BIOSURFACTANTS: A SUSTAINABLE APPROACH FOR HYDROCARBON BIOREMEDIATION AND INDUSTRIAL APPLICATIONS

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Abstract

A significant amount of waste is produced and released into the environment due to the increased use of crude oil and other oil-related products. Hydrocarbon-degrading bacteria tend to form a surface-active biomolecule known as a biosurfactant during the biodegradation process. Biosurfactants can form intracellularly and extracellularly and are hydrophobic and hydrophilic in nature, while lowering the interfacial surface tension. A wide range of microorganisms, including bacterial species of genera *Pseudomonas*, *Bacillus*, *Acinetobacter*, etc., and filamentous fungi of the genera *Aspergillus, Penicillium*, etc., and yeast-like *Candida*, etc., have been identified as efficient biosurfactant producers. There are many advantageous characteristics of biosurfactants, such as low toxicity, biodegradability, environmental compatibility, etc. Accordingly, biosurfactants have received increasing attention for a wide range of applications in various fields. In environmental protection, they are widely significant for their role in the bioremediation process. On the other hand, biosurfactants intended for use in food, pharmaceutical, and agriculture fields are produced under safe conditions using non-pathogenic strains and substrates. This article presents a review of available data and publications regarding surfactants, biosurfactants, biosurfactant classification, biosurfactant-producing bacteria, and applications.

Keywords: Biosurfactants, Petroleum Pollution, Hydrocarbon Bioremediation, Microbial Surfactants, Petroleum Degradation, Industrial Applications

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Background

A large amount of waste is being released into the natural environment due to the increasing reliance on crude oil and other petroleum-based products, which has significantly increased environmental pollution. These pollutants, which include hazardous petroleum hydrocarbons and heavy metals, cause severe harm to both terrestrial and aquatic environments due to their toxicity, low biodegradability, and persistence (Ambaye et al., 2021). Physical and chemical remediation methods often have limitations such as high cost & secondary pollution. However, bioremediation has been considered as an eco-friendly, sustainable approach for hydrocarbon degradation.

Biosurfactants are naturally occurring, surface-active substances produced by microorganisms such as bacteria, fungi, and yeast (Fardami et al., 2022). Biosurfactant-producing bacteria play an important role in bioremediation as biosurfactants have gained considerable attention for their ability to address environmental contamination. These microbially derived biomolecules can reduce surface and interfacial tension in organic and non-organic mixtures (Ambaye et al., 2021). Qualities like emulsification, foaming, wetting, and surface activity make biosurfactants applicable in various industrial settings.

Biosurfactants can be categorized into various classes according to their molecular structure and chemical composition, including phospholipids, fatty acids, polysaccharide-protein complexes, glycolipids, lipopeptides, and neutral lipids. Some of these classes can be divided again into sub-classes (Simões et al., 2024). These biosurfactants increase the bioavailability of petroleum pollutants, enabling degradation by microorganisms. Various microorganisms produce biosurfactants with different applications, and some examples of microorganisms producing biosurfactants include *Pseudomonas aeruginosa* (Chabhadiya et al., 2024), *Candida* spp. , *Bacillus subtilis*, and *Acinetobacter*, and some yeast species (Batool et al., 2017; Fardami et al., 2022).

Biosurfactants have different advantageous characteristics. Due to their eco-friendly nature, less toxicity, environmental compatibility, and biodegradability, biosurfactants have been increasingly recognized as sustainable alternatives in a wide range of industries and greater demand on a global scale. According to the biosurfactants market, the global biosurfactant market has shown consistent growth. It is estimated to grow from $4.20 billion in 2017 to $5.52 billion in 2022, with a compound yearly growth rate of 5.6% (Ambaye et al., 2021).

Across a variety of industries, biosurfactants have shown notable applicability. These may include pharmaceuticals, the food industry, the petroleum industry, the agricultural industry, the cosmetic industry, and environmental protection. In environmental biotechnology, they are utilized in the bioremediation of heavy metals, enhancing oil recovery, and reducing metal toxicity in contaminated soils (Xi et al., 2021). Moreover, biosurfactants are potential candidates for antimicrobial substances, with some types having antifungal and antibacterial effects. Their role in the food industry, petroleum sector, detergent manufacturing, and agricultural advancements further highlights their significance (Gayathiri et al., 2022; A. Kumar et al., 2021; Xi et al., 2021).

The research on biosurfactant-producing microorganisms has progressed rapidly due to their diverse advantages and industrial potential. This review explores the surfactants, biosurfactants, classification, microbial sources, and applications to understand the role of biosurfactants.

Petroleum Hydrocarbons

The use of petroleum has exponentially expanded in today's world, severely contaminating and polluting the environment. According to the International Tanker Owners Pollution Federation, there have been more than 5 million tons of oil leaks since 1970, which have caused significant health issues (Budsabun, 2015). Therefore, one essential contributor to global pollution is the discharge of toxins into the environment, particularly those from petroleum and its products (Rahman et al., n.d.). Since many of these pollutants are carcinogenic, there is also a risk to human and animal health (Priyadarshanee et al., 2022). Hydrocarbon molecules are difficult to remove when discharged into the environment because they adhere to surfaces and are entrapped by capillarity in a water-immiscible phase. Using the metabolic abilities of microorganisms that can use hydrocarbons as a source of carbon and energy or that can change them through co-metabolism, bioremediation has been shown to be a viable option for reducing the impacts caused by hydrocarbon pollution of soil and water. The chemical structure of the substance, its bioavailability (concentration, toxicity, mobility, and access), and the environmental physicochemical conditions all directly impact the effectiveness of removal (Christofi & Ivshina, 2002).

Polycyclic aromatic hydrocarbons are a prominent pollutant in petroleum oil, which is widely utilized in the automobile industry. Their strong affinity for soil and sediment and low water solubility significantly restrict microbial absorption, hindering biodegradation (Xia et al., 2023). Both physicochemical methods and bioremediation methods can be used to remediate these pollutants. These strategies rely on the capability of native microorganisms to generate toxic pollutants, yet their bioavailability remains a critical barrier (Imam et al., 2022;

Sah et al., 2022). Hydrocarbon-degrading bacteria tend to form surface-active molecules known as biosurfactants during the biodegradation process to aid in absorbing insoluble substrates (Xia et al., 2023).

Surfactants

A surfactant is a fundamental chemical raw material that can be derived from monosodium glutamate. Monosodium glutamate has a unique and significant role in the oil and food sectors and environmental engineering. However, most surfactants are chemically produced from petroleum, are highly hazardous, and are not biodegradable, which results in significant environmental pollution issues (Liu et al., 2011b). Surfactants are surface-active substances that lessen the friction or interfacial tension at the interface of two liquids or between a liquid and a solid. Surfactants possess both hydrophilic moieties (tail part) and hydrophobic moieties (head part). Hydrophilic means water-loving or water-soluble, while hydrophobic moieties are water-insoluble and behave as water-repellent groups. Moieties lower the surface and interfacial tension by accumulating near the interface of two immiscible fluids, such as oil and water. Almost all surfactants are made from petroleum sources using hydroformylation, ethoxylation, sulfonation, and fractional distillation. As most surfactants contain branched side chains, they tend to collect in the environment and are hardly ever broken down by microorganisms (Chandankere et al., 2014). Surfactants have a biological or synthetic origin. Synthetic surfactants tend to produce harmful contaminants like polychlorinated biphenyls when their concentration in soil is high. Some of these contaminants affect marine species in ways that they have hormone-like synthetic surfactants, which are harmful, tend to persist, and are scarcely broken down by microbes (Dukhande & Warde, 2016). The scientific and industrial communities' interest has been growing due to their intriguing qualities, which include lesser toxicity, a higher degree of biodegradability, increased foaming capacity, and excellent action at severe temperatures, PH levels, and salinity. Moreover, microbial surfactant production has attracted a lot of attention because synthetic surfactants have been connected to environmental hazards (Kosaric, 1992).

Detergents, shampoos, toothpaste, oil additives, and other consumer and commercial goods contain surfactants as essential constituents. They comprise a significant group of industrial chemicals utilized in practically all areas of contemporary industry. Due to their variety, eco-friendliness, potential for large-scale production, selectivity, performance under demanding conditions, and upcoming applications in environmental fortification, microbial surfactants have seen an increase in interest over the past several years (Sumathi & Yogananth, 2016).

Biosurfactants

Biosurfactants are surface-active biomolecules generated from microorganisms (Madaki & Rabi'u, 2025). Aerobic microorganisms that use carbon sources such as carbohydrates, hydrocarbons, animal or vegetable oils, or a combination of them produce the majority of microbial biosurfactants (Viramontes-Ramos et al., 2010). Biosurfactants may be discharged into the media (extracellular) or remain attached to the cell wall (intracellular) (Sharma et al., 2021). When biosurfactants are found outside of cells, they aid in the solubilization of substrates and typically have a complex structure made of lipids, proteins, and carbohydrates. Intracellular biosurfactants have a structure that includes membrane lipids and promote the transport of insoluble substrates through the membrane (Viramontes-Ramos et al., 2010). These heterogeneous compounds have hydrophilic and hydrophobic constituents (Yu et al., n.d.). The hydrophilic head, which accounts for the most chemical differences among the various biosurfactant molecules, allows for a wide range of diversity in their physical and biological characteristics.

Biosurfactants are fascinating compounds with solid surfaces and emulsification functions (Ahmad et al., 2016). It has been discovered that biosurfactants with a hydrophobic tail and hydrophilic head can affect the characteristics of the bacterial cell surface and enhance the bioavailability of hydrophobic water-insoluble substrates (Rodrigues et al., 2006). These substances help to lower the surface tension of organic and non-organic mixtures. They create interfaces between different solutions according to their polarities, like oil and water, which reduces the interfacial tension (El-Sheshtawy et al., 2015). Bio-surfactants are substances that are often utilized because they are produced from cheaper substrates, have low toxicity, are easily degraded, and are environmentally benign. These substances have shown significant surface behavior (Batool et al., 2017).

Oil has a limited solubility in water, which makes it difficult for microorganisms to use it as a carbon source when they are grown on hydrophobic substrates. They are either efficiently transported across the cell membrane and taken up directly, or they are solubilized or emulsified inside the cell by secreting certain extracellular substances. Biosurfactant is one of these extracellular solubilizing mediators (Dukhande & Warde, 2016).

Although all bio-emulsifiers are considered biosurfactants, not all biosurfactants generate stable emulsions, even though the terms biosurfactant and bio-emulsifier are often used interchangeably in the literature (Annuar et al., 2023). By forming and stabilizing droplets of the dispersed phase, bio-emulsifiers cause the dispersion of undissolved material throughout the liquid, whereas biosurfactants can lower the surface tension between two liquids (Desai & Banat, 1997; Fiechter, 1992).

Biosurfactants Producing Microorganisms

Several microorganisms produce biosurfactants, which are primarily released extracellularly or adhered to cell surfaces during development on water-immiscible substrates (Desai & Banat, 1997). A variety of microbes, such as filamentous fungi, bacteria, and yeast, have been employed to produce biosurfactants (Fardami et al., 2022). Although yeast and filamentous fungi can produce biosurfactants, the most documented biosurfactant production comes from bacteria. Both water-soluble and water-immiscible substrates can be used to make them (Ahmad et al., 2016).

When the carbon source is an insoluble substrate, such as hydrocarbon, microorganisms produce a range of chemicals known as biosurfactants to facilitate the diffusion of the carbon source into the cell (Kalia et al., 2022). Hydrocarbon substrates in the growing medium are emulsified by ionic surfactants secreted by certain bacteria and yeasts (Karanth et al., 1999). Biosurfactants' primary physiological function is to enable microorganisms to grow on water-immiscible substrates by lowering the surface tension at the interface between two distinct phases. As a result, the substrate is more readily available for uptake and metabolism through the molecular mechanism related to substrate uptake (Desai & Banat, 1997). The antibacterial properties of biosurfactants toward different microorganisms serve as another physiological function. Different surfactants typically hinder various taxonomies. Additionally, it has been demonstrated that biosurfactants play a role in virulence, cell desorption, and cell adhesion, which confer the most stability under adverse environmental conditions (Fakruddin, 2012). So, many organisms create biosurfactants to metabolize water-immiscible substrates and enable their adsorption, emulsification, or dispersion. The ability of microorganisms to produce biosurfactants in soil benefits them in particular environments (Viramontes-Ramos et al., 2010). These microbes have been discovered in polluted areas, including industrial waste and petroleum hydrocarbon byproducts (Liu et al., 2011a).

Some of the examples of biosurfactants and biosurfactant-producing bacteria can be shown as follows. According to reports, the genera *Pseudomonas, Bacillus, Corynebacterium* sp., *Acinetobacter* sp., *Flavobacterium* sp., Proteobacteria, and *Archromobacter* sp. are excellent biosurfactant makers (Ahmad et al., 2016). Numerous bacteria have been found to create biosurfactants, including surfactants by *Bacillus subtilis* and rhamnolipids by *Pseudomonas aeruginosa* (Fardami et al., 2022; Madaki & Rabi'u, 2025). Compared to synthetic surfactants like Sodium Dodecyl Sulfate (SDS) and Tween 80, *Pseudomonas aeruginosa* B189 from the milk industry showed stronger surfactant activity (Liu et al., 2011a). It has been observed that many *Bacillus* species, including *B. coagulans*, *B. pumilus*, and *B. licheniformis*, generate surfactant and lichenysin. They are engaged in the removal of metals from contaminated soil, oil recovery augmentation, and the biodegradation of hydrocarbons (Batool et al., 2017). A class of biosurfactants known as polymeric biosurfactants, including mannoproteins, Alaskan, bio-dispersan, and emulsion, is typically made by certain yeast species and Acinetobacter (Maier, 2003). Another example of a biosurfactant is sophorolipids produced by *Candida* spp. (Price et al., 2012).

Biosurfactant Classification

Biosurfactants are primarily grouped based on their microbial origin and chemical content (Fardami et al., 2022), unlike chemically manufactured surfactants, which are grouped based on the polar grouping type in which they are found (Ahmad et al., 2016). Their main structural components include a hydrophilic part (which consists of amino acids/peptides, anions or cations, mono-, di-, or polysaccharides), and a hydrophobic part (which consists of unsaturated, saturated, or fatty acids) (Desai & Banat, 1997). They are divided into several groups, including lipopeptides, neutral lipids, polysaccharide-protein complexes, phospholipids, lipopolysaccharides, fatty acids, and glycolipids (Hassanshahian et al., 2014). Glycolipids and lipopeptides are the most frequently isolated biosurfactants found in nature. Low molecular weight surfactants include glycolipids and lipopeptides (Madaki & Rabi'u, 2025). Glycolipids and lipopeptides have low molecular weights and can reduce surface tension, but do not produce stable emulsions (Christofi & Ivshina, 2002). Rhamnolipids, trehalolipids, and sophorolipids are the three subgroups of glycolipids that are further. Polysaccharides, lipopolysaccharides, proteins, lipoproteins, or complex mixtures of these biopolymers are examples of high molecular weight biosurfactants (Abo Elsoud, 2021). Biopolymers are highly effective in producing emulsions and have a high degree of substrate specificity, although they are less effective at reducing surface tension (Ron & Rosenberg, 2002; Viramontes-Ramos et al., 2010).

Glycolipids

Glycolipids are the most well-known biosurfactants (Sałek et al., 2022). They are long-chain aliphatic acids or aliphatic hydroxy acids combined with carbohydrates. Glucose, mannose, galactose, glucuronic acid, rhamnose, and galactose sulfate are among the constituents of monosaccharides, disaccharides, trisaccharides, and tetrasaccharides. In most cases, the phospholipids of the same microorganism share a composition with the fatty acid component. The most well-known glycolipids are sophorolipids, trehalolipids, and rhamnolipids (Abo Elsoud, 2021; Desai & Banat, 1997). In nature, glycolipids are lipids that have a hydrophilic carbohydrate joined by a glycosidic linkage.

Rhamnolipids

Rhamnolipids are the most well-researched glycolipids, which contain rhamnose molecules (one or two) connected to one or two β-hydroxy-decanoic acid molecules (Iordache & Babeanu, 2024). Jarvis and Johnson were the first researchers to describe that *Pseudomonas aeruginosa* produced glycolipids with rhamnose (Jarvis & Johnson, 1949). The main glycolipids that *P. aeruginosa* produces are L-Rhamnosyl-L-Rhamnosyl-β-hydroxy decanol-β-hydroxy decanoate and L-Rhamnosyl-β-hydroxy decanol-β-hydroxy decanoate, also known as rhamnolipid 1 and 2, respectively (Edwards & Hayashi, 1965; Hisatsuka et al., 1971, 2014). The production of rhamnolipid types 3 and 4 containing one β-hydroxy decanoic acid with one and two rhamnose units, respectively (Syldatk et al., 1985). It has also been observed that rhamnolipids with alternate fatty acid chains and methyl ester derivatives of rhamnolipids 1 and 2 exist (Hirayama & Kato, 1982). It has been shown that rhamnolipids from *Pseudomonas* spp. may reduce the surface tension to 25 to 30 m N/m and the interfacial tension against n-hexadecane to 1 m N/m (Desai & Banat, 1997). Additionally, they emulsify alkanes and promote *P. aeruginosa* growth on hexadecane. *P. aeruginosa* PU-1 and PU-2, two mutants that Itoh and Suzuki identified, did not grow well on alkanes because they could not synthesize rhamnolipids (Itoh & Suzuki, 1972). When rhamnolipid was added to the growth medium, these mutants developed normally.

Trehalolipids

Many species of the *Mycobacterium* genus exhibit serpentine growth, which is caused by trehalose esters on the cell surface. The size and structure of the mycolic acid esters in cord factors from various species of *Mycobacteria, Corynebacteria, Nocardia, and Brevibacteria* vary (Khandare & Madankar, 2024). There have been reports of many structural varieties of trehalolipid biosurfactants produced by microorganisms (Kuyukina & Ivshina, 2019). Most species of *Mycobacterium, Nocardia*, and *Corynebacterium* are associated with mycolic acids to disaccharide trehalose linked to C-6 and C-69 (Khandare & Madankar, 2024). Mycolic acids are long-chain, branched fatty acids. Carbon atoms, degree of unsaturation, and size and structure of mycolic acid of trehalolipid vary among various organisms (Desai & Desai, 1993). Several studies have been conducted on the trehalose dimycolate that *Rhodococcus erythropolis* produces (Kuyukina & Ivshina, 2019; Semeniuk et al., 2022). Additionally, *R. erythropolis* produces a novel anionic trehalose lipid (Madihalli et al., 2019). Trehalose lipids from *R. erythropolis* and *Arthrobacter* sp. decrease the surface and interfacial tensions in the culture broth to 25–40 and 1–5 m N/m, respectively (Rapp et al., 1979).

Sophorolipids

These are created by several *Torulopsis* yeast strains (Liepins et al., 2021). The principal producers of sophorolipids are yeasts like *Torulopsis bombicola* (Inoue & Ito, 1982), *T. apicola* (Tulloch et al., 1967), *T. petrophilum* (Cooper & Paddock, 1983). They are made up of a long-chain hydroxy fatty acid attached to a dimeric carbohydrate, sophorose. There are a minimum of six to nine distinct hydrophobic sophorolipids in these biosurfactants (Desai & Banat, 1997). It has also been stated that many yeasts produce similar combinations of water-soluble sophorolipids (Hommel et al., 1987). According to Cutler and Light (Cutler & Light, 1979), *Candida bogoriensis* generates glycolipids in which sophorose is connected to docosanoic acid diacetate. On water-insoluble substrates like alkanes and vegetable oils, *T. petrophilum* formed sophorolipids (Cooper & Paddock, 1983). Acidic sophorolipids exhibited outstanding stability toward pH and temperature variations and reduced the interfacial tension between n-hexadecane and water from 40 to 5 m N/m (Desai & Banat, 1997).

Lipopeptides and Lipoproteins

Decapeptide antibiotics (gramicidins), which are produced by *Bacillus brevis*, and lipopeptide antibiotics (polymyxins), which are produced by *Bacillus polymyxa*, are just two examples of the numerous cyclic lipopeptides that have extraordinary surface-active capabilities (Iordache & Babeanu, 2024). Excellent biosurfactant activity is also demonstrated by ornithine-containing lipids from *P. rubescens* (Yamane, 1987) and *Thiobacillus thiooxidans* (Knoche & Shively, 1972), cerilipin, ornithine- and taurine-containing lipids from *Gluconobacter cerinus* IFO 3267 (Tahara, Kameda, et al., 1976), and lysine-containing lipids from *Agrobacterium tumefaciens* IFO 3058 (Tahara, Yamada, et al., 1976). One of the most potent biosurfactants is the cyclic lipopeptide surfactant made by the bacteria B. subtilis ATCC 21332 (Júnior et al., 2022). At concentrations as low as 0.005%, it reduces surface tension from 72 to 27.9 m N/m (Desai & Desai, 1993).

Fatty Acids, Phospholipids, and Neutral Lipids

When growing on n-alkanes, a variety of bacteria and yeasts create significant amounts of fatty acid and phospholipid surfactants (Ismail et al., 2019). The hydrocarbon chain length in their structures is directly correlated with the hydrophilic-lipophilic balance. Rich vesicles are formed by *Acinetobacter* sp. strain HO1-N phosphatidylethanolamine, which creates optically transparent microemulsions of alkanes in water (Rawat et al., 2020). Some *Aspergillus spp.* and *Thiobacillus thiooxidans* have also been found to produce phospholipids in quantifiable amounts (V. Singh, 2022). When grown on hexadecane and olive oil, *P. aeruginosa* 44T1 and *Arthrobacter* strain AK-19 can accumulate up to 40 to 80% (wt/wt) of these lipids (Ratledge et al., 1984; Robert et al., 1989). Phosphatidylethanolamine, which was produced by *R. erythropolis* grew on n-alkane, reduced the interfacial tension between water and hexadecane to less than 1 m N/m and resulted in a CMC of 30 mg/liter (Kretschmer et al., 1982).

Polymeric Biosurfactants

Emulsan, liposan, mannoprotein, and other polysaccharide-protein complexes are the polymeric biosurfactants that have undergone the most research (Simões et al., 2024). Emulsan is a powerful polyanionic amphipathic heteropolysaccharide emulsifier that is produced by *Acinetobacter calcoaceticus* RAG-1 (Mujumdar et al., 2019). The repeating trisaccharide of N-acetyl-D-galactosamine, N-acetyl galactosamine uronic acid, and an unnamed N-acetyl amino sugar makes up the heteropolysaccharide backbone (Saranraj et al., 2022). Emulsan resists inversion even at a water-to-oil ratio of 1:1 and is a powerful emulsifying agent for hydrocarbons in water (Belsky et al., 1979; Zosim et al., 1982). An anionic heteropolysaccharide called biodispersan has four reducing sugars and an average molecular weight of 51,400, which is produced by *A. calcoaceticus* (Ahmadi-Ashtiani et al., 2020). Alasan, an anionic alanine-containing hetero polysaccharide-protein biosurfactant that was isolated from *Acinetobacter radioresistens* KA-53 (Ahmadi-Ashtiani et al., 2020), was found that when heated under conditions like neutral or alkaline found to be more active (2.5-3 times) (Navon-Venezia et al., 1995).

Liposan is an extracellular water-soluble emulsifier. *Candida lipolytica* produces liposan with 83% carbohydrates and 17% proteins (Srivastava et al., 2022). Glucose, galactose, galactosamine, and galacturonic acid comprise this heteropolysaccharide (Sondhi, 2023). Sar and Rosenberg (Sar & Rosenberg, 1983) showed that while polysaccharides had no emulsification action by themselves, when coupled with proteins, they became powerful emulsifiers.

Saccharomyces cerevisiae produces a lot of mannoproteins, which exhibit good emulsifying properties with a variety of oils, alkanes, and organic solvents (Bhosale & Pinjari, 2021). From *Candida tropicalis* cultured on alkanes, Kappeli et al. extracted a mannan-fatty acid complex that stabilized hexadecane-in-water emulsions (Käppeli et al., 1978, 1984). It has been determined that the biosurfactant produced by *Schizonella malanogramma* and *Ustilago maydis* is an erythritol- and mannose-containing lipid (Desai & Desai, 1993).

Advantages of Biosurfactants

Microbial surfactants are getting a lot of attention because of their special characteristics. When compared to their chemically manufactured counterparts, biosurfactants have advantageous qualities (Mukherjee et al., 2006). As alternative surfactantsandosurfactants provide excellent benefits such as high biodegradability, low toxicity, a specific action or high stability at severe temperatures, pH levels, and salinities (A. P. Kumar et al., 2015), compatibility with the environment, ability to be produced from renewable sources (Bodour et al., 2003; Kosaric, 2001), high selectivity, and, availability of raw materials for their production, reduction in surface tension, and interface activity, digestibility, and biocompatibility.

Availability of raw material: From extremely inexpensive raw materials that are widely accessible, biosurfactants can be made. Hydrocarbons, carbohydrates, and/or lipids are possible sources of carbon and can be employed singly or in combination (Kosaric, 2001).

Physical factors: Environmental variables including temperature, pH, and ionic strength tolerances have little impact on many biosurfactants. Temperatures up to 50 °C, a pH range of 4-5 to 9.0, a NaCl concentration of 50 g/l, and a Ca concentration of 25 g/l had no effect on the lichenysin generated by the *Bacillus licheniformis* strain (Article & Access, 2012).

Surface and interface activity: Mulligan (Mulligan, 2005) reported that a suitable surfactant might reduce the surface tension of water from 75 to 35 m N/m and the interfacial tension between water and hexadecane from 40 to 1 m N/M. Surfactants may lower the surface tension of water to 25 m N/M and the interfacial tension of water and hexadecane to 1 m N/M (Article & Access, 2012).

Applications

Surfactants are now being used in a wide range of industrial sectors, including agriculture, the food and beverage business, the pharmaceutical industry, the design of washing agents, the petroleum industry, and environmental protection (Deleu & Paquot, 2004; A. Singh et al., 2007).

In pollution Control

Biodegradation of Hydrocarbons

Biosurfactants are used in the growing technology of microbial remediation of hydrocarbon and crude oil-contaminated soils (Patowary et al., 2018). The primary method for removing hydrocarbon pollutants from the environment is through the biodegradation of hydrocarbons by indigenous microbial communities (Ławniczak et al., 2020). Bioaugmentation stimulates indigenous bacteria to degrade hydrocarbons at higher rates than nutrients alone (Behera et al., 2021). Rhamnolipid from *P. aeruginosa* has removed oil from contaminated Alaskan gravel. In situ bioremediation on the Exxon Valdez oil spill has been demonstrated by Bragg et al. (Bragg et al., 1994) and Van Dyke et al. (Dyke et al., 1993), with rhamnolipid from *P. aeruginosa* (Scheibenbogen et al., 1994). Glycolipid biosurfactants increase hydrocarbon removal and mineralization.

Biosurfactants' capacity to emulsify mixtures of hydrocarbon and water has a long history of research. This characteristic has been shown to drastically speed up hydrocarbon breakdown, making it potentially helpful for controlling oil spills (Desai & Banat, 1997). Schulz et al. (Schulz et al., 1991) isolated biosurfactant-producing *Alcaligenes sp.* strain MM-1, *Arthrobacter sp.* strain EK1, and *Arthrobacter* strain S-II while investigating oil-degrading marine microbes from the North Sea. Dave et al. (Dave et al., 1994) showed that the bioaugmentation of soil contaminated with slop oil from a petrochemical industry led to the bio-reclamation of soil, and Ghosh et al. (Ghosh et al., 1995) showed an improvement in the bioremediation of soil contaminated with polyaromatic hydrocarbons and soil containing polychlorinated biphenyls.

Metal Remediation

Microbes create biosurfactants, which are useful in the bioremediation of heavy metal, pesticide, and hydrocarbon-contaminated environments. (Juwarkar et al., 2008). Oil is being contaminated with metals due to industrial discharge, improper disposal of waste, spills, and failure of land disposal facilities (Mambwe et al., 2021). Metals such as lead, chromium, cadmium, arsenic, copper, and zinc have been detected in most sites, with mercury and nickel present in some (Miller, 1995). The existence and fate of metals in soil are a matter of concern due to their potential impact on microbial communities, a health hazard for humans, and the potential for groundwater contamination. Metal contaminants in soil are tightly bound to colloidal particles and organic matter, making it difficult to remove using current in situ remediation technologies. A promising new remedial strategy is biosurfactants that are non-toxic to the soil structure (Juwarkar et al., 2008). Metal removal from multi-metal contaminated soil using biosurfactant is nontoxic, biodegradable, and has diverse chemical forms to maximize metal removal efficiency (Klik et al., 2019).

In contrast to metals attaching to the soil, biosurfactants create complexes with metals via strong interactions in soil, which are essential in the remediation of some heavy metals. Handling wastewater polluted with heavy metals may benefit from this procedure (Das et al., 2009b). Researchers contend that the combination of metal complexation and the modification of cell surface characteristics through the release of LPS, which results in enhanced bioremediation, enables rhamnolipid to reduce metal toxicity to microbial associations in co-contaminated soils (Sandrin et al., 2000).

Oil Recovery

One of the prospective applications is in the oil industry, with a minimum purity requirement to enable the use of whole-cell broth (Sarkar et al., 1989). In comparison to chemical surfactants, they are highly selective; just a tiny amount is needed for them to work, and they are effective in a wide variety of oil and reservoir conditions (Pines et al., 1983; Ramsay et al., 1989), and they are environmentally favorable in protecting coastal areas from further harm caused by synthetic chemicals (Poremba et al., 1991). Using trehalolipids from *Nocardia rhodochrous* improved total oil recovery from subterranean sandstone by about 30% (Khandare & Madankar, 2024).

Other applications include enhancing oil recovery from oil reservoirs and creating techniques for extracting lingering oil from remote reservoir areas where duct pressure has trapped it in holes (Sen, 2008). Moving heavy crude oil transporting pipelines and cleaning oil sludge from oil storage facilities are also included (Lang & Wullbrandt, 1999). In addition to making the best biosurfactants, *B. licheniformis* JF-2, an isolate from oilfield injection water, also has the anaerobic, halotolerant, and thermotolerant characteristics that make its biosurfactants potentially useful for in situ microbially enhanced oil recovery (Nikolova & Gutierrez, 2020). According to research by Hayes et al. (Desai & Banat, 1997), the viscosity of Boscan, Venezuelan heavy crude oil, decreased from 200,000 to 100 cP after being treated with emulsan. As a result, despite the failure of traditional chemical surfactant treatment, heavy oil could be pumped 26,000 miles in a commercial pipeline following this treatment.

Food Industry

The biosurfactants, which are biocompatible, biodegradable, and nontoxic, have a unique mix of features that make them particularly helpful in the food industry as emulsifiers, foaming, wetting, solubilizers, adhesives, and antibacterial agents (Dini et al., 2024; Nagtode et al., 2023).

Food Emulsifier

Biosurfactants exhibit various characteristics, including emulsion-based compositions with broad potential uses in the food industry. A heterogeneous system of at least one non-miscible liquid that is intimately and continuously disseminated in another liquid in droplet form is called an emulsion. Emulsifiers benefit low-fat products, especially because they improve the texture and creaminess of dairy products. Polymeric surfactants, on the other hand, cover the oil droplets and create extremely stable emulsions that never coalesce. Making oil/water emulsions for food and cosmetics is made simpler because of this feature (Rosenberg & Ron, 1999; Shoeb et al., 2013b). The food industries all over the world use lecithin and its derivatives, fatty acid esters such as glycerol, sorbitan, or ethylene glycol, and ethoxylated derivatives of monoglycerides, including a recently discovered oligopeptide (Desai & Banat, 1997). For salad dressing, a bio-emulsifier from *Candida utilis* can be used (Sondhi, 2023).

Food Stabilizer

In ice cream and bread recipes, biosurfactants serve as consistency regulators. Additionally, they are also used as anti-spattering agents and fat stabilizers during the cooking of fats and oils (Kosaric, 2001). Rhamnolipid surfactants are used in the food processing industry to enhance the quality and validity of items containing starch, as well as the stability and rheological characteristics of wheat dough (Shoeb et al., 2013b). Surfactants may also be used to regulate the texture of products containing fat, stabilize aerated systems, and prevent the aggregation of fat globules. L-Rhamnose is synthesized by hydrolyzing rhamnolipid surfactants generated by *P. aeruginosa*, which are already used in the food industry as a precursor to premium flavor components like Furaneol (Linhardt et al., 1989).

Antiadhesive Activity

Biosurfactants' antiadhesive properties are utilized as a novel tool for preventing and disassembling the biofilms that various bacterial groups generate on surfaces that contact with food (da Silva et al., 2021). Limiting the adherence of microbes to food contact surfaces is crucial for providing consumers with high-quality and safe products because bacterial biofilms present in the food industry are potential causes of contamination that could cause food spoiling and transmission of diseases (Hood & Zottola, 1995).

Medical Industry

Genetic Manipulation

Basic sciences and clinical applications such as gene therapy depend on the creation of safe and efficient methods for introducing foreign nucleotides into mammalian cells (Gharaei-Fathabad, 2011). Among the several known methods of gene transfection, lipofection employing cationic liposomes appears to be a safe way to deliver a foreign gene to the target cells without causing any negative effects (Fujita et al., 2009; Puchana-Rosero et al., 2016; Zhang et al., 2010). Biosurfactant-based liposomes exhibit greater gene transfection efficacy than commercially available cationic liposomes (Iordache & Babeanu, 2024). Some strategies and procedures have been developed in the last few years for liposome-based gene transfection. Some researchers investigated the potential for gene transfection in MEL-A-containing liposomes by introducing biosurfactants into this area (Nakanishi et al., 2013).

Immune Modulatory Action

When combined with conventional antigens, bacterial lipopeptides operate as a powerful immunological adjuvant that is neither poisonous nor pyrogenic (Gharaei-Fathabad, 2011). Combining poly-L-lysine (MLR-PLL) with the low molecular mass antigens iturin-AL, herbicolin-A, and microcystin (MLR) significantly improved the humoral immune response in rabbits and chickens (Ceresa et al., 2021).

Toxic Activity against Microorganisms

Numerous biosurfactants have strong antifungal, antibacterial, and antiviral activity; this varying performance results from the various structural variations of biosurfactants (Zhao et al., 2010). Some biosurfactants function as therapeutic and antibacterial agents (De Giani et al., 2021). The structure of biosurfactants is intended to have a detergent-like impact on the permeability of cell membranes by exerting their toxicity. By examining the antibacterial properties of biosurfactants derived from *Bacillus subtilis*, Fernandes et al. (2007) showed that lipopeptides exhibit a wide range of antimicrobial activity against pathogens with a multidrug resistance profile (Fernandes et al., 2007). Rhamnolipid generated by strains has been shown in several investigations to have specific antibacterial and antifungal properties (Cameotra & Makkar, 2004). There are numerous biosurfactants made by *Pseudomonas aeruginosa, Candida antartica, B. subtilis*, and *B. licheniformis* that have harmful effects on bacteria (Rodrigues et al., 2006)

Anti-Adhesive Agents

Biosurfactant adhesion to solid surfaces may represent a novel and efficient strategy for preventing the colonization of surfaces by harmful microorganisms (Rivardo et al., 2009). It has been discovered that biosurfactants prevent pathogenic microbes from sticking to the infection site (Das et al., 2009a). These surfactants are effective anti-adhesive agents and can be used as probiotics and therapeutic agents to treat various medical conditions. In addition, bio-surfactants are used in the pharmaceutical industry as a stimulant for the metabolism of stem fibroblasts, and in prematurely born infants, a lack of pulmonary surfactant and a phospholipid protein complex also results in failure of respiration. However, the isolation of genes for these surfactant protein molecules from other proteins and the cloning of bacteria have made it possible to produce fermentation for medical use (Shoeb et al., 2013a).

Cosmetic Industry

Biosurfactants have several applications in the cosmetic sector due to their exceptional surface qualities, which include detergency, emulsifying, wetting, solubilizing, foaming, and dispersing effects (Ahmadi-Ashtiani et al., 2020). Since biosurfactants are known to have advantages over synthetic surfactants, including better moisturizing characteristics, compatibility with skin, and less irritancy or anti-irritating effects, they are in great demand. Sophorolipids, rhamnolipids, and mannosyl erythritol lipids are the biosurfactant glycolipids that are most commonly utilized in cosmetics (Karnwal et al., 2023). Rhamnolipids, which are natural surfactants and emulsifiers, can replace the petrochemical-based surfactants that are currently utilized in most cosmetic products due to their superior moisturizing and skin-friendliness. Due to their high surface and emulsifying properties, they have also been found in toothpaste, deodorants, nail care products, acne pads, anti-dandruff, anti-wrinkle, and anti-aging treatments (Piljac & Piljac, 1999; Shoeb et al., 2013a). To avoid rough skin, mannosyl erythritol lipids are typically employed as the active component in skin care formulations (Masaru et al., 2007).

Agricultural Industry

Surfactants can improve the solubility of bio-hazardous chemical compounds like PAH by acting as mobilizing agents. They aid microbes in adsorbing pollutants from soil particles, decreasing diffusion path length. Surfactants are also used in agriculture for hydrophilization, ensuring wettability, even fertilizer distribution, and promoting toxicant penetration (Fakruddin, 2012). To protect plants against various illnesses and increase crop yields, they are also utilized as biocontrol agents (Hultberg et al., 2010; Snook et al., 2009). They have a lot of potential to be employed in agriculture, namely in soil management and plant protection techniques, to create a better environment for the production of sustainable food, based on their functional features (Ahmad et al., 2016).

Conclusion

Biosurfactants offer a sustainable and environmentally friendly alternative to synthetic surfactants, addressing environmental pollution, especially hydrocarbon pollution. A diverse variety of microorganisms, such as bacteria, yeast, and molds, are capable of producing biosurfactants. There are many advantageous characteristics, like their ability to lower the interfacial surface tension, which helps microbial hydrocarbon degradation and makes them a powerful tool in the bioremediation process. Additionally, their low toxicity, biodegradability, and production from renewable sources emphasize their industrial importance and sustainability. These qualities make them useful in a wide range of industries, including pollution control, pharmaceutical, food, cosmetics, and agriculture. Despite current limitations in cost effectiveness and large-scale production, recent progress in microbial technology is paving the way to overcome these challenges and to develop economically feasible biosurfactant technologies.

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