to high salinity and temperature gives them a unique advantage over synthetic surfactants in offshore and deep-sea petroleum operations [11].

3.4 Wastewater Treatment and Industrial Applications

Marine biosurfactants are increasingly applied in wastewater treatment, particularly for the removal of oily effluents, bilge water, and other hydrophobic waste streams [13]. Their exceptional stability under saline and extreme environmental conditions makes them suitable for marine and offshore industrial applications. In addition to wastewater treatment, they are used in processes such as emulsification, foam control, and dispersant formulations. Their low toxicity, biodegradability, and biocompatibility position them as sustainable alternatives to conventional surfactants in industrial, pharmaceutical, and environmental technologies [14].

4. Challenges and Bottlenecks

The significant promise, marine biosurfactant (BS) development and commercialization face several technical, economic, and regulatory challenges. Marine biosurfactants typically suffer from low yields and high production costs compared to synthetic surfactants. The complexity of marine microbial growth requirements, coupled with limited process optimization, contributes to higher costs. This limits large-scale production and commercialization despite the growing demand for eco-friendly surfactants [15]. The recovery, purification, and formulation of biosurfactants remain major bottlenecks. Downstream processing often accounts for more than 60% of total production costs, requiring optimization to improve efficiency and product purity. Advanced separation techniques and sustainable solvent systems are being investigated to overcome this issue [16]. Few marine biosurfactant products have reached commercial scale. The global surfactant market remains highly cost-sensitive, dominated by petrochemical-based products. Although some pilot-scale studies have been successful, industrial-scale production remains limited due to cost and process stability concerns [17]. Many marine biosurfactants remain poorly characterized at the molecular level. Incomplete knowledge of their structure–function relationships hampers regulatory approval for environmental release. Comprehensive toxicological, ecological, and biodegradation assessments are required to meet safety and environmental standards [18]. While using renewable and waste-derived substrates offers sustainability advantages, variability in substrate quality and availability can affect biosurfactant yield and quality. Maintaining consistent culture conditions for marine microorganisms in large-scale bioreactors remains a significant challenge [19]. Although marine biosurfactants are generally biodegradable and less toxic than synthetic counterparts, their ecological fate and potential long-term effects in real marine ecosystems require further evaluation. Understanding degradation kinetics, by-product formation, and ecosystem interactions will be crucial for responsible application [20].

5. Future Perspectives

Advancing marine biosurfactants from laboratory research to industrial and environmental implementation demands innovative, multidisciplinary approaches. Since a majority of marine microbes remain uncultured, metagenomic mining and genome-resolved metagenomics can uncover novel biosurfactant gene clusters. Synthetic biology approaches, including heterologous expression and metabolic engineering, may enable scalable production of complex marine biosurfactants [21]. Integration of biosurfactant production with marine biorefineries—using waste substrates such as oily effluents, seafood residues, or algal biomass—could reduce costs and enhance sustainability. Process intensification through optimized bioreactor designs and continuous fermentation systems may further improve productivity [22]. Marine microorganisms are naturally adapted to high salinity, pressure, and temperature environments. Engineering biosurfactants with enhanced tolerance to such conditions can expand their use in applications such as deep-sea oil recovery, polar remediation, and high-salinity wastewater treatment [23]. Comprehensive life-cycle and techno-economic assessments will be essential to evaluate the true environmental and economic potential of marine biosurfactants. These analyses can help identify energy-intensive steps, optimize costs, and demonstrate competitiveness with synthetic alternatives [24]. Translating laboratory findings into real-world applications requires pilot and field-scale trials. Testing biosurfactant performance in oil-spill response, marine sediment remediation, and bilge-water treatment will provide valuable data on efficiency, stability, and ecological compatibility [25]. The establishment of standardized evaluation methods, environmental safety guidelines, and certification protocols will facilitate wider acceptance and market entry of marine biosurfactants. Collaborative frameworks involving academia, industry, and regulatory agencies are needed to ensure environmental and commercial success.

6. Conclusion

Marine biosurfactants represent a promising class of eco-friendly, biodegradable, and efficient surface-active molecules with vast potential in environmental biotechnology. Their ability to function effectively under extreme marine conditions—such as high salinity, temperature, and pressure—makes them suitable for diverse applications, including oil spill remediation, heavy metal removal, enhanced oil recovery, and wastewater treatment. And their potential, challenges persist in terms of production yield, high downstream processing costs, and limited commercialization due to regulatory and scalability barriers. Recent advances in metagenomics, synthetic biology, and bioprocess optimization are paving the way for enhanced biosurfactant discovery and sustainable production.

Integrating biosurfactant synthesis into circular biorefineries and validating their performance through field-scale trials will be essential for real-world deployment, marine biosurfactants hold strong promise as key biotechnological tools for promoting sustainable environmental management and reducing dependency on synthetic, petroleum-based surfactants.

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