Chinese Industry and Technology of Eco-environment
2025, VOL. 6, NO. 3, 59-62
DOI: 10.47297/wspciateWSP2633-772X11.20250603

Advances in the Research of Natural Surfactants

Youmin Zhu, Shengjie Zhu, Wang Chen, Yuncai Tian

Shanghai AZ Science and Technology Co., Ltd., Shanghai, 201109, China

ABSTRACT

Natural surfactants, as a class of biomolecules derived from biomass and possessing amphiphilic structures, have attracted widespread attention across various fields—including cosmetics, food, pharmaceuticals, agriculture, oil extraction, and environmental remediation—due to their green, renewable nature and excellent biodegradability. This review provides a comprehensive review of the major types, biosynthesis methods, functional properties, and recent advances in the application of natural surfactants. It offers an in-depth analysis of the raw material sources, structural characteristics, and preparation strategies of bio-based, plant-derived, and animal-derived surfactants, while elucidating their functional behaviors such as interfacial activity and self-assembly properties. Furthermore, the review examines the current applications of natural surfactants in diverse areas including daily chemical cleaning, drug delivery, food processing, agriculture, and environmental restoration. Addressing existing challenges, it also proposes future development directions, offering theoretical insights to support further research and practical utilization of natural surfactants.

KEYWORDS

Natural surfactants; Biodegradability; Advances

1 Introduction

Surfactants are amphiphilic molecules featuring both hydrophilic and hydrophobic ends, capable of reducing interfacial tension and forming aggregated structures such as micelles and emulsions. They are widely used in various industrial fields including cleaning products, cosmetics, pharmaceuticals, food processing, and oil extraction. The global surfactant market continues to grow steadily. However, most conventional surfactants are derived from petrochemical feedstocks and pose environmental concerns such as persistence, bioaccumulation, and ecotoxicity. With increasing global emphasis on sustainability and environmental protection, the development of natural surfactants sourced from renewable materials has become a key research focus in both industry and academia. Natural surfactants refer to surface-active substances extracted from plants, animals, or microorganisms, or synthesized through biocatalytic processes, including saponins, phospholipids, proteins, and polysaccharide derivatives. Compared to synthetic surfactants, natural surfactants offer significant advantages, including renewable raw materials, excellent biodegradability, high environmental compatibility, and low toxicity [1]. This paper aims to provide a comprehensive overview of the research progress on natural surfactants, systematically reviewing their types and sources, synthesis and preparation techniques, functional properties, and application areas. It also offers insights into future challenges and prospects, serving as a reference for researchers and industry professionals in related fields.

2 Main types and sources

Natural surfactants can be categorized into three main groups based on their origin: plant-based, animal-based, and microbial-based. Classified by chemical structure, they include saponins, phospholipids, proteins, polysaccharides, and lipopeptides. Each type possesses distinct chemical properties and practical applications.

2.1 Bio-based surfactants

Bio-based surfactants are surface-active agents synthesized from biomass feedstocks through chemical or biological processes. One important class is derived from natural aldehydes and amino acids. For instance, citral can undergo reductive amination with glycine under alkaline conditions to quantitatively yield N-geranyl glycine, which upon further hydrogenation produces N-tetrahydrogeranyl serine—a compound exhibiting excellent surfactant properties. Rosin, an abundant and low-cost renewable forest resource, features a hydrophobic tricyclic diterpene structure. By introducing hydrophilic groups, rosin can be transformed into high-value, biodegradable green surfactants. Rosin-based surfactants encompass various types, including anionic (carboxylates, sulfonates, sulfates, and phosphates), cationic (e.g., quaternary ammonium salts), nonionic (polyol-type and polyoxyethylene-type), and zwitterionic (betaine-type and amine oxide-type). Li et al. developed a novel anionic rosin-based surfactant, sodium dialkyl phosphate diester (DDPDS), which demonstrates high surface activity and strong emulsifying capability [2].

2.2 Plant-derived surfactants

Plant-derived surfactants are surface-active substances extracted from plant tissues, primarily including saponins, phospholipids, proteins, and polysaccharides. Phospholipids, a key class of amphiphilic molecules, are mainly obtained from oil-rich crops such as soybeans and rapeseed. They exhibit excellent emulsifying properties and biocompatibility, making them widely used in food, pharmaceutical, and cosmetic industries. Protein-based surfactants are peptide-rich compounds produced through enzymatic or chemical hydrolysis of plant proteins—such as soy and wheat proteins—and offer strong interfacial activity with mild characteristics, making them particularly suitable for personal care formulations. Saponins, naturally occurring glycosides found in many plants, consist of a sapogenin core linked to sugar chains and demonstrate effective foaming and emulsifying capabilities. Common examples include tea saponins extracted from tea seeds and gleditsia saponins derived from soap pods. Fernandez-Vazquez et al. found that saponin-based surfactants can enhance the degradation of oily contaminants in soil [3].

2.3 Animal-derived surfactants

Surfactants of animal origin are primarily obtained from animal tissues or secretions and include phospholipids, proteins, and polysaccharides. Lecithin, a key phospholipid surfactant extracted from egg yolk or animal liver, is widely used in the food and pharmaceutical industries due to its excellent emulsifying properties and nutritional benefits. Bile salts, naturally occurring surfactants found in animal bile, play a crucial role in the digestion and absorption of fats in the intestine. Piñon-Gómez et al. successfully developed a food-grade microemulsion using bile salts as the surfactant. This microemulsion demonstrated exceptional stability, remaining clear and phase-stable even under conditions of high-speed shear mixing or elevated temperatures [4].

2.4 Microbial surfactants

Microbial surfactants are surface-active compounds produced by microorganisms, encompassing a diverse group of substances such as glycolipids, lipopeptides, phospholipids, fatty acids, and polymeric surfactants. Glycolipids are formed through the esterification of carbohydrates with long-chain or hydroxy fatty acids. Notable examples include rhamnolipids produced by Pseudomonas aeruginosa and trehalose lipids synthesized by yeasts, both of which exhibit excellent emulsifying, foaming, and wetting properties. Lipopeptides consist of fatty acid chains linked to amino acid sequences via peptide bonds. A prominent example is surfactin, generated by Bacillus subtilis, whose molecular structure features both a hydrophobic lipid tail and a hydrophilic peptide ring, endowing it with exceptional surface activity. These compounds show great promise in applications ranging from enhanced oil recovery and environmental bioremediation to household products and pharmaceuticals [5].

3 Functional features and mechanisms

3.1 Interfacial activity and self-assembly

The primary function of natural surfactants is to reduce interfacial tension, thereby facilitating the formation and stabilization of emulsions. Interfacial activity is typically characterized by parameters such as the critical micelle concentration (CMC) and the minimum surface tension (γCMC). When the concentration exceeds the CMC, surfactant molecules spontaneously organize into ordered aggregates in solution, including micelles, reverse micelles, and vesicles [6].

3.2 Stabilization mechanisms

The stabilization mechanisms of natural surfactants primarily involve electrostatic repulsion, steric hindrance, and interfacial film reinforcement. Electrostatic repulsion plays a key role in preventing droplet aggregation by generating repulsive forces between charged droplets in emulsions stabilized by ionic surfactants. Steric hindrance works by forming a thick adsorbed layer of surfactant molecules on the droplet surface, physically blocking close approach. Interfacial film reinforcement enhances stability by creating a mechanically robust interfacial film that resists external stresses [7].

4 Biosynthesis technologies for natural surfactants

The biosynthesis of natural surfactants primarily relies on microbial fermentation and plant extraction. This process essentially harnesses microbial metabolism to convert hydrophobic carbon sources and other molecules into amphiphilic surface-active compounds. Fermentation-based production currently stands as the most established and widely adopted industrial method. Its core strategy involves optimizing fermentation conditions and selecting high-performance microbial strains to significantly boost yields. Metabolic engineering and synthetic biology employ genetic tools to rationally redesign high-yield strains, creating "cell factories" that overcome the production limitations of natural strains. Overexpressing genes encoding key enzymes strengthens biosynthetic pathways and enhances flux toward the target product. Meanwhile, knocking out or suppressing competing pathways that consume precursors redirects metabolic flux to the desired surfactant. For instance, Wu et al. engineered multiple genes in Bacillus subtilis, ultimately increasing surfactin production to 12.8 g/L [8].

5 Application areas

Natural surfactants are widely used in industries such as cosmetics, food, pharmaceuticals, agriculture, oil recovery, and environmental remediation. Glycolipids (e.g., rhamnolipids) and lipopeptides exhibit excellent emulsifying, solubilizing, and foaming properties, making them ideal for formulating facial cleansers, shampoos, and body washes—offering gentle cleansing with reduced skin irritation. Certain natural surfactants can enhance food texture and improve processing characteristics. Thanks to their strong antibacterial, antiviral, and antifungal activities, lipopeptides are promising candidates for developing novel antibiotics. Some lipopeptides effectively suppress plant pathogens and can serve as bio-based agricultural fungicides. Glycolipids significantly reduce interfacial tension in crude oil, thereby enhancing oil recovery rates. Additionally, certain natural surfactants facilitate the breakdown and removal of environmental pollutants, supporting ecosystem restoration efforts [9].

6 Challenges and future prospects

6.1 Challenges

Despite significant progress in the research of natural surfactants, several challenges remain. The extraction and purification of many natural surfactants involve high costs, making them less competitive compared to synthetic counterparts. Certain natural surfactants may fall short in specific performance aspects—such as stability or foaming capacity—compared to synthetic versions, necessitating chemical modification or formulation blending to enhance their properties. Additionally, the lack of standardized regulations results in inconsistent product quality across the market.

6.2 Future outlook

Future research should focus on the application of emerging technologies, development of novel products, and expansion into new application areas. Advances in synthetic biology and metabolic engineering offer powerful new tools for the efficient production of natural surfactants, paving the way for greener transformations in industries such as cleaning, cosmetics, and food. In terms of product innovation, emphasis should be placed on designing multifunctional natural surfactants that combine surface activity with additional functional properties, tailored to meet the demands of diverse applications.

Sustainability will be a key driver in the future development of natural surfactants. The exploration of renewable feedstocks for novel surfactant design, coupled with green synthesis and manufacturing technologies, will be essential in minimizing environmental impact—marking an inevitable shift toward sustainable development in the surfactant industry.

7 Conclusion

As eco-friendly alternatives to synthetic surfactants, natural surfactants demonstrate broad application potential across industries including cosmetics, food, pharmaceuticals, agriculture, oil recovery, and environmental remediation. Beyond their effective surface-active properties, they offer distinct advantages such as excellent biodegradability, high environmental compatibility, and low toxicity.They often possess unique biological activities as well. However, research and application of natural surfactants still face several challenges, including high production costs, performance optimization, and incomplete regulatory standards. Future efforts should focus on the adoption of innovative technologies, development of novel products, and expansion into emerging application areas. With the growing consumer demand for green and sustainable solutions, natural surfactants are poised for significant growth. Through continuous research and innovation, they hold strong potential to replace a large portion of synthetic surfactants, offering safer, healthier, and more environmentally friendly alternatives in surface engineering.

About the Author

Youmin Zhu, May 1984, male, Han Nationality, native place: Taian, Shandong province, education or professional title, intermediate professional title, engaged in research direction or work field, Synthetic Biology.

References

[1] Grzywaczyk A, Rojewska M, Smułek W, et al. Glycyrrhiza glabra L. Saponins Modulate the Biophysical Properties of Bacterial Model Membranes and Affect Their Interactions with Tobramycin. Langmuir. 2025;41(18):11701-11710.

[2] Li J, Lin HX, Chen XY, et al. Self-assembled structures and excellent surface properties of a novel anionic phosphate diester surfactant derived from natural rosin acids. J Colloid Interface Sci. 2017;486:67-74.

[3] Fernandez-Vazquez A, Posada-Baquero R, Ortega-Calvo JJ. A plant biosurfactant enhances the biodegradation of slowly desorbing PAHs in contaminated soil. J Hazard Mater. 2025;495:139102.

[4] Piñon-Gómez L, Gutiérrez-Méndez N, Rodríguez-Figueroa JC, et al. Formulation and heat stability of self-assembled O/W food-grade microemulsions formulated with bile salts or tween 80 as surfactants. Colloids Surf B Biointerfaces. 2025;251:114589.

[5] Qin WQ, Liu YF, Gang HZ, et al. Structural diversity of surfactin lipopeptides and their molecular behaviors in solutions and at interfaces. Adv Colloid Interface Sci. 2025;343:103581.

[6] Pollard BL, Liu Y, Gardiner MG, Connal LA. N-Geranylated Amino Acid Surfactants with Low Critical Micelle Concentrations from Abundant, Naturally Derived Starting Materials. ChemistryOpen. Published online August 21, 2025.

[7] Bazyari A, Hashemi A, Soulgani BS. Experimental and theoretical investigation of zwitterionic surfactant adsorption on calcite for enhanced oil recovery. Sci Rep. 2025;15(1):22730. Published 2025 Jul 2.

[8] Wu Q, Zhi Y, Xu Y. Systematically engineering the biosynthesis of a green biosurfactant surfactin by Bacillus subtilis 168. Metab Eng. 2019;52: 87-97.

[9] Blanco-Llamero C, García-García P, Señoráns FJ. Efficient Green Extraction of Nutraceutical Compounds from Nannochloropsis gaditana: A Comparative Electrospray Ionization LC-MS and GC-MS Analysis for Lipid Profiling. Foods. 2024;13(24):4117. Published 2024 Dec 19.