Journal of Pharmaceutics and Pharmacy Practice (JPPP)
ISSN: 3139-2733 | Vol. 02, Issue-01, Jan-June 2026 | pp. 26-49

Biosurfactants: Production, Characterization, and Multifunctional Applications in Biotechnology and Nanoscience

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Abstract:

Biosurfactants are natural surfactants produced by microorganisms, such as bacteria, yeast, and fungus, which are either released into the environment or synthesized on microbial cell surfaces. These amphiphilic molecules display a variety of bioactivities and physical characteristics determined by their history, manufacturing, and purifying techniques. Glycolipids, such as rhamnolipids, mannosylerythritol lipids (MELs), sophorolipids, and trehalolipids, represent the predominant biosurfactants, including mono- or disaccharides combined with hydroxy- or long-chain aliphatic acids. They augment the solubility of hydrophobic compounds by rising their hydrophobicity and generating micelles and compartments at certain pH settings. Lipopeptides, including surfactin, lichenysin, and iturin, are produced by non-ribosomal routes by enzyme complexes such as surfactin synthetase, wherein the component SrfD is essential. Biosurfactants have remarkable surface and interfacial properties, decreasing surface tension and creating stable emulsions and foams. The combination of these qualities, together with a low critical micelle concentration (CMC), increased solubility, and greater detergency, renders biosurfactants more advantageous than conventional surfactants. Their effectiveness is contingent upon characteristics such as oil-water interfacial tension and surface tension, which range from 1 to 30 mN/m at CMC levels between 1 and 2000 mg/L. Biosurfactants has distinctive physicochemical properties, making them advantageous for drug delivery systems by enhancing solubility, stability, and effectiveness relative to traditional surfactants. They embody a sustainable and creative methodology in pharmaceutical applications.

Keywords: Biosurfactants; Solid State Fermentation; Microbially Enhanced oil Recovery; Lipopeptides

Received: Jan. 11, 2026 **Revised: Feb. 28, 2026** **Accepted: March. 26,2026** **Published: June 10, 2026**

DOI:

https://jppp.nknpub.com/1/issue/archive

1. Introduction:

Surface-active agents, sometimes referred to as surfactants, express that alternate boundary characteristics caused by their wide chemically compositions. Because they differ from artificial surfactants in their surface-active characteristics and expand the variety of surfactant types accessible, biosurfactants are technically essential. Furthermore, they are often biodegradable, which lowers the possibility of spoilage. Biosurfactants could be recycled and used as a technology in tertiary oil recovery operations as well as flocculating agents, emulsifiers, demulsifies, detergents, and adhesives[1]. In an ecosystem, biosystems make advantage of each of these characteristics. A categorized description of the chemical varieties of biosurfactants and their ensuing characteristics are given with particular emphasis in this summary of biosurfactants.

Biosurfactants can be commonly classified as phospholipids, fatty acids, neutral lipids, or component chemical groups that comprise carbohydrates or amino acids. Glycolipids are often the extracellular biosurfactants that bacteria create[2]. The hydrocarbon network of a fatty acid is the most prevalent hydrophobic group. Numerous functional groups of organic matter are included in the polar or hydrophilic group. Examples include the phosphate-containing regions of phospholipids, the sugars of glycolipids, the acetate groups, and the ester and alcohol functional groups of neutral lipids. In the latter technique, the biosurfactant stabilizes the metallic NPs' surface after being adsorption on it, which inhibits the NPs from aggregating[3]. The type of biosurfactant and the amount of thickness of the adsorbed film influence this adsorption. Biosurfactants can do this by serving as a template for nanoparticles and enhancing their physicochemical, structural, and functional properties[4]. The tuning procedure to produce structures with particular form and characteristics is the main difficulty in the synthesis of nanoparticles. Since the production of metal nanoparticles is a size/shape-dependent process, external parameters such as pH, temperature, surfactant content, and ionic strength of solutions aid in achieving the appropriate morphology. The capping agent, however, is a crucial factor that affects the particles' ultimate quality[4]. The recently major acute respiratory syndrome-coronavirus-2 (SARS-CoV-2) outbreak has shown just how completely inexperienced countries are to handle the demands of a worldwide pandemic, in particular one in which the only effective treatments available are those that address the symptoms rather than the underlying cause of the virus. Scientists start turning to new research directions as the death toll climbs, and novelty turns out to be an incredible and as-yet-underappreciated resource[5]. The demand for innovative biosurfactants in the processing of food, pharmaceutical bases, cosmetic formulations, and environmental applications is steadily expanding. The established biomedical characteristics of biosurfactants, along with their newly discovered uses in food, nanotechnology production, and cosmetic formulations, suggest that further study on biosurfactants is worthwhile[6]. However, one barrier to the commercialization of biosurfactants is the expense of manufacture. Additionally, the little amounts of biosurfactants used in food, pharmaceuticals preparation, and biomedical applications might offset the high production costs or production expenses[7].

They are generally made-up from number different types.

1.1 The hydrophilic (friends of water as well): Mostly composed of protons and neutrons, the core of an atom has a high attraction for polar compounds including water-based fluids. Electrostatic interactions between the nucleus and the dipole moments of polar molecules give this attraction[8]. The somewhat mild intermolecular interactions controlling fluid dynamics contrasts strikingly with the dense, positively charged character of the atomic core. Mostly by hydrogen bonding and van der Waals interactions, atoms interact in water-based fluids. But the interaction of the atomic core is fundamentally different: it interacts strongly with the surrounding fluid atoms, producing a force far greater and opposite in character from the normal intermolecular behaviour of the fluid[9]. A unique energy exchange produced by this interaction affects molecule orientation, solubility, and medium stability. Unlike free-moving, adaptable fluid particles responding to external forces, the atomic core stays strongly localised and generates a significant force upsetting conventional fluid interactions[10]. This behaviour difference emphasises the basic distinction between fluid dynamics and atomic-scale attraction. Consequently, the effect of the core on polar fluids might result in surprising structural changes, changed reaction kinetics, and special physicochemical characteristics[11].

1.2 Hydro(water)-hating (hydrophobic) the ends(tails): the section of an atom which avoids fluids (which is water) is extra attraction with that are bipolar substances[12]. That solution's compositions move onto one another furthermore instead of until liquid(water). Hydrophobic tails in the mixture prefer to decrease its attraction to fluid(water) via organizing themself beyond the watery phase if a substance called surfactant gets introduced. Particles also transfer to intersection where two phases meet, for example, the interface between air and water or the interface between two immiscible liquids [13]. The hydrophilic heads, meanwhile, stay in the water phase or engage with the aquatic surroundings [14]. Due to the fact, these isomers inhibit the interactions across the solvent particles when in interaction [15], their configuration decreases interfacial [16]. surface tension. Whereas the heads that are hydrophilic interact effectively within a solution, generating a more lasting configuration at the contact point, Hydro(water)-hating (hydrophobic) the ends(tails) produce disarrangement inside the fluid's mechanism [17]. Natural surfactants called biosurfactants are created by microorganisms including yeast, fungus, and bacteria. They are either released into the surrounding environment or produced at the surface of the microbial cell [17]. Their main purpose is to lessen the tension at the liquid's surface as well as the tension between two immiscible liquids, or interfacial tension. The fundamentals of biosurfactants interactions with various interface types. To elucidate and broaden the range of contacts at which biosurfactants may exhibit activity [18]. The connection via a fluid(liquid) and a gaseous state: starting with the outer layer of fluid(water) that interacts with oxygen, is recognized called the fluid(liquid) and a gaseous state. Over its interface, biosurfactants decrease the interfacial surface tension, which could have an impact on circulating and production of foam [19]. Solids/Liquid Interfaces: There, biosurfactants may affect its wetting and adherence factors while a solid layer contacts a fluid(liquid). Techniques such improved oil recycling and clearing depend upon this relationship.Liquid/Liquid Interfaces: It happen when two insoluble liquids, like as oil and water, comes into contact. These substances(biosurfactants) facilitate a mixture of liquids that are normally insoluble through decreasing the interfacial surface tension, helping to maintain the emulsion [20.] Container barriers: Biosurfactants have may affect how a fluid acts along with a solid surface whenever it gets into contact with the walls of the container, modifying factors such dispersion and forming films [21].

2. **Regarding the origins of biosurfactants**:

Extracellular Products: Microorganisms secrete a large number of biosurfactants into their surroundings. These extracellular biosurfactants are frequently used in environmental remediation and microbial enhanced oil recovery procedures. Cell Surface Compounds: A portion of biosurfactants can be found in the surface structures or cell membranes of microorganisms[22–24]. These surfactants may be involved in the production of biofilms, interactions with other substances in the environment, and cell adhesion. In fact, because of their efficiency in lowering surface tension, lower molecular weight biosurfactants, like glycolipids, low-molecular-weight lipopeptides (LPs), and phospholipids, are acknowledged for their industrial potential [25.]

3. Synthesis and Physicochemical Analysis:

Emphasising glycolipids and lipopeptides the production and physicochemical properties of biosurfactants. Biodegradability and low toxicity, these naturally occurring surfactants by microorganisms offer environmentally beneficial substitutes for synthetic equivalents [26]. The training looks at their production techniques, adjusting circumstances to improve and functionality [27,28]. Analysed are structural properties including molecular composition and amphiphilic nature to better understand their behaviour at surfaces. Surface tension, solubility, assessed under a range of pH, temperature, and salinity. Stability fit for harsh conditions, glycolipids show surface tension decrease and are hence perfect for emulsification. Their interfacial performance, which is essential for uses in environmental cleanup, medication delivery, and sustainable technologies[29,30].

In medicine, the biocompatibility of biosurfactants promotes focused medication distribution, hence improving therapeutic efficacy. Their capacity to organize pollutants helps bioremediation of oil spills and heavy metal cleaning in environmental remediation[31]. In sustainable technologies, they are green formulations, therefore lessening dependence on petrochemicals.

3.1 Production of Biosurfactants of Microbes Origin

Biosurfactants can be produced extracellularly with the aid of biocatalyst enzymes, through enzyme-substrate [32] reactions and fermentation processes, or through the activity of microorganisms like Bacillus and Pseudomonas. There are two distinct approaches to synthesise the hydrophobic and hydrophilic sections of biosurfactants: either one can be de novo synthesised while the other is driven by the substrate, or both can be substrate dependent [33].

3.2 Glycolipid Surfactants:

The most prevalent kind of biosurfactant is glycolipid. Mannosylerythritol lipids (MELs), trehalolipids, sophorolipids, and rhamnolipids are a few examples of common glycolipid biosurfactants that contain mono and disaccharides together with hydroxy- or long-chain aliphatic acids [34].The enzymes required for this initial stage are often located in the majority of bacteria, although the particular enzymes required for the rhamnolipids' production are detected in Burkholderia and P. aeruginosa species almost exclusivelyFive distinct enzymes, There have been reports linking the role of RhlA, RhlB, RhlC, RhlG, and RhlI to rhamnolipid biosynthesis in Pseudomonas algae [34,35].

3.3 Lipopeptide Biosurfactants: Surfactin synthetase, a protein complex with four enzyme subunits, catalyzes the non-ribosomal method that produces surfactin [11]. SrfD is an essential subunit that initiates the process of synthesis. These synthesis compounds also create other lipopeptide biosurfactants, including lichenysin, arthrofactin, and iturin [12]. The primary bacteria used in the synthesis of surfactin is Bacillus subtilis. There have been reports of improving the low yield through genetic modification of the wild-type strain. Wu and colleagues (2019) engineered 53 distinct genes in Bacillus subtilis to get a yield around 42% greater than the expected yield [13]. Solid state fermentation (SSF), a method in which microbes grow on or between rigid supports or substrates when there's no open space radicals, is another way to make surfactin outside conventional fermentation [14.]

3.4 Physical-Chemical Analysis: Numerous biosurfactants with varying degrees of bioactivity can be produced by microorganisms. The techniques of manufacture and purification have an impact on these biosurfactants physicochemical properties in addition to their source. Comprehending these attributes is crucial for accurately identifying their industrial use. This section clarifies a few key biosurfactant characteristics that are essential to their application as emulsifiers [16].

4. **SURFACE TENSION OF COMMON BACTERIAL:** Recent research on bacterial surface tension shows its fundamental importance in environmental adaption, biofilm formation, and microbial adhesion. microorganism interactions with surfaces are strongly influenced by surface tension resulting from cohesive molecular forces. Many bacterial species have been studied in order to better grasp their adhesion processes and biofilm production. Research on bacterial surface tension characteristics utilising techniques including the pendant drop technique, Wilhelmy plate method, and contact angle measurements has shed light on Escherichia coli, for example, has little surface tension which helps it to stick to food surfaces and medical equipment. Extracellular polymeric compounds (EPS) lower surface tension, thereby enabling the formation of biofilm. Common pathogen Staphylococcus aureus has reduced surface tension because to surface-active chemicals improving tissue adherence and causing ongoing infections. Strong biofilm formation-oriented Pseudomonas aeruginosa generates biosurfactants that significantly reduce surface tension, hence facilitating colonising on industrial pipes and hospital surfaces. A soil bacterium, Bacillus subtilis controls its surface tension by producing lipopeptides, therefore enabling its competition in challenging microbial environments. Bacterial surface tension is much influenced by several environmental elements: temperature, pH levels, nutrition availability, antimicrobial agents, etc. While antibiotics and surfactants can change surface tension qualities, therefore influencing microbial growth and attachment, higher temperatures and suitable nutritional circumstances usually improve bacterial adhesion and biofilm stability. In food, bioremediation, and medicine, knowledge of bacterial surface tension finds numerous uses. While bacterial biosurfactants provide possible solutions for environmental cleanup, including oil leak correction, controlling bacterial adherence to medical implants can help prevent biofilm-associated infections. Controlling bacterial surface tension in the food sector lowers processing surface contamination risk, therefore enhancing food safety. Future studies seek to control bacterial surface tension by means of genetic changes, therefore producing new antibacterial treatments and industrial developments. Modern imaging methods and computer models are supposed to improve knowledge of bacterial surface interactions even more. New approaches for industrial

uses and infection control are provided by recent results stressing the importance of bacterial surface tension in forming microbial behaviour.

Table No. 01: Concentration of Metabolic Products in Aqueous Solution

SOLUTE	T^{O}C	Weight (%)
Acetic acid	30	5
Acetone	25	55.5
n-Butanol	30	9.5
n-Propanol	25	49.3
Propionic acid	25	49

This table 01 displays the solutes with their corresponding Total Organic Carbon (TOC) and weight percentages.

5.Surface and Interfacial tension

The capacity of a bio-emulsifier to lower interfacial and surface tension is a crucial characteristic. Amphiphilic molecules play a crucial role in the creation of kinetically stabilized emulsions. These molecules replace water or oil molecules along the interface and lessen the Surface or interfacial tension and the intermolecular tensions between molecules of solvent when they adsorb on interfaces (air/liquid, liquid/liquid, and solid/liquid) [18].

These distinct surface characteristics are linked to the more intricate chemical structure of biosurfactants. They have branching or ring structures and an unclear polarity [17,18] distribution, in contrast to synthetic surfactants. Lipopeptide surfactin has the ability to create spherical structures that help with low aggregation number and close packing at interfaces [16].

5.1 Self-build

By heating secure nanoparticles are generated by the equilibrium procedure of mitcellization. In solutions of water, surfactants at concentrations over the level of the CMC naturally develop into the micelles [19]. A high-quality biosurfactant can lower the water's surface tension from 72 mN/m to 30 mN/m [18].

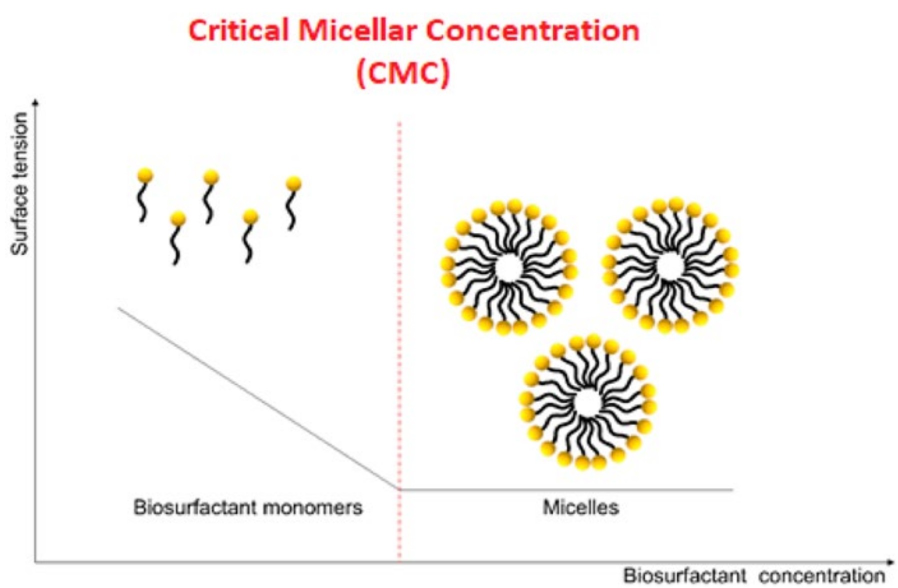


Figure 1: Effect of Biosurfactants on Micelle Formation Upon Reaching Critical Micellar Concentration (CMC) **[20]**

5.2 Fluidification: By converting molecules that are amphiphilic more hydrophobic, rhamnolipids can promote the dissolution of substances that are hydrophobic. With rising the pH level, biosurfactant components have an affinity to form compartments and micelles, which inhibits another compounds' dissolution. Biosurfactants have characteristics unique to the substrate, like solubilizing or emulsifier multiple hydrocarbons at different rates [21].

5.3 Homogenize: It is common knowledge that introducing another element to a mixture is required to create an emulsion with excellent stability. We describe to this kind of stabilizer as an emulsifier or emulsifying agent [20]. A bio-emulsifier consists of an emulsifying substance obtained from biological resources. In basic terms, an emulsifier promotes two separate procedures: the production of dispersed phase droplets and their subsequent stabilization [21]. The emulsifier's relative attraction for water and oil determines which kind of emulsion it is likely to encourage, which is either O/W or W/O [1]. It hydrophilic-lipophilic balance (HLB) ratio(value) is used to quantify this [3].

5. Biosurfactants produced by Fungus and Bacteria:

Produced by microorganisms including bacteria and fungi biosurfactants are surface-active molecules resulting from microbial metabolism. These natural surfactants interact with both water and oil because they are amphiphilic molecules that is, they have both hydrophilic (water-loving) and hydrophobic (water-repelling) sections. Because they can break down complicated molecules, improve nutrient solubility, and help hydrophobic chemicals be more widely distributed, the synthesis of biosurfactants is a fundamental adaptation for microbes to survive in many settings. Particularly in bioremediation, agriculture, medicines, and food processing, this makes biosurfactants quite important in many different industrial uses. The main microorganisms causing the synthesis of biosurfactants are fungi and bacteria; each group generates a different form of biosurfactant. Among the most well-known biosurfactant manufacturers are bacteria including Rhodococcus, Bacillus, and Pseudomonas; glycolipids, lipopeptides, and phospholipids are produced by these organisms. Commonly investigated for their surface-active effects, these microorganisms' synthesis glycolipids including rhamnolipids, mannosylerythritol lipids (MELs), and sophorolipids. Furthermore, generating lipopeptides with great antibacterial and emulsiating effects are bacteria: surfactin, iturin, and fengycin.

Though less researched than bacterial equivalents, fungal biosurfactants are attracting interest for their unusual characteristics. [20] Biosurfactants especially glycolipids, with a range of uses in business and medicine have been produced by fungus including Candida, Aspergillus, Penicillium, and Saccharomyces. For instance, whilst Aspergillus species can generate complex lipopeptides with antibacterial action, sophorolipids produced by Candida species are well-known for their capacity to lower surface tension and generate stable emulsions.

Fungi and bacteria produce biosurfactants via intricate metabolic pathways whereby each microorganism uses particular enzymes and biosynthesis to synthesis these molecules. Usually generated by Pseudomonas strains, glycolipids such as rhamnolipids are found in bacteria by means of rhamnosyltransferase enzymes. But non-ribosomal peptide synthetases control the synthesis of lipopeptides including surfactin in Bacillus species. In fungus, polyketide synthases and other enzymatic pathways commonly help to synthesise biosurfactants [21].

Several elements influence the characteristics of biosurfactants generated by bacteria and fungi, including the species of the microorganisms, growth circumstances, and production substrates. For example, the synthesis and yield of biosurfactants can be much influenced by the kind and concentration of carbon sources. While bacteria frequently prefer simpler sugars or organic acids as carbon sources, fungi often generate more yields of some biosurfactants when growing on organic substrates like oils. Often harmful and non-biodegradable, synthetic surfactants are replaced in environmental friendliness and sustainability by biosurfactants. For uses in environmental cleanup, where they are employed to emulsify and eliminate hydrophobic contaminants from contaminated locations, biosurfactants' low toxicity and biodegradability make them especially appealing. While in the culinary and pharmaceutical sectors are utilised for their emulsiating, foaming, and antibacterial qualities, in agriculture they can improve the bioavailability of pesticides and fertilisers [22].

Ultimately, a range of biosurfactants with special qualities having industrial, environmental, and biological uses are produced by both fungus and bacteria. Research on these natural surfactants is still developing, and as such, the full potential of biosurfactants especially those generated by fungus and bacteria will probably be realised in fields ranging from bioremediation to drug delivery, so rendering them indispensable in the search of sustainable technologies and solutions.

6. Classification:

Based on the ionic charge in the polar portion of the molecule. Surfactants can be classified as anionic, cationic, non-ionic, or amphoteric based on whether they have a charge that is electrical (Maneerat,2005; Ron and Rosenberg, 2001). Only a small percentage of biosurfactants those with amine groups, for example are cationic, while the majority are neutral or anionic.Long-chain fatty acids are the hydrophobic moiety, while carbohydrates, amino acids, cyclic peptides, phosphate, carboxyl acid, or alcohol are the hydrophilic moiety (Bognolo,1999).

Normally, biosurfactants are categorized according to the microbial producer species or their biochemical makeup. These compounds can be divided into five primary classes based on their structural similarities (Rahman and Gakpe,2008). Glycolipids: the hydrocarbons utilized as substrate determine the degree of polarity; examples include Pseudomonas aeruginosa generates rhamnolipids, whereas different kinds of Candida establish sophorolipids. [23]. Lipopolysaccharide- which include emulsan, an extracellular emulsifier made from hydrocarbons by the bacterium Acinotobactercalcoaceticus, often have a large molecular mass and are soluble in water. Lipopeptide- Bacillus subtilis produces surfactin, which is one of the strongest biosurfactants reported to exist.Phospholipid- Numerous microbes share phospholipid structures.

Corynebacterium lepus biosurfactant, for instance. Fatty acid- include hydrophobic proteins and neutral lipids, some of which can be classified as glycolipids [22].

Classification Criteria	Category	Description
Chemical Structure	**Glycolipids**	Contain sugar molecules linked to fatty acids. E.g., rhamnolipids, sophorolipids.
	Lipoproteins / Lipopolysaccharides	Composed of lipids, proteins, or polysaccharides. E.g., surfactin, iturin.
	Phospholipids	Contain phosphoric acid groups. E.g., phosphatidyl choline.
	Fatty Acids	Simple long-chain fatty acids with surface-active properties. E.g., fatty acid derivatives.
	Polymeric Biosurfactants	High molecular weight biosurfactants with repeating subunits. E.g., emulsan.
Microbial Origin	**Bacteria**	The majority of biosurfactants, including rhamnolipids, surfactin, and others.
	Fungi	E.g., mycosubtilin, produced by certain fungal species.
	Yeasts	E.g., sophorolipids produced by yeasts like *Candida bombicola*.
	Actinomycetes	E.g., dipropyl esters, produced by *Streptomyces* species.
Properties	**Anionic**	Negatively charged biosurfactants, like rhamnolipids.
	Cationic	Positively charged biosurfactants, like some lipopeptides.
	Nonionic	No charge on the surface-active compound, e.g., sophorolipids.

	Amphoteric	Biosurfactants with both positive and negative charges, e.g., lecithin.
Molecular Weight	**Low Molecular Weight**	Small molecules that are highly effective in reducing surface tension.
	High Molecular Weight	Larger, polymeric biosurfactants with emulsifying properties.

7. Properties:

Biosurfactants' physicochemical characteristics, include reduced tension on the surface, foam and emulsion ability, and stabilising [24] When evaluating performance and selecting microbes with the capability to establish such agents, factors including ability, reduce CMC, solubility, and detergency are essential (Deleu and Paquot,2004). In spite of A wide range of compounds with chemical composition and characteristics, various Most biosurfactants have specific characteristics, a lot of which They're better to traditional surfactants (Nitschkeet al 2007). Interfacial and surface activity: Biosurfactants lead to a reduced Surface tension at lower intensity that displays larger Effectiveness and efficacy in relation to traditional surfactants [25] that are The biosurfactant's CMC, or coefficient of efficiency varies between 1 and 2000 mg/L, depending on the oil/water interfacial tension and surface tension, accordingly, are roughly 1 and 30 mN/m [18].

8. Application

In a variety of manufacturing procedures, which includes lubricant, wetting, softening, completing colorants(dyes), emulsification, preserving dispersions, foaming, and foam prevention, and also in the food, biological, and pharmaceutical industries [27] ,as well as biological remediation of organic or inorganic-contaminated sites, biosurfactants have the potential to replace synthetic(artificial) surfactants. The two most significant biosurfactants (BS) for commercial use are glycolipids and lipopeptides [26].

9.1 In Food Industry

In food production, surfactants serve a variety of other roles in addition to their well-known function as agents that reduce interfacial and surface tension, leading to the creation and stabilisation of emulsions [25].

Biosurfactants behave as agents during the heating of fats and oils in bread and ice-cream mixes regulating the texture, delaying staling, and solubilising the flavour oils [26]. Rhamnolipid surfactants are added to bread goods to enhance the volume, appearance, stability of dough, and storage [28].

9.2 In Petrolium Industry

One of the primary sources of energy is petroleum. Global energy consumption is predicted to reach 15.3 billion tonnes of oil year, while production of barrels of oil is estimated to rise by 1.7% between 2000 and 2030. If present levels of consumption continue to rise, oil reserves may fulfil global demand for approximately 40 years. Improvement of technology that enable the effective use of this resource is therefore crucial. The International Energy Agency reports that the production of petroleum is gradually shifting away from medium- and light-weight crude oils and towards unusual crude oils like extra-heavy and very heavy oils [30].

In nations like Canada, China, Mexico, Venezuela, and USA, at least half of the accessible petroleum resources have been made up of heavy and extra-heavy petroleum products [29].

9.3 In Crude Oil Isolation from Reservoirs

All over the world, a number of improved oil isolation techniques are now in use, including thermal, chemical, and physical methods [30]. Nevertheless, these methods are not only costly but also detrimental to the environment. Thus, the quest for creative, economical, sustainable alternatives to the chemical and thermal enhanced oil recovery procedures is essential. In the present energy crisis, several biotechnology-based methods have been put out to boost oil production. In this field, biosurfactants are useful because they are organic substances that accelerate the mobilisation of hydrocarbons, which in turn increases crude oil recovery from reservoirs through a process known as microbially enhanced oil recovery (MEOR) [31].

9.4 In Drug Industry: clinical studies, and regulatory clearances, the pharmaceutical business creates life-saving medications. It includes formulation, manufacturing, marketing, and medication discovery. Following rigorous quality and safety criteria, advances in biotechnology and artificial intelligence hasten drug research, guaranteeing safer, more effective therapies for worldwide healthcare concerns.

9.4.1 Anti-neoplastic agents

Certain microbial extracellular glycolipids induce the human promyelocytic leukaemia cell line to go through cell division rather than proliferation. Additionally, MEL exposure increased acetylcholine esterase activity, halted the cycle of the cell at the G1 phase, leading to neurite overgrowth and partial cell differentiation. These findings suggest that MEL induces differentiation of neurones in PC 12 cells and provides the basis for the application of extracellular glycolipids from microbes as novel reage [31].

9.4.2Antifungal Agents

A glycolipid bio-surfactant known as flocculosin was shown to have in-vitro antifungal activity against a number of harmful yeasts in a recent study associated with mycoses in human beings [30.]

9.4.3 Antimicrobial Agents

The permeability of the plasma membrane can be impacted by the toxic effects of bio-surfactants in a manner similar to that of surfactants due to their molecular characteristics. Two biosurfactants generated by *Lactococcus lactis* and *Streptococcus thermophilus A* have been tested for their antibacterial efficacy against a range of bacterial and yeast strains recovered from voice prosthesis that have been implanted [30].

Bacillus subtilis R14 synthesised a lipopeptide-type biosurfactant that showed antibacterial efficacy against 29 different bacterial strains. In comparison, a marine Bacillus circulars biosurfactant exhibited potent antibacterial properties against gm (+) and gm (-) pathogens [32].

9.5 In Gene delivery

According to Gharaei-Fathabad, the invention of an effective and secure technique for introducing exogenous nucleotides into mother cells is essential for both clinical and basic research purposes [30].

9.6 In Agriculture as Biopesticides

The standard method for controlling arthropods entails using insecticides and broad-spectrum pesticides, which might have unfavorable effects. Additionally, the rise in the cost of new chemical pesticides and the advent of pesticide-resistant insect populations have prompted a quest for more environmentally acceptable vector control methods. A number of microbes create lipopeptide biosurfactants, which show insecticidal efficacy against fruit-eating Drosophila melanogaster and hence have promise for application as biopesticides [31].

9.7 In Bionanotechnology

The future generation of ecologically friendly or biotechnology nanocatalysts is expected to consist of biosurfactants derived from microorganisms and nanomaterials. Ecological rehabilitation provides significant possibilities for the generation of nanomaterials via biosurfactant-mediated mechanisms. The nanoparticles synthesized using biosurfactants must, however, be economically viable. Biosurfactant microorganisms may stabilize and decrease nanomaterial production. Microorganisms synthesize nanoparticles such as gold, silver, and titanium.

9.8 In Oncologic Therapy

Biosurfactants contain a vital capacity to modulate mammalian cell functions and, thus, may be utilized in oncologic therapy. These substances have been established for sustaining sever functions, including cellular immune responses, distinction, and transmission of signals. For instance, glycolipids, were observed to induce an end to growth and death in B16 melanoma cells in mice. The elevation of reactive oxygen species (ROS) production, suppression of Bcl-2 expression, facilitating of cytochrome c (Cyto-c) release, stimulation of caspase pathways, inhibition of 12-O-tetradecanoylphorbol-13-acetate (TPA)-induced migration, colony formation, and invasion via MMP-9 modulation, alongside apoptosis and DNA damage, may represent critical mechanisms employed by biosurfactants to exert anticancer properties.

9. Biosurfactant with Nanoparticles

The Greek word nanos, which means dwarf, is the source of the prefix "nano," which designates objects that are one-billionth (10−9 m) in size. Because of their special qualities and numerous uses in many aspects of our everyday lives, nanostructures having at least one dimension between 1 and 100 nm have been gaining attention. Because of its many possible uses, the development of straightforward techniques for creating nano-sized metal particles has so garnered a lot of interest. In a variety of industries, including biotechnology, electronics, medicine, energy, cosmetics, coatings, and packaging, nanomaterials provide answers to technical and environmental problems. Nanotechnology research and development differs from other scientific domains. The shape, total size, size range distribution, and composition of nanoparticles (NPs) all have a significant impact on their properties [34].

10.1 Nanoparticle Synthesis Mediated via Biosurfactants

As alternatives approach, the requirements for new, environmentally friendly biological processing advancements for nanoparticle production are changing. Microbial production of nanoparticles of metal and biosurfactant mediated technique are emerging as safe, non-toxic, and clean "green preparation" techniques. Surface active agent-mediated nanoparticle synthesis is better than methods based on bacterial or fungal synthesis because biosurfactants prevent aggregation formation and speed up the production of nanoparticles with a consistent shape. Both metallic nanoparticles and biosurfactants have a wide range of uses in agriculture, healthcare, nutrition, and the environment. The production of metallic nanoparticles contributed by biosurfactants is a safe, and effective process; nevertheless, additional research is required to fully understand the combined impact of biosurfactant and metallic nanoparticles, which will eventually give rise to new advancements. Capping agents are primarily important in determining the ultimate quality of metallic nanoparticles. In essence, it shields a surface by initiating electrostatic reactions, which reduces the tendency of metal nanoparticles to clump together stabilization.

Comparison of Surfactants, Nano-surfactants, and Biosurfactants

Property	Surfactants	Nano-surfactants	Biosurfactants
Definition	Surface-active agents that reduce surface and interfacial tension.	Surfactants at the nanoscale (1-100 nm) with enhanced properties.	Surface-active compounds produced by microorganisms.
Origin	Synthetic or natural	Synthetic or natural	Microbial or biological
Size	Micro to macro scale	Nanoscale (1-100 nm)	Varies (often micro to nano)
Biodegradability	Variable	Variable	High
Environmental Impact	Potentially toxic, some non-biodegradable	Generally safer, depends on material	Eco-friendly and low toxicity
Production Method	Chemical synthesis	Chemical or physical methods	Fermentation using microbes
Cost	Generally low	Moderate to high	Often higher, but improving

Surface Activity	Good	Enhanced due to high surface area	Comparable or better than synthetic surfactants
Stability	Moderate	High stability in extreme conditions	Stable, but depends on conditions
Applications	Detergents, emulsifiers, dispersants	Enhanced oil recovery, drug delivery, nanotechnology	Bioremediation, agriculture, pharmaceuticals, cosmetics
Examples	Sodium dodecyl sulfate (SDS), CTAB	Nanomicelles, liposomes, nanoemulsions	Rhamnolipids, surfactin, sophorolipids

12.Conclusion:

Numerous review papers have explored the special features of biosurfactants that including their antibacterial, emulsifying, and anti-adhesive capabilities. These compounds could be generated chemical or by the activity of microorganisms and their potential uses in a variety of industries have been mentioned. The production of novel Microorganisms (bacteria, yeasts, and fungi) generates biosurfactants (glycolipids, surfactin, and high-molecular-weight biosurfactants) that enhance antimicrobial activity, in particular in applications of food and medication quality. Protection of animals and plants, and prevention and treatment. These biosurfactants can help in identifying of various molecules according to their arrangement and physical and chemical characteristics. Their ability to self-assemble and amphiphilic nature provide new opportunities for the creation of antibacterial formulations that offer pharmaceutically interesting bio-actives.The molecules of choice for the future in food compositions, nanoparticle synthesizing, biological, and healthcare services are biosurfactants. Research to reduce the production and operational costs of biosurfactant production will increase consumption of surface-active compounds. To develop biosurfactant-mediated procedures, it is essential to evaluate the biosurfactant's toxicity and integration with materials related to animals and human beings. Furthermore, more research and a better fundamental evaluation of the biosurfactant must be conducted for industrial growth and applications in the future.

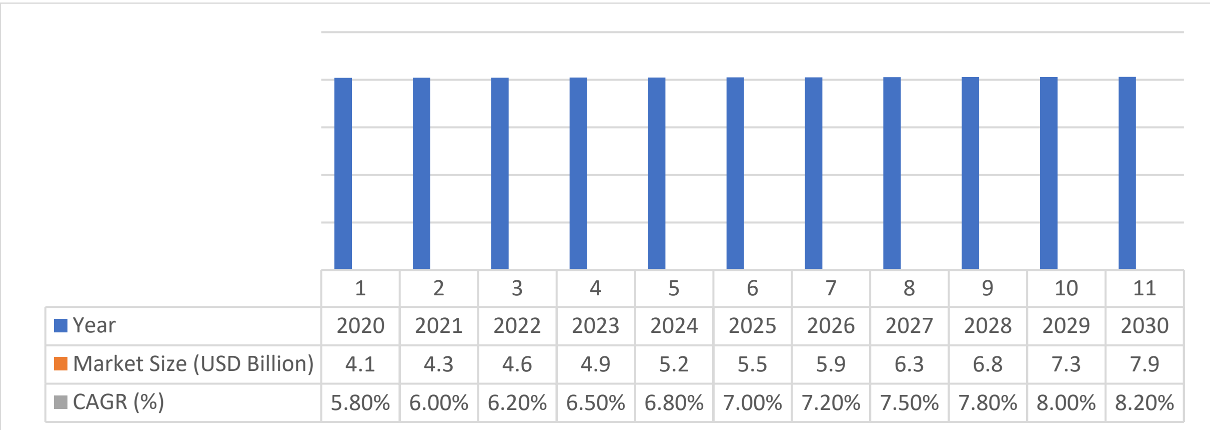
11. Future Prospects and Market

The worldwide surfactants market is expected to grow at a compound annual growth rate (CAGR) of 4.9% between 2021 and 2028, from $41.22 billion in 2021 to $57.81 billion. The industry produces 17 million metric tons of surfactants a year, most of which are eventually discharged as effluent and some of which come into direct contact with customers. Given this volume, resolving environmental challenges is essential for a sector dealing with growing customer awareness and regulations [30].

The projected valuation of the green surfactants market in 2020 was approximately USD 2.54 billion. From 2022 to 2027, the global market for green surfactants is expected to grow at a compound annual growth rate (CAGR) of 5.7%, with a projected value of $3.56 billion by 2026. The industry is booming as a result of the rising demand for green surfactants produced from agricultural raw materials and waste biomass.

In addition to impacting end-user industrial demand, the coronavirus disease (COVID-19) pandemic also raises questions regarding the sustainability of the raw material supply. Since the initial ingredients makeup to 50% of the cost of making glycolipids and 10% to 30% of the cost of other biosurfactant products, their long-term sustainability is a critical concern. 60% of production costs are incurred in purification; however, using biosurfactants in their raw forms may lower this amount [31,32,33].

Year	Market Size (USD Billion)	CAGR (%)	Key Growth Drivers
2020	4.1	5.80%	Growing demand for eco-friendly surfactants
2021	4.3	6.00%	Increased use in personal care and detergents
2022	4.6	6.20%	Expansion in pharmaceutical & food industries
2023	4.9	6.50%	Rising awareness of sustainability
2024	5.2	6.80%	Government regulations promoting green chemicals
2025	5.5	7.00%	Technological advancements in production
2026	5.9	7.20%	Increasing adoption in oil & gas industry
2027	6.3	7.50%	Growing R&D investments in biotechnology
2028	6.8	7.80%	Expanding applications in agriculture & food processing
2029	7.3	8.00%	Rising consumer preference for bio-based products
2030	7.9	8.20%	Sustainable manufacturing practices & raw material availability



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