Biosurfactants: Sustainable and Versatile Molecules for Industrial and Environmental Applications

Monali Aniruddha Kohinkar[1], Neha Bhola Sahani[2], Divya Vidyasagar Kshirsagar[3], Prachi Arvind Jagdale[4]

[1,2,3,4]Lokmanya Tilak Institute of Pharmaceutical Sciences, Pune.

Corresponding author: Monalikalbhor3131@gmail.com
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Abstract:

Biosurfactants are amphiphilic compounds mainly generated by microorganisms, comprising both hydrophilic and hydrophobic parts that position themselves at liquid–liquid, liquid–gas, or liquid–solid interfaces. Their distinctive properties enable them to facilitate emulsification, detergency, and dispersion, making them precious across various industrial applications. Biosurfactants are synthesized by a variety of microorganisms and have some unique advantages over synthetic surfactants, such as mild production requirements, greater biodegradability, and lower toxicity during the microbial synthesis of active compounds. Because they can decrease surface tension, stabilize emulsions, and upgrade biodegradation, they are increasingly in demand as substitutes for chemical surfactants in both research and practical applications. In the food industry, biosurfactants are commonly employed as formulation ingredients and anti-adhesive agents, functioning as emulsifiers, de-emulsifiers, foaming agents, and detergents, with further uses in agriculture, industrial processes, and environmental recreation. The article discusses the potential applications of biosurfactants in the food and agricultural field, along with current efforts to decrease their production cost by using unconventional waste materials as substrates.

Keywords: Anti-adhesive, Biodegradable, Surfactants, Amphiphilic substance antimicrobial agents, Nanotechnology, Bioemulsifier.

INTRODUCTION

Surfactants are surface-active molecules containing both hydrophilic and hydrophobic regions. They can reduce the surface and interfacial tension at the dividing line between solids, liquid and gases. These compounds create microemulsions in which hydrocarbons can dissolve in water or water can dissolve in hydrocarbons. Because of these properties, surfactants exhibit excellent detergent, emulsifying, foaming, and dispersing abilities, making them highly versatile process chemicals [1,2]. Biosurfactants, known for their strong surface-activating properties and their ability to significantly lower surface and interfacial tensions, constitute a diverse group of surface-active molecules. These amphiphilic compounds contain both hydrophilic and hydrophobic segments within their molecular structure [3,4] .The hydrophilic portion may include mono-, oligo-, or polysaccharides, peptides, or proteins, while the hydrophobic part typically consists of saturated, unsaturated, or hydroxylated fatty acids or fatty alcohols [5].These two elements tend to orient themselves at the interfaces of fluid phases with differing polarity and hydrogen-bonding characteristics, such as air–water or oil–water interfaces. This behaviour underlies their wide applicability in environmental processes, the medical field, and the oil industry [6,7]. Microbially derived surfactants may remain attached to the cell surface or be secreted extracellularly into the growth medium. They contain both hydrophobic and hydrophilic components, enabling them to accumulate at the boundaries between fluid phases and effectively reduce surface and interfacial tensions [8,9]. The word 'biosurfactants' and 'bioemulsifiers' are not physically identical. Biosurfactants, produced by microorganisms, are defined by their ability to reduce surface tension at interfaces, whereas bioemulsifiers are compounds that promote emulsification. Although biosurfactants often exhibit emulsifying properties, bioemulsifiers do not always lower surface tension [10,11].

GENERAL PROPERTIES OF BIOSURFACTANTS

The exceptional surface activity of biosurfactants makes them more effective emulsifying, foaming, and dispersing agents than their chemically synthesized counterparts [12].

There are several important properties of biosurfactants, which are described below: -

1) Surface activity:

The adsorption behaviour of biosurfactants at surfaces and interfaces has drawn considerable attention. This is mainly because biosurfactants tend to be more effective and efficient, with critical micelle concentrations (CMC) generally much lower than those of chemical surfactants. Surfactin produced by B. subtilis can lower the surface tension of water to 25 mN m^{-1} and reduce the interfacial tension in a water/hexadecane system to below 1 mN m^{-1} [13].

2)pH and thermal activity:

The surface activities of many biosurfactants remain stable under natural conditions such as variations in temperature and pH. For instance, surfactin becomes less soluble in water at lower pH levels due to protonation of its carboxyl group [14]. In contrast, under neutral or alkaline conditions, where the carboxyl group exists in its ionic form, both its solubility and emulsifying capacity increase in aqueous solutions [15].

3)Antiadhesive Property:

Biofilm formation is a process in which microorganisms irreversibly attach to a surface, grow, and produce extracellular polymers that support attachment and matrix development, ultimately altering their phenotype in terms of growth rate and gene expression. Bacteria, fungi, and protists are among the microorganisms known to form biofilms [16]. Biosurfactants have attracted significant attention, especially in clinical and hygienic fields, because of their ability to disrupt microbial biofilms often more effectively than conventional inhibitory agents used against bacterial and yeast biofilms. Studies have shown that pre-coating solid surfaces with biosurfactants may offer a novel and effective strategy to prevent the colonization of pathogenic microorganisms [17].

4. Biodegradability:

A major advantage of compounds produced by microorganisms is their ease of degradation compared to synthetic counterparts, making them suitable for environmental applications such as bioremediation, anticorrosive treatments, and biosorption [18,19]. Consequently, biosurfactants are viewed as viable alternatives in response to growing ecological concerns, since synthetic surfactants pose significant environmental risks due to their non-biodegradable nature. The biodegradability of biosurfactants measured as the BOD/TOD ratio (biochemical oxygen demand to total oxygen demand) has been reported to reach 61% for sophorolipids after eight days of cultivation [20].

5)Emulsifying Ability:

A natural characteristic of biosurfactants is their ability to function as emulsifiers. An emulsion is heterogeneous complex in which one non-miscible liquid is dispersed in another as droplets. These systems typically show low stability, but the addition of surfactants can enhance stability by lowering interfacial tension and reducing the surface energy between the two phases [21,22].

Other notable properties include non-toxicity, an effective critical micelle concentration, demulsification ability, antioxidant activity, and antimicrobial effects, along with stability under various environmental conditions such as wide pH ranges, high salt concentrations, and extreme temperatures [12].

CLASSIFICATION OF BIOSURFACTANTS

While chemical surfactants are typically classified based on the type of their polar head groups, biosurfactants are mainly grouped according to their chemical structure and the microorganisms that produce them [2].

Table1.1 Classification of biosurfactant [23,24,25,26,27,27,28,29,30,16,31,32,33,15,34,35,36,37,38,39,40,41].

Biosurfactant		**Microorganisms/ Producers**	**Applications**
Group	Class		
Glycolipids	Rhamnolipids	Pseudomonas Aeruginosa	Increase degradation of hydrocarbons, antimicrobial activity.
	Trehalolipids	Mycobacterium tuberculosis	Facilitates the bioavailability of hydrocarbons, anti-adhesive activity against various bacteria.
	Sophorolipids	Candida bombicola, candida apicola	Increase the oil recovery, antimicrobial activity.

	Xylolipids	Lactococcuslactis	Control the stability of cell membrane
	Cellobiolipids	Cryptococcus humicola	Bioremediation
Lipopeptides	Surfactin	Bacillus subtilis	Moving heavy metal from contaminated soil, antifungal, antitumour activity.
	Lichenysin	Bacillus licheniformis	Improve oil recovery, antibacterial activity.
	Iturin	Bacillus subtilis	Enhancement of electrical conductance of biomolecular lipid membrane, non-toxic and non-pyrogenic adjuvant.
	Fengysin	Bacillus subtilis	Antifungal activity
	Viscosin	P. libanensis	Antibacterial activity.
	Flavolipid	Flavobacterium sp.	Biotechnological field.
Polymeric biosurfactant	Emulsan	Acinetobactorcalcoaceticus	Balance the hydrocarbon-in-water emulsions.
	Alosan	Acinetobactor radioresistens RAG-1	Balance the hydrocarbon-in-water emulsions.
	Biodispersan	Acinetobactorcalcoaceticus A2	Dispersion of limestone in water.
	Liposan	Candida lipolytica	Balance the hydrocarbon-in-water emulsions.
	Mannoprotein	Saccharomyces cerevistae	Dispersion of limestone in water.

Fatty acid, phospholipids, neutral lipids	Corynomycolic acid	Corynebacteriumlepus	Improve bitumen recovery
	Spiculisporic acid	Penicillumzpiculisporum	Removal of metal ion from aqueous solutions,
	Phosphatidylethanolamine	Acinetobacter sp.	Enhancement of tolerance of bacteria to heavy metals

FACTORS AFFECTING BIOSURFACTANT PRODUCTION

The producer strain is a major factor in determining the type and emulsifying properties of a biosurfactant. Additionally, the nature of the carbon and nitrogen sources, the C:N ratio, nutrient limitations, and environmental conditions such as pH, aeration, and salinity significantly influence the type, activity, and overall yield of biosurfactant production.

1)Carbon source:

The nature of the carbon substance crucially effects feature of the biosurfactant produced [42]. Diesel and crude oil have been identified as effective carbon sources for biosurfactant synthesis [43]. Water-soluble substance like glucose, sucrose, and glycerol also serve as crucial carbon sources. Hydrophobic substrates including corn oil, lard (which contains both saturated and unsaturated fats), and long-chain alcohols tend to enhance biosurfactant production, whereas hydrophilic substrates like glucose and succinate generally result in lower yields [44].

2)Nitrogen source:

Because nitrogen is essential for protein and enzyme synthesis, it plays a crucial role in microbial growth and, consequently, in biosurfactant production. For Arthrobacter paraffineus, ammonium salts and urea serve as the most suitable nitrogen sources, whereas in P. aeruginosa, ammonium nitrate yields the highest biosurfactant production [4].

3)Environmental conditions:

Environmental conditions such as pH, temperature, and oxygen availability influence microbial growth and activity, and therefore affect the efficiency and extent of biosurfactant production. In contrast, rhamnolipid production by Pseudomonas species is highest at a pH between 6 and 6.5, and declines sharply above pH 7. Most biosurfactants are produced within a temperature range of 25–30 °C, indicating that biosurfactant synthesis generally exhibits moderate thermal stability. Agitation and oxygen availability likewise influence biosurfactant production by promoting microbial growth and improving oxygen transfer from the gas phase to the liquid medium [45].

APPLICATION OF BIOSURFACTANT

In addition to their uses in environmental biotechnology and medicine, biosurfactants are also widely applied in industries such as petroleum, food and beverages, cosmetics, detergents, textiles, paints, mining, and nanotechnology [46].

1)Petroleum industry

For enhanced oil recovery, heat, surfactants, and gas injection are essential to extract the large amount of residual oil left behind during the primary process. However, the high cost of chemical surfactants remains a major economic limitation. Biosurfactants effectively lower oil–water and oil–rock interfacial tension, reduce capillary forces, and form emulsions, thereby improving the recovery of trapped residual oil [47].

2)Bioremediation

Bioremediation offers an effective, natural method for breaking down these toxic pollutants through plants and microorganisms, converting them into less harmful substances or even completely into carbon dioxide and water. In this process, biosurfactants serve as a safe option to enhance the solubility of hydrophobic hydrocarbons by promoting their desorption and solubilization, making them easier for microbes to degrade [48].

3)Removal of heavy metals

Heavy metals typically bind to soil surfaces as ions or metal compounds, and can be removed through surface complexation [49] or ion exchange [50]. Surfactant-enhanced bio-extraction is therefore useful for cleaning heavy-metal-contaminated soils, and the effectiveness of surfactin, rhamnolipids, and sophorolipids in this process has been well demonstrated [51,52].

4) Nanotechnology

The use of biosurfactants in nanoparticle synthesis is an emerging area of green chemistry. For instance, a biosurfactant produced by P. aeruginosa in a low-cost medium has been used to stabilize silver nanoparticles in solution [53].

CONCLUSION

Biosurfactants are eco-friendly amphiphilic molecules with strong surface-active properties that enable them to lower surface and interfacial tensions more effectively than many synthetic surfactants. Their low CMC values, stability across varying pH and temperature conditions, strong emulsifying ability, antiadhesive action against biofilms, and excellent biodegradability make them highly suitable for environmental, industrial, agricultural, and food applications. With increasing efforts to reduce production costs using renewable or waste substrates, biosurfactants continue to emerge as sustainable, multifunctional alternatives capable of meeting modern industrial and environmental needs.

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