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Biosurfactants: Eco-Friendly Tools for Environmental Remediation

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Abstract

Environmental pollution is one of the most serious global issues affecting human health and ecosystems, contributing significantly to mortality, morbidity, and environmental degradation. Among numerous remediation methods, biosurfactants have arisen as promising and sustainable agents for environmental remediation due to their ability to improve the solubilization, mobilization, and biodegradation of pollutants. Due to their surface-active nature, high biodegradability, emulsification potential, and low toxicity, they are broadly utilized in the remediation of petroleum hydrocarbons, oil spills, heavy metals, pesticides, industrial pollutants, and wastewater treatment. Advances in biotechnology and low-cost production strategies can further enhance their potential as eco-friendly alternatives to synthetic surfactants.

Introduction

Rapid industrialization and continuously increasing anthropogenic activities have raised concerns about the release and accumulation of different contaminants in natural ecosystems, thereby adversely affecting ecosystem functioning and human livelihoods. The natural environment is often contaminated with hydrophobic pollutants such as long-chain hydrocarbons, petrochemicals, oil spills, pesticides, and heavy metals. Hydrophobic, toxic pollutants with slow degradation rates and low solubility pose serious threats to the environment and human health (Sharma *et al.*, 2022). Surfactants have a wide range of applications in controlling environmental pollution, especially organic contaminants. However, most commercially used surfactants are synthetic, produced using petrochemicals as precursors via organochemical synthesis. These surfactants are listed amongst organic hydrocarbon pollutants, which can pose several associated risks. Recently, microbial strains and their derivatives have been used to degrade environmental contaminants. The ease of availability, high energy efficiency, lack of toxic residues, and cost-effectiveness have made microbes a preferred resource for environmental management. Microorganisms hold promise for manufacturing innovative biosurfactants due to their immense genetic diversity. Biosurfactants are surface-active biomolecules with amphiphilic properties and are widely used as lubricants, foaming agents, dye fixers, emulsion makers, and dispersion stabilizers in various fields, including agriculture, pharmaceuticals, and environmental contaminant cleanup (Kumar *et* *al.*, 2021). Consequently, biosurfactants are termed green surfactants because they can replace synthetic surfactants and are nontoxic, sustainable, and biodegradable (Markam *et al.*, 2024).

What are Biosurfactants?

Biosurfactants are amphiphilic compounds, produced by microorganisms during growth on hydrophobic or hydrophilic substrates, that contain both hydrophobic (nonpolar) and hydrophilic (polar) moieties. The non-polar part of a surfactant is typically comprised of a hydrocarbon chain, while the polar part (hydrophilic head group) consists of peptides, carbohydrates, phosphates, and proteins. The amphiphilic nature of biosurfactants enables them to exhibit a wide range of properties, namely, their capacity to reduce surface and interfacial tensions among various phases: liquid–solid, liquid–air, and liquid–liquid. This increases the solubility and mobility of hydrophobic pollutants, thereby making them more accessible to microbial degradation (Sehrawat *et al.*, 2025).

The majority of biosurfactants are synthesized extracellularly as lipopeptides and glycolipids, although they could be bound to the plasma membrane, mostly as glycolipopeptides. The number of microbes able to produce biosurfactant, namely *Bacillus* spp., *Pseudomonas* spp., *Arthrobacter* spp. and *Candida* spp., and their production involves

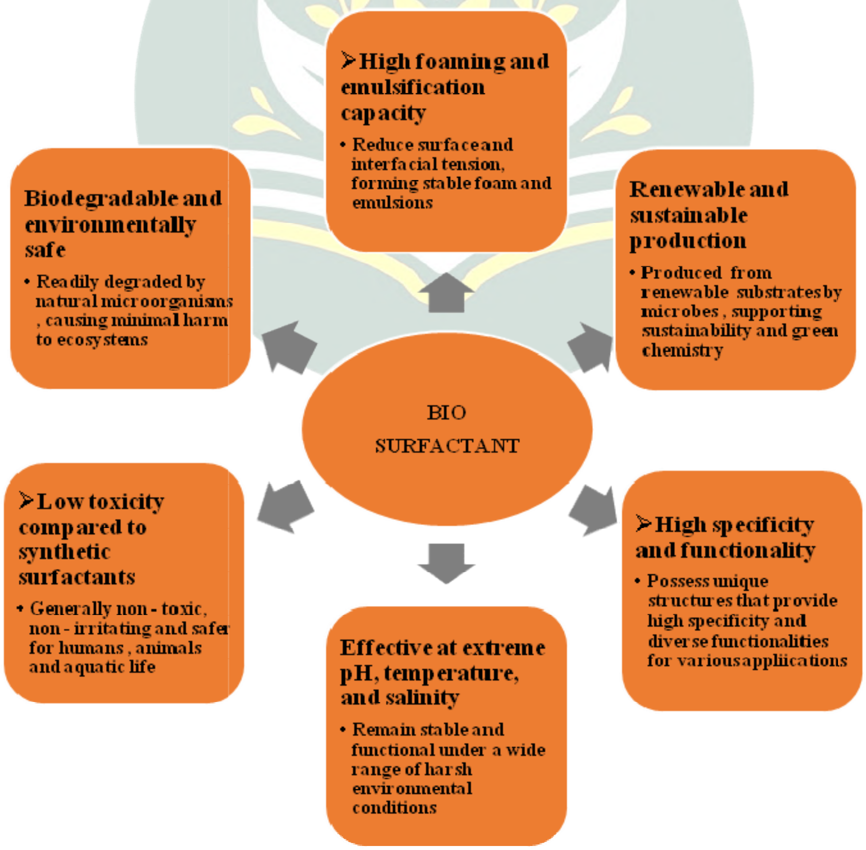

Fig. 1: Characteristics of Biosurfactants

Type of Biosurfactant	Chemical Nature	Biosurfactant Example	Application	Major producing microbes
Glycolipids	Carbohydrate + lipid	Rhamnolipids, Sophorolipids, Trehalolipids	Oil spill remediation, detergents	*Pseudomonas, Candida, Rhodococcus, Mycobacterium*
Lipopeptides	Peptide + lipid	Surfactin, Iturin, Fengycin, Lichenysin	Antimicrobial agents, bioremediation, plant disease suppression, pharmaceutical applications	*Bacillus*spp.
Phospholipids	Fatty acids + phosphate groups	Phosphatidylethanolamine, Phosphatidylglycerol, Cardiolipins	Hydrocarbon degradation, emulsification, membrane stabilization	*Acinetobacter, Thiobacillus, Corynebacterium*
Polymeric biosurfactants	Complex polymers	Emulsan, Liposan, Alasan	Dispersion of pollutants, biofilm formation, and industrial emulsification	*Acinetobacter, Candida*
Particulate biosurfactants	Membrane vesicles	Membrane vesicles of *Acinetobacter spp.* and *Pseudomonas spp.*	Metal removal and emulsification	*Acinetobacter*, *Pseudomonas*
Neutral lipids	Neutral fatty acid esters and waxes	Triacylglycerols,Wax esters	Lubrication, biodegradation of hydrophobic pollutants	*Nocardia*, *Rhodococcus*, *Mycobacterium*

fermentation, bioreactor systems, and genetic engineering techniques. The selection of a suitable substrate is crucial as it contributes to approximately 50% of the total production cost. Physicochemical parameters, including carbon (C) and nitrogen (N) sources, C: N ratios, and environmental factors such as pH and aeration rate, also affect the concentration (Dini *et al.,* 2024). To reduce production costs, using low-cost materials such as agricultural by-products (*e.g.,* corn steep liquor and orange peel), food waste (*e.g.*, frying oil, molasses, and cheese whey), and dairy waste is a feasible option. For the economical production of biosurfactants, it is essential to integrate both upstream production and downstream processing strategies. Enhancement of biosurfactant yield can be achieved through advanced optimization techniques such as response surface methodology, as well as Artificial Intelligence (AI)-based approaches including Artificial Neural Networks integrated with Genetic Algorithms (ANN-GA). Additionally, the use of genetically engineered or recombinant bacterial strains can further improve production efficiency and overall process performance (Sarubbo *et al*., 2022).

Major characteristics of biosurfactants

- Biodegradable and environmentally safe
- Low toxicity compared to synthetic surfactants
- Effective at extreme pH, temperature, and salinity
- High foaming and emulsification capacity
- Renewable and sustainable production
- High specificity and functionality

Classification of Biosurfactants

The classification of biosurfactants mainly depends on the origin of the microbes and their chemical composition. Based on molecular weight, biosurfactants are divided into two types: low-molecular-weight compounds, which have lower interfacial surface tension, and high-molecular-weight biosurfactants, which are the most efficient stabilizing agents and are known for their emulsifying properties (Salek *et al.*, 2022). The low molecular-weight biosurfactants include glycolipids, lipopeptides, and phospholipids, neutral lipids, whereas high molecular-weight biosurfactants include particulate biosurfactants (Shoeb *et al*., 2013; Sharma *et al.,* 2022).

Mechanism of Biosurfactant-Mediated Pollutant Removal

Biosurfactants play an important role in environmental remediation by increasing the bioavailability of hydrophobic contaminants through various mechanisms.

Major Mechanisms

1. Reduction of Surface and Interfacial Tension

Biosurfactants reduce surface and interfacial tension between liquids, solids, and gases, thereby enhancing the solubilization and emulsification of hydrophobic pollutants.

2. Micelle Formation

Biosurfactants form micelles at the critical micelle concentration (CMC), which encapsulate hydrophobic contaminants and increase their solubility. Critical Micelle Concentration is defined as the minimum concentration of surfactant required to achieve the lowest surface tension.

3. Enhanced Microbial Attachment

Biosurfactants alter microbial cell surface hydrophobicity, promoting attachment to hydrocarbons and improving degradation efficiency.

4. Mobilization and Solubilization

They mobilize contaminants trapped in soil pores and increase the transport of pollutants for biodegradation.

Applications of Biosurfactants in Environmental Remediation

- Remediation of petroleum hydrocarbons from oil-contaminated soils and refinery waste sites.
- Cleanup of oil spills in coastal and marine ecosystems through streamlined biodegradation and emulsification.
- Removal of heavy metals, namely lead (Pb), cadmium (Cd), chromium (Cr), and zinc (Zn), from contaminated soil and wastewater.

- Degradation of pesticides and detoxification of agricultural contaminants in soil.
- Industrial wastewater treatment for removal of oils, greases and toxic organic pollutants.
- Polycyclic aromatic hydrocarbon (PAH) degradation in polluted sediments and industrial sites.
- Bioremediation of contaminated groundwater through enhanced microbial degradation of hydrophobic pollutants
- Desorption and mobilization of pollutants from soil particles to enhance the biodegradation efficiency

Advances and Future Perspectives of Biosurfactants

- Development of cost-effective biosurfactant production technologies through renewable substrates and agro-industrial wastes.
- Advances in genetic engineering, synthetic biology, and fermentation processes to increase the yield and stability of biosurfactants.
- Expanding integration of biosurfactants with bioremediation, phytoremediation and nanotechnology for efficient elimination of pollutants.
- Expansion in various applications including wastewater treatment, petroleum remediation, pharmaceuticals, sustainable agriculture and green industries.
- Future large-scale commercialization of biodegradable biosurfactants as eco-friendly alternatives to synthetic surfactants for sustainable environmental management.

Conclusion

Biosurfactants are eco-friendly microbial surface-active compounds with significant potential in pollution control and environmental remediation. Their biodegradability, low toxicity, and efficient emulsification properties make them suitable alternatives to synthetic surfactants. Owing to their diverse applications in hydrocarbon degradation, wastewater treatment, and sustainable agriculture, biosurfactants are considered promising tools for future green and sustainable technologies.

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