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Biosurfactant-Producing Soil-Derived Bacterium *Pseudomonas stutzeri* and Its Potential Applications- A Mini Review

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Abstract: Biosurfactants are amphipathic biomolecules synthesized by microorganisms and have gained increasing attention as sustainable alternatives to synthetic surfactants. This mini review focuses on biosurfactant production by soil-derived bacteria of the genus *Pseudomonas*, with particular emphasis on *Pseudomonas stutzeri*. The review highlights the diversity, production strategies, and functional properties of biosurfactants produced by *P. stutzeri*, as well as their potential applications in food processing, environmental remediation, agriculture, and biotechnology. The ecological advantages of biosurfactants, including biodegradability, low toxicity, and effectiveness under extreme conditions, are discussed in comparison with conventional surfactants. Challenges related to high production costs, complex genetic regulation, and regulatory approval are also addressed. Further research focusing on strain improvement, cost-effective substrates, and process optimization is required to enhance the commercial competitiveness of *P. stutzeri*-derived biosurfactants.

Keywords: *Pseudomonas stutzeri*; biosurfactants; soil bacteria; bioremediation; food biotechnology; sustainable surfactants

Introduction

Surfactants are surface-active agents composed of amphipathic moieties and play a pivotal role in a wide range of industries, including paints, cosmetics, detergents, paper, petroleum, pharmaceuticals, food processing, and wastewater treatment (Akbari et al. 2023). However, the widespread use of synthetic surfactants is increasingly restricted due to concerns related to toxicity, poor biocompatibility, and adverse environmental impacts (Sarubbo et al. 2022). In contrast, biosurfactants are naturally derived surface-active compounds produced by microorganisms through sustainable and eco-friendly processes.

Recent life cycle assessments indicate that replacing synthetic surfactants with biosurfactants can reduce lifetime CO_2 emissions by approximately 8%, preventing nearly 1.5 million tonnes of CO_2 emissions annually (Farias et al. 2021; Rocha et al. 2019; Banat et al. 2021). Global surfactant production is estimated at nearly 10 million tonnes per year, with biosurfactants currently accounting for approximately 10% of the market share. Nevertheless, the growing demand for green and sustainable alternatives has positioned biosurfactants as a promising frontier in microbial biotechnology.

Biosurfactants exhibit excellent surface tension reduction, emulsification, foaming, wetting, and dispersion properties, enabling their application across agriculture, pharmaceuticals, cosmetics, food processing, environmental remediation, and emerging nanotechnological fields (Akbari et al. 2023; Kumar et al. 2021). Compared with their synthetic counterparts, microbial biosurfactants are biodegradable, less toxic, highly selective, and effective under extreme environmental conditions, making them particularly suitable for bioremediation and microbial enhanced oil recovery (Soberón-Chávez et al. 2021).

Soil bacteria represent a rich and sustainable reservoir of biosurfactant-producing microorganisms due to their remarkable adaptability to diverse and often harsh environmental conditions. Biosurfactant production, composition, and physicochemical properties are influenced by ecological, physiological, genetic, and biochemical factors (Dias and Nitschke 2023). Consequently, exploration of biosurfactant-producing strains from contaminated, extreme, endophytic, and diazotrophic environments has gained increasing attention, as these niches may harbor microorganisms capable of producing novel biosurfactants with unique functional properties.

Biosurfactant Production from *Pseudomonas* Species

Among biosurfactant-producing microorganisms, bacterial genera such as *Acinetobacter*, *Bacillus*, and *Pseudomonas* are the most extensively studied. Based on molecular weight and chemical structure, biosurfactants are broadly classified into low-molecular-weight biosurfactants and high-molecular-weight bioemulsifiers. These groups are further categorized into glycolipids, lipopeptides, lipoproteins, phospholipids, lipopolysaccharides, and fatty acid–based surfactants (Charan and Patel 2017).

Biosurfactants produced by *Pseudomonas* species are of particular interest due to their versatility and high surface activity. These biomolecules have demonstrated significant potential in environmental remediation, agriculture, biomedicine, food processing, and nanotechnology. *Pseudomonas aeruginosa* is well known for producing rhamnolipids—glycolipid biosurfactants composed of rhamnose units linked to β-hydroxy fatty acids—which exhibit superior emulsifying and biodegradation-enhancing properties (Adetunji and Olaniran 2021; Dobler et al. 2020).

Biosurfactant Production by *Pseudomonas stutzeri* and Its Applications

Recent studies have highlighted *Pseudomonas stutzeri* as an emerging biosurfactant-producing bacterium capable of utilizing a wide range of carbon sources, including hydrocarbons and agro-industrial wastes. Several soil- and sediment-derived strains of *P. stutzeri* have been reported to produce biosurfactants and bioemulsifiers with strong surface activity, stability under extreme environmental conditions, and biodegradability (Fan et al. 2017).

Biosurfactants produced by *P. stutzeri* have demonstrated promising applications in the food industry as natural emulsifiers, preservatives, and antimicrobial agents. Their antibacterial, antiadhesive, and non-fouling properties enable their use in improving food safety and extending shelf life (Satpute et al. 2018; Anaukwu et al. 2024; Nalini et al. 2020). In addition, the strain *P. stutzeri* NJtech 11-1 produces a robust bioemulsifier with excellent emulsification efficiency, making it suitable for industrial and food-related applications (Fan et al. 2017).

Environmental applications of *P. stutzeri* biosurfactants are particularly noteworthy. Strains isolated from oil-contaminated soils, such as *P. stutzeri* SJ3 and Z12, have demonstrated high efficiency in hydrocarbon degradation and crude oil–contaminated soil remediation (Harikrishnan et al. 2021; Pourfadakari et al. 2020). Recent studies have further reported biosurfactant-assisted electrokinetic remediation of heavy metal–contaminated soils using *P. stutzeri* biosurfactants, significantly enhancing metal mobilization and removal efficiency (Narenkumar et al. 2024).

Table 1. Summary of Biosurfactant production by *Pseudomonas stutzeri* and applications

***P.stutzeri* Strain/Source**	**Isolation Source**	**Type of Biosurfactant / Bioemulsifier**	**Key Characteristics**	**Applications**	**Reference**
P. stutzeri (soil isolate)	Soil	Bioemulsifier	High emulsification activity; stable over wide pH and temperature ranges	Industrial emulsification processes	Li et al. (2016)
P. stutzeri (environmental isolate)	Soil	Bioemulsifier	Effective hydrocarbon emulsification; biodegradability	Environmental remediation	Fan et al. (2017)
P. stutzeri Z12	Extreme environment	Glycolipid-type biosurfactant	High stability in salinity and temperature extremes	Hydrocarbon-contaminated soil remediation	Pourfadakari et al. (2020)
P. stutzeri SJ3	Oil-contaminated soil	Biosurfactant	High crude oil degradation efficiency; surface tension reduction	Bioremediation of petroleum-polluted soil	Harikrishnan et al. (2021)
P. stutzeri (waste-derived strain)	Shrimp shell waste	Biosurfactant	Utilizes agro-industrial waste; eco-friendly production	Sustainable biosurfactant production	Kadam & Savant (2019)
Pseudomonas spp. (comparative studies)	Soil / wastewater	Rhamnolipids / Lipopeptides	High emulsification index; antimicrobial potential	Agriculture, food, pharmaceutical industries	Mnif & Ghribi (2015); Kumar et al. (2021)

Recent advancements and Nanotechnology Integrations

Recent advancements have expanded the application spectrum of *P. stutzeri* biosurfactants into nanotechnology. A 2024 study reported biosurfactant-mediated synthesis of zinc oxide nanoparticles using *P. stutzeri* isolated from oil-contaminated soil, demonstrating enhanced antimicrobial and biological activity (Sanuj and Vanitha 2024). Such findings highlight the dual role of biosurfactants as both stabilizing and reducing agents in green nanoparticle synthesis.

Furthermore, the use of low-cost substrates such as shrimp shell waste, fish waste, and agricultural residues has been shown to significantly reduce production costs while enhancing sustainability (Kadam and Savant 2019). These developments underscore the growing interest in integrating waste valorization, biosurfactant production, and nanotechnology for sustainable industrial applications.

Challenges and Future Prospects

Despite their significant potential, large-scale commercialization of biosurfactants remains constrained by high production costs, complex genetic regulation of biosynthetic pathways, and regulatory hurdles, particularly in food and pharmaceutical applications. Future research should focus on metabolic engineering, optimization of fermentation processes, utilization of renewable substrates, and biosurfactant-mediated nanotechnological applications to enhance economic feasibility and industrial scalability.

Conclusion

This mini-review highlights the growing importance of biosurfactants produced by *Pseudomonas stutzeri* as sustainable alternatives to synthetic surfactants. With applications spanning food processing, environmental remediation, agriculture, biomedicine, and nanotechnology, *P. stutzeri* biosurfactants represent a promising class of microbial biomolecules. Addressing production challenges, improving cost-effectiveness, and ensuring regulatory compliance will be critical for their broader industrial adoption.

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