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# Eco-Interfaces: Charting the Next Frontier with Natural Surfactants

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**ABSTRACT**

Surfactants, or surface-active substances, are compounds that greatly reduce the surface and interfacial tension between different phases. This makes them useful in many everyday processes like spreading, mixing, wetting surfaces, and creating foam. Historically, synthetic surfactants have been used widely across various industries such as oil and gas, pharmaceuticals, cosmetics, and farming. However, concerns have grown over their environmental impact because many of these chemicals do not break down easily and can be toxic. To address this, researchers are exploring eco-friendly alternatives like biosurfactants and natural surfactants. Natural options tend to be less harmful and break down more easily because they come from renewable sources such as plant oils, sugars, and fatty acids. Microorganisms like bacteria, yeasts, and fungi can produce biosurfactants too. These biological surfactants not only have similar physical and chemical properties but also bring added benefits, such as fighting bacteria and working well even in tough conditions.

Environmentally friendly and sustainable reinforcement of biodegradable surfactants, natural surfactants are being taken from organic and renewable materials such as plants, microorganisms, and animals. This paper has carried out a complete natural surfactants review, starting from classification, their physiochemical properties, the way they are produced, and to the range of industrial uses. The latest work in biosurfactants research will be discussed as well as possible future directions and hurdles to be overcome before commercialization. Like the approach taken in the paper, data from recent studies were summarized and put into flow charts, tables, and graphs for better understanding.

***Keywords:*** *Surfactants, Natural surfactants, Biosurfactants, Biodegradability, Eco-friendly, Emulsification, Microbial surfactants, Sustainable chemistry.*

## 1. INTRODUCTION

Surfactants, or amphiphilic compounds, can indeed reduce the surface and interfacial tensions of liquids, solids, and gases to a large extent, which is very important for the progress of many industries. Historically, petroleum-based surfactants have enjoyed the lion's share of the market due to their strong efficacy and little cost. Nevertheless, the same synthetic materials are dangerous and do not decompose naturally, and so they are posing serious threats to human health as well as the environment. However, these natural alternatives, which are also less toxic, biodegradable, and sustainable in their production, have been well-received lately. The term "biosurfactant" originates from the culture of microorganisms, which is able to produce surfactants, while "surfactant" stands for a raw material made from plants and animals.[1,2] Surfactants are the most prominent of the compounds that have fundamentally changed our life. One special quality of surfactants is their amphiphilicity. Amphiphilic organic or organometallic substances are known as surface-active agents, or surfactants. They have a lengthy, nonpolar tail that is connected to a polar head group.[3,6] This characteristic offers a clear hydrophobic and hydrophilic properties of surfactants. These molecules accumulate their name because they reduce the solvent's surface tension. This ideal surface activity is caused by the equilibrium between lyophobic and lyophilic properties[4,5]

The monomers of these molecules are dispersed randomly in an aqueous solution, and when the concentration rises, the monomers begin to aggregate to form clusters known as "micelles." The CMC, also known as the Critical Micelle

Concentration (CMC), is the lowest concentration at which micelles first become detectable.[7,10] CMC is the specific concentration range where these aggregates become observable. Around CMC, the solution's physicochemical characteristics abruptly alter. This aggregation gives solubilizes (a special medium that is both hydrophilic and hydrophobic). Consequently, compounds that are hydrophilic or hydrophobic can become soluble in surfactant systems. This characteristic gives rise to a series of intriguing options. [6]

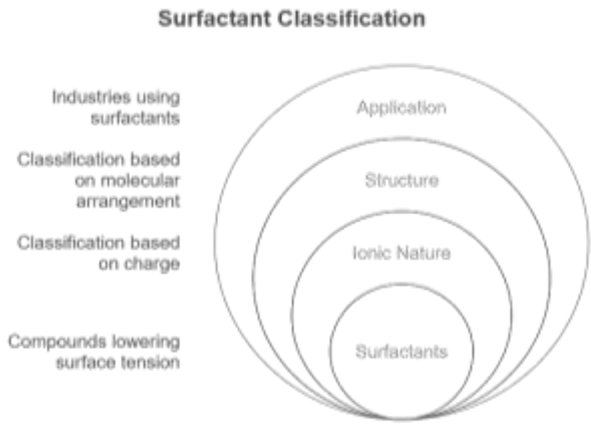


**Fig. 1: Surfactants General Classification**

***What are Natural Surfactants?***

Natural surfactants come from plants, animals, or microbes and are amphiphilic compounds, means they contain both hydrophilic and hydrophobic components. They are generally considered to be non-toxic, biodegradable, and harmless to the environment substitutes for synthetic surfactants since they can lower surface and interfacial tension.[8,9]

The surface tension between two substances, such as liquids or a liquid and a solid, can be reduced by natural surfactants. They come from natural sources, such as plants and animals, and because of their environmentally favourable qualities, they are being used more and more in a variety of businesses. This paper examines the meaning, origins, uses, and advantages of natural surfactants, emphasizing their importance in consumer and industrial goods.

Natural surfactants, also known as saponins, are a class of water-soluble glucosides that have an ether bond connecting a hydrophobic group made up of a sugar chain and a polycyclic aglycone known as a sapogenin (Fig. 2). Both polar (sugar) and non-polar (aglycone) groups give saponins their surface-active qualities. Saponin is found in plants as a combination of several surfactants with comparable polarity and structural similarities[8,9,10]

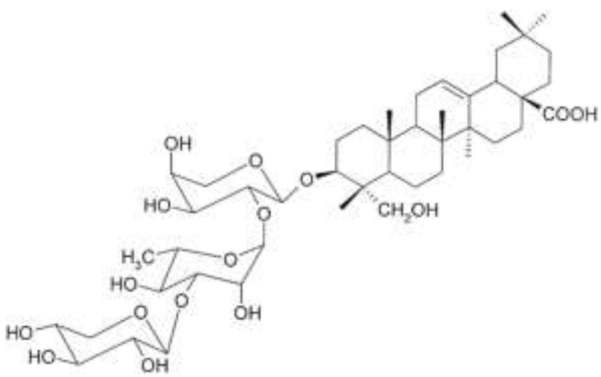


**Fig. 2: Generalized structure of Saponin.**

A class of substances known as saponins is extensively found in the kingdom of plants. Saponins can be used as natural biosurfactants because of their amphiphilic characteristic structure, which in turn gives them high surface activity and self-assembly properties.

The primary cause of the lack of natural surfactants in the true sense of the word is not a lack of supply. Amphiphiles, also known as polar lipids, are widely distributed in both the plant and animal kingdoms. Surface active agents are utilized in biological systems in a manner similar to that of surfactants in technical systems: to change surfaces, as emulsifiers, as dispersants, and to solve solubility issues.

The cost of work-up is the element that hinders the manufacturing of really natural surfactants. The products are typically found in trace amounts, and the process of separation is laborious. The majority of the time, the cost of separation and isolation will be significantly more than the cost of producing comparable synthetic surfactants. [11,12]


**Fig. 3 : Importance of Natural Surfactants**

A sustainable substitute for synthetic surfactants, natural surfactants minimize environmental impact while offering efficient solutions for a range of industries. They are extremely useful in promoting eco-friendly behaviours and goods because of their wide range of sources and uses. The investigation and application of natural surfactants is anticipated to grow in tandem with the growing demand for natural ingredients, opening the door to creative and sustainable solutions. [13]

A naturally occurring surfactant that has both hydrophilic and hydrophobic qualities. It facilitates the blending of incompatible liquids. It produces a stable foamy substance and increases the speed of liquid on the surface.

This substance comes from renewable resources and can decompose organically.[14,15]

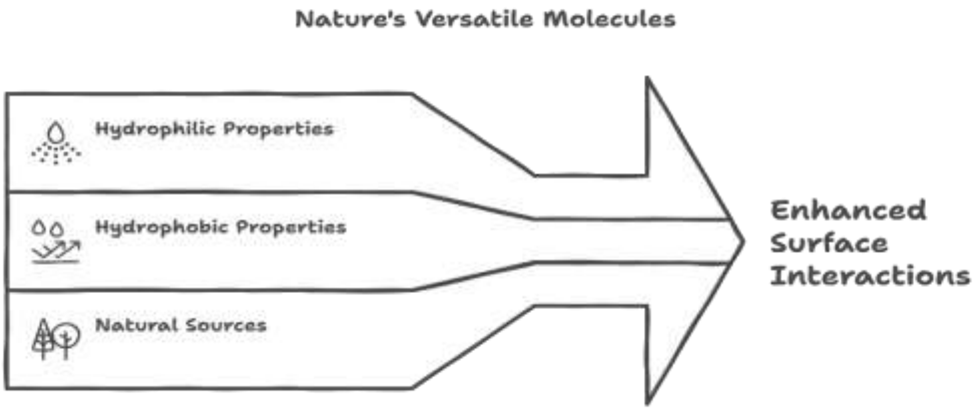


**Fig.4 : Advantages Of Natural Surfactants**

The harmony of hydrophilic and hydrophobic characteristics in natural surfactants is essential for improving surface interactions in a safe and sustainable way. Usually, plant oils, sugars, or amino acids—renewable natural resources—are the source of these surfactants. The hydrophilic part, which is frequently made up of sugar or amino acid groups, enhances the surfactant's solubility and wetting by enabling it to interact effectively with water. The hydrophobic part bonds to oils and dirt and is typically produced from the fatty acid chains of coconut, palm, or other plant oils. Natural surfactants can effectively clean or emulsify things, produce micelles, and lower surface tension thanks to their amphiphilic structure. They are perfect for use in personal care because of their natural origin, which also improves biodegradability, lowers toxicity, and lessens skin irritation.[17,18]

**Advantages Of Natural Surfactants:**

- Derived from organic materials such as plants, carbohydrates, and oils.
- Because they are mild and less irritating, they are safe for skin.
- They are biodegradable and readily broken down, making them environmentally friendly.[16]
- Clean well—by combining water and oil, they eliminate filth and oil.
- Facilitates the lathering and spreading of ingredients on the surface.
- Because they are gentle and efficient, they are used in soaps and shampoos.
- No harsh chemicals—neither synthetic compounds nor sulfates are present.
- Examples include Sodium Cocoyl Glutamate, Lauryl Glucoside, and Cocamidopropyl Betaine.[20]

## 2. COMPARISON OF NATURAL AND SYNTHETIC SURFACTANTS

Natural surfactants are more effective than synthetic surfactants in many different ways and hence this is the reason why they are being preferred more by the users and industries because of their features and uniqueness. The following table shows a in detail comparision between Natural and synthetic Surfactants. [19]

| **Feature** | **Natural Surfactants** | **Synthetic Surfactants** |
|---|---|---|
| Source | Obtained from natural sources, such as sugars and plants. | produced chemically from petroleum or other substances |
| Biodegradability | Biodegradable in general | Varies, with some not being biodegradable. |
| Toxicity | generally low toxicity | Can be harmful to both humans and aquatic life. |
| Compatibility of Skin | Mild and less grating | May result in allergic reactions or discomfort. |
| The price | More costly | typically less expensive to produce in bulk |
| Performance | Good, but it might require more focus. | Very good at lower dosages |
| Effects on the Environment | Higher environmental load frequently results from lower environmental effect | High Environmental Damage |
| Consistency | Less stable in storage conditions, heat, or pH | More resilient and adaptable in a variety of circumstances |
| Uses | utilized in infant items, food, and eco-friendly cosmetics | prevalent in personal care, industrial, and detergent products |
| Regulatory Approval | Because of its natural basis, regulatory approval is frequently simpler. | may necessitate thorough testing and adherence to |

**Table 1 : Comparison of Natural and Synthetic Surfactants**

The origin, performance, environmental effect, and safety profiles of natural and synthetic surfactants differ significantly. Natural surfactants provide a more sustainable and eco-friendly option because they are made from renewable resources including plant oils, sugars, and amino acids. Because these surfactants are often less harmful, biodegradable, and prone to irritation, they can be used in formulations that are environmentally conscious and acceptable for sensitive skin, such as cosmetics, personal care items, and baby care. They may, however, need larger concentrations to perform comparably to their synthetic counterparts and frequently have higher production costs.[21,22]

Conversely, synthetic surfactants provide a very efficient and cost-effective substitute and are made chemically from petroleum-based feedstocks. Their remarkable stability under a range of conditions and their effectiveness at lower concentrations make them ideal for mass-market and industrial applications, such as detergents and personal care products. Synthetic surfactants may provide environmental issues despite their performance advantages because some of them are harmful to aquatic life and difficult to biodegrade. They may also cause skin irritation or allergic responses in some individuals.[25]

Although synthetic surfactants continue to dominate in terms of cost and performance efficiency, natural surfactants are gaining popularity due to their safety, sustainability, and suitability for product formulations that are environmentally and health-conscious.[23,24]

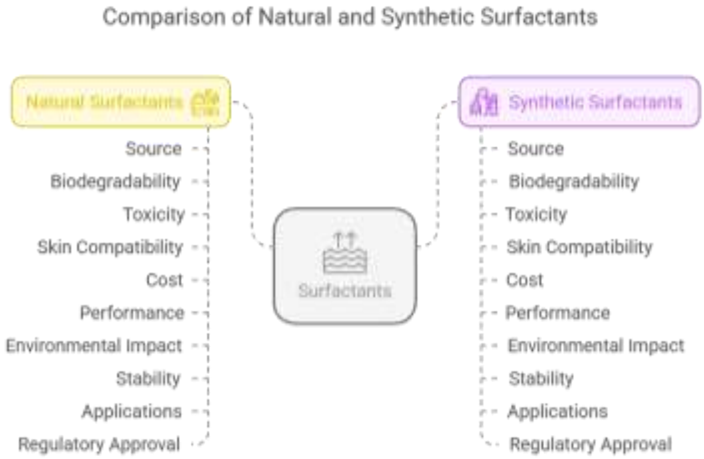


**Fig 5: Comparison between Natural and Synthetic Surfactants**

Natural and synthetic surfactants have been evaluated across several key areas, with ongoing debate regarding their overall effectiveness. The comparison can be outlined under the following headings: [24,23]

1) **Physical Properties:**

The performance of surfactants has been evaluated using a variety of methods, including the surface balance, pulsating bubble surf-actometer, and captive bubble method. The enhanced properties of natural surfactants, such as improved surface adsorption, spreading, respreading, and film compressibility, are repeatedly demonstrated.

2) **Physiological Effects**:

Research using animal models, including preterm lambs, shows that natural surfactants increase survival rates, enhance lung compliance, and improve oxygenation. Natural surfactants, for example, have demonstrated better results than synthetic ones.

3) **Additional Aspects**:

Clinical study outcomes, variations in side effects, quality control procedures, and financial considerations are some additional aspects that compare natural and synthetic surfactants. Synthetic surfactants may be more cost-effective and consistent, even if natural one frequently exhibit better therapeutic results.

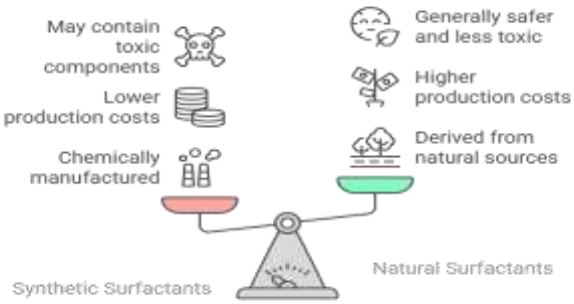


**Fig.6 : Balancing Synthetic and Natural Surfactants**

**Opportunities with Natural Surfactants:**

- Biodegradability: Natural surfactants decompose quickly, reducing their environmental impact, but manufactured surfactants may persist in ecosystems.
- Skin Compatibility: This product is gentler on skin and ideal for sensitive skin types because it is less likely to irritate it than synthetic substitutes.
- Sustainability: Although synthetic surfactants are made from renewable plant materials, they usually employ non-renewable petrochemicals, which promotes sustainable practices. [26,27]
- Non-Toxicity: Natural surfactants are less likely to contain harmful substances than some synthetic ones, which may contain hazardous consequences.
- Mildness and Non-Irritation: Preserve the natural oils of the skin without causing severe skin stripping.
- Versatility in Applications: Works well in a range of formulations (personal care, cleaning products, and industrial uses) and provides additional benefits like moisturizing or conditioning. [29,28]
- Decreased Environmental Impact: Typically produced through organic farming.

## 3. APPLICATIONS OF NATURAL SURFACTANT IN COSMETICS

The market for surfactants is looking at natural and renewable sources as a result of the depletion of fossil fuels and rising ecological consciousness. These substitutes seek to improve product benefits while reducing environmental damage. Natural surfactants are surface-active compounds made from renewable resources such as waste and agricultural by products, microbes, plants, and animals. Their definitions differ depending on the literature, however they are frequently referred to as bio-based surfactants, green surfactants, or biosurfactants.

Because of their physical-chemical and biological characteristics, saponins or extracts rich in saponins offer the potential for a variety of biotechnological uses. Furthermore, saponins have demonstrated a great deal of promise for use in skincare products, shampoos, and conditioners. Numerous patents have been granted for shampoos that contain saponins, demonstrating the broad range of action of these molecules. These patents include cleaning properties as well as anti-dandruff, anti-itch, and anti-inflammatory properties.[34,29]

In a much larger sense, modern natural surfactants are surface-active substances made from natural source ingredients, as was previously indicated. Furthermore, a natural surfactant, whether hydrophilic or hydrophobic, may only contain one component derived from a renewable resource. Consequently, there are three types of natural surfactants: amphiphiles of microbial origin (made by bacteria or yeast), amphiphiles with a natural hydrophobic tail, and amphiphiles with a natural polar head group. The latter are also known as biosurfactants or biological surfactants.

CMC of natural surfactant is lower than the CMC of conventional surfactants, allowing the use of significantly smaller concentrations. For plant-based surfactants, the CMC value depends on factors like plant type and extraction method.[30,32]

| Type | Name | CMC [g/L] | Reduced Surface Tension [mN/m] | Temperature [°C] |
|---|---|---|---|---|
| **Non-renewable surfactants** | Sodium lauryl sulfate (SLS) | 2.004 | 39.2 | 20 |
| | Sodium dodecyl sulfate (SDS) | 2.36 | 25 | N.A. |
| | Cetyl trimethyl ammonium bromide (CTAB) | 1.131 | N.A. | 25 |
| | Unknown (ID: 353) | 33.4 | 25 | |
| **Bio-based surfactants** | Decyl glycoside from D-glucose (APG) | 0.994 | 26 | N.A. |
| | Decyl glycoside from D-xylose (APG) | 0.301 | 28 | N.A. |

| | | | | |
|---|---|---|---|---|
| | Betula pendula saponins (leaves) | 0.24 | 45.7 | 20 |
| | Bellis perennis saponins (flowers) | 0.076 | 36.8 | 20 |
| | Genipa americana saponins (fruits) | 0.65 | 31.39 ± 0.15 | 25 ± 1 |
| **Biosurfactants** | Sophorolipids | 0.04–0.1 | 30–40 | N.A. |
| | Rhamnolipids | 0.01–0.02 | 26 | N.A. |
| | Hydrophilic mannosylerythritol lipid (MEL) | 0.1 | 27 | 25 ± 2 |
| | Hydrophilic mannosylerythritol lipid (MEL)—G | 0.125 | 30.5 | 25 ± 2 |
| | Surfactin | 0.02 | 27 | N.A. |
| | Iturin C3 | 0.04183 | N.A. | 20 |
| | Hydrophobin | 0.005 | 30 | N.A. |

**Table 2: Widely used Surfactants in Cosmetics**

Discussing about the natural surfactant used in cosmetics, we already know that natural surfactant are derived from many organic sources like (plant-based or microbial etc):

1) Sugars (Glucose): The derived compound of sugar is Decyl glucoside, lauryl glucoside. These derived surfactants are non-ionic, very mild and biodegradable. It is mostly common in baby care and sensitive skin products as it not harmful and toxic for the skin. (e.g., glucose, sucrose)[31,33]

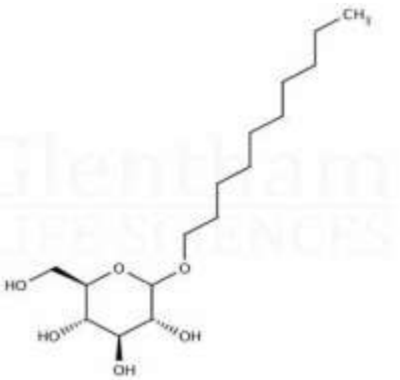


**Fig 7: Decyl glucoside**

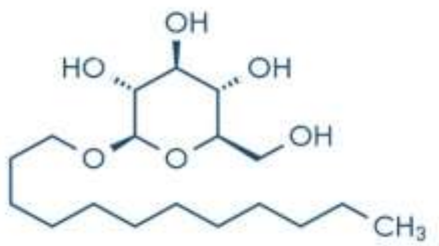


**Fig 8: Lauryl glucoside**

2) Coconut Oil: The derived compounds of coconut oil is Coco glucoside, sodium cocoyl isethionate, sodium lauryl sulfate. coconut oil is rich in lauric acid, as well as used to produce mild, skin-friendly surfactants for shampoos, body washes, and facial cleansers as it contains vitamin E, antioxidant and anti-aging properties.

Fig 9: Coco glucoside

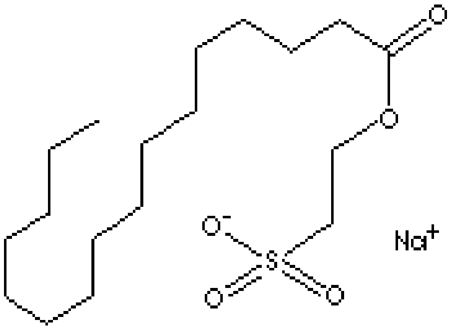

Fig 10 : Sodium cocoyl isethionate

3) Palm Kernel Oil: The derived compound of Palm Kernel Oil is Sodium lauroyl sarcosinate, sodium lauryl sulfoacetate. It is used to produce both anionic as well as non-ionic surfactants with better foaming and cleansing properties. It is used for its nourishing and protective properties too.[34,33]

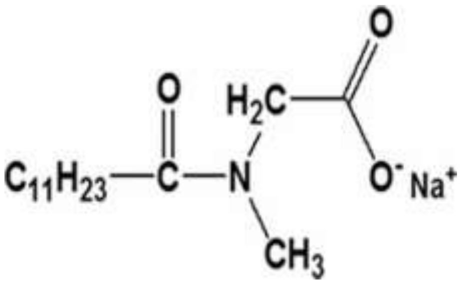

**Fig 11: Sodium Lauryl sarcosinate**

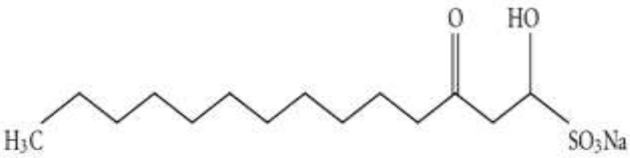

**Fig 12: sodium lauryl sulfoacetate**

4) Soyabean Oil: The derived compound of soyabean oil is Lecithin.

Lecithin also known as phospholipid that acts as a natural emulsifier which improve the texture and stability of cosmetic formulations.[35,36]

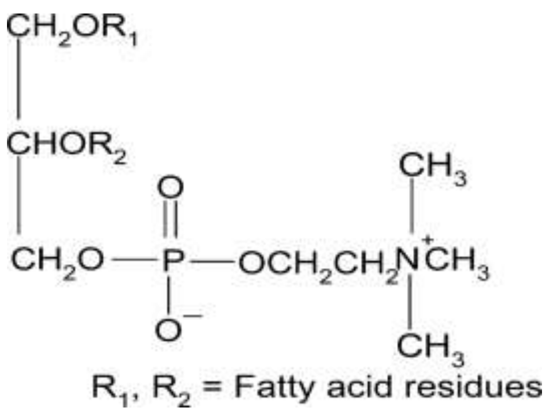


**Fig 13 : Structure of lecithin**

**Classification of Natural Surfactants**

[A] **Basis of Origin** : Natural surfactants are broadly classified based on their origin—plant, animal, or microbial—and their chemical structure. This classification aids in understanding their specific properties and applications. On the basis of origin Surfactants are classified as follows:

1. Plant-derived: Saponins, lecithin, Alkyl polyglucosides, glycyrrhizin, soapwort It is used in cosmetics (shampoo, facial cleansers and for gentle use). In pharmacetuicals. It is a natural emulsifier as well as it used in biopesticide

formulations and a wetting agents. [37]

2. Animal-derived: Bile salts, lanolin, casein, wool fat. It enhance absorption of hydrophobic drugs.
3. It is widely used in moisturizers, lip balms etc. It enhance absorption of hydrophobic drugs.
4. Microbial-derived (biosurfactants): Rhamnolipids, sophorolipids, lipopeptides. It is used in oil spill clean-up as it has an ability to emulsify hydrocarbons. It is usen in formulation and coatings. Applied in microbial to improve displacement.[38]

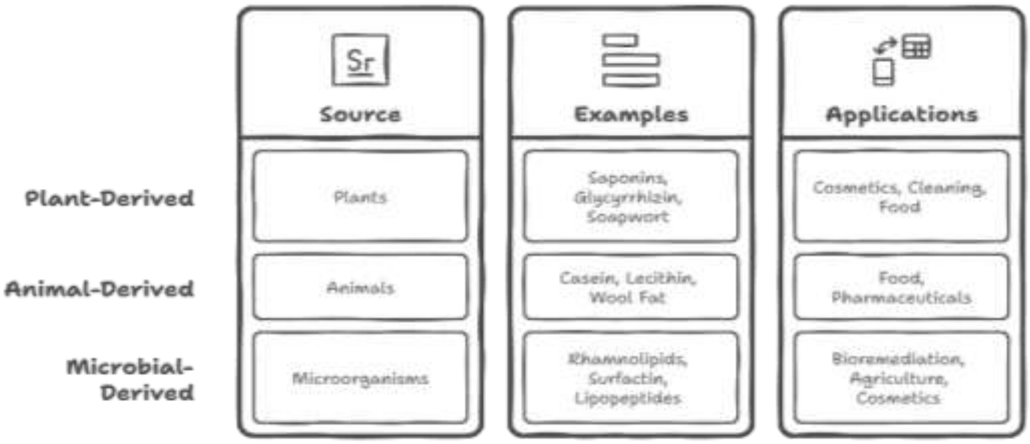


**Fig 14 : Classification of Surfactants on the basis of their Origin**

**[B] Based on their Ionic Charge**: Renewable surfactants can be classified according to the source of renewable resources or the processes and techniques used in their synthesis. Compound production is used to classify natural surfactants. First-generation natural surfactants, also referred to as bio-based surfactants, like saponins and alkyl polyglucosides (APGs), are separated, refined, or chemically synthesized from plant and animal-based feedstock in order to obtain the proper surfactant structure. Second-generation natural surfactants are produced by direct biosynthesis by microorganisms, plants, or animals using biological processes like fermentation and renewable raw materials, by-products, or agro-industrial waste. The most well-known commercially in this group are sophorolipids and rhamnolipids, which are known as biosurfactants..[39,40]

1. 1st gen Natural Surfactants: Bio-Based Surfactants

The main sources of bio-based surfactants are plants and animals. The hydrophilic component is typically made up of carbohydrates, glycerol, and amino acids, while the hydrophobic portion is made up of fatty acids from different plants or leftover cooking oils. Both of these elements can be joined chemically or enzymatically to create the amphiphilic structure of surfactants. The main sources of bio-based surfactants are plants and animals. The hydrophilic component is typically made up of carbohydrates, glycerol, and amino acids, while the hydrophobic portion is made up of fatty acids from different plants or leftover cooking oils. Both of these components can be joined chemically or enzymatically to create the amphiphilic structure of surfactants..[41,42]

i. Glycerol-Based Surfactants

Crude glycerol, a by-product of the biodiesel and oligo-chemical industries, is an important renewable resource. The level of its quality is determined by production and purification processes. Crude glycerol can be produced by a number of chemical procedures such as fermentation with yeast, bacteria, or algae; transformation for the production of biodiesel; and saponification and hydrolysis reactions in oleochemical plants.

ii. Due to its affordability and accessibility, glycerol is a sustainable hydrophilic head group used in the synthesis of natural surfactants. Glycerol-based surfactants can be made by transesterifying glycerol natural fats or oils or by directly esterifying glycerol and fatty acids. These surfactants' emulsification, alkali tolerance, foam stability, and capacity to dissolve hydrophobic colors in aqueous media make them ideal for laundry applications. [43,44,45]

iii. Animal-Based Surfactants

Nowadays, the biomedical industry primarily uses animal-derived surfactants to treat respiratory distress syndrome (RDS), a major contributor to neonatal respiratory failure. The most popular FDA-approved lung surfactants are made from the lung tissue of either pigs or cows. Organic solvents are used to purify and extract this tissue: poractant alfa (Curosurf) contains a high concentration of phospholipids derived from pigs, while calfactant (Infasurf) and beractant (Survanta) are derived from bovine species. Recent studies have suggested the use of animal-derived surfactants as drug carriers for pulmonary therapies and other treatments due to their rapid spreading properties [70]. Furthermore, it has been shown that the use of exogenous surfactants, especially those derived from animals, significantly reduces morbidity and mortality in clinical applications.[48]

iv. Plant-Based Surfactants—Saponins

These compounds are non-ionic bio-based surfactants that are naturally produced by over 100 species of vascular plants and some marine organisms. One important source of natural surfactants is plants. Chemical defenses against infections and herbivores are provided by saponins. Plants contain them in their leaves, roots, flowers, seeds, pericarp, and fruits. They can be extracted using conventional methods (like maceration, soxhlet extraction, and reflux extraction) or advanced techniques (like enzyme-assisted extraction, pressurized liquid extraction, enzyme-assisted extraction, ultrasound-assisted extraction, microwave-assisted extraction, and accelerated solvent extraction).[49]

v. Sugar-based Surfactants-- Saponins

Carbohydrates from agricultural biomasses and industrial waste, such as sugar and starch, are used as hydrophilic head groups in the synthesis of bio-based surfactants due to their accessibility, affordability, and versatility. Sugar-based surfactants have low toxicity, cutaneous tolerance, good surface activity, high wetting, foaming, and emulsifying properties, high biocompatibility, high biodegradability, and environmental compatibility.[46] They are commonly present in a wide range of personal care products, including food, detergents, cosmetics, and medications. The most popular sugar-based surfactants are sorbitan esters, sucrose esters, and alkyl polyglucosides (APGs).[49]

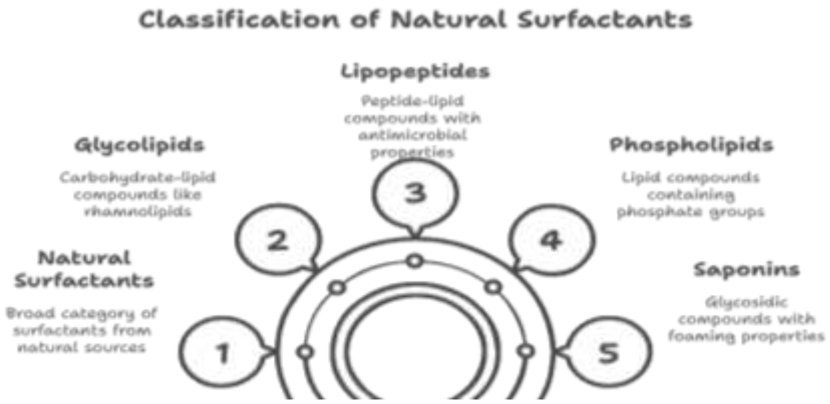


**Fig 15: Chemical based classification Of Natural Surfactants**

**Sources of Natural Surfactants**

1. Plant-derived Surfactants: Plant-based surfactants are extracted from seeds, fruits, and leaves. Saponins, found in soapnut (Sapindus spp.) and yucca, are glycoside compounds with strong foaming properties. Lecithin, a phospholipid derived from soybeans and sunflower seeds, is a natural emulsifier widely used in the food and cosmetic industries. Alkyl polyglucosides, synthesized from glucose and fatty alcohols, offer high biodegradability and mildness, making them suitable for personal care products.[47,50,22]

| Surfactant | Source Plant | Application |
|---|---|---|
| **Saponins** | Soapnut, Yucca | Detergents, Foaming Agent |
| **Lecithin** | Soybean, Sunflower | Emulsifier in Food |
| **Alkyl Polyglucosides** | Glucose + Fatty Alcohol | Shampoos, Cleansers |

**Table 3: Examples of Plant-Derived Surfactants and Their Sources**

2. Animal-derived Surfactants: These surfactants are less commonly used due to ethical concerns and sustainability issues. Lanolin, extracted from wool, acts as a moisturizer and emulsifier in cosmetics. Bile salts, such as sodium taurocholate, function as natural emulsifiers in the digestive tract and have applications in pharmaceutical formulations. [51,9,60]

3. Microbial Biosurfactants: Biosurfactants are secondary metabolites produced by various microorganisms. Rhamnolipids from *Pseudomonas aeruginosa*, sophorolipids from *Candida bombicola*, and lipopeptides like surfactin from *Bacillus subtilis* are notable examples. These surfactants offer surface tension reduction and emulsification comparable to synthetic variants and show promising applications in biore mediation, pharmaceuticals, and agriculture. [53,55]

## 4. PHYSICOCHEMICAL PROPERTIES OF NATURAL SURFACTANTS

The physicochemical properties of natural surfactants are central to their functionality and suitability for various industrial applications. Their solubility, emulsifying capacity, surface tension decrease, and interactions with other chemicals are all influenced by these characteristics. The following are the main physicochemical properties of natural surfactants:

1) Concentration of Critical Micelles (CMC): The concentration at which surfactant molecules in a solution start to group together and form micelles is known as the CMC. Because it establishes a surfactant's efficiency, it is a crucial parameter. Strong surface activity at low concentrations is indicated by the low CMC values of natural surfactants like surfactin and rhamnolipids. For example, the CMC of rhamnolipids varies from 10 to 200 mg/L, depending on strain and purity, while that of surfactin is approximately 0.01 to 0.025 g/L. [52,54]The CMS measures the capacity of natural surfactants to lower surface and interfacial tensions. Greater efficiency is indicated by a lower CMC. Environmental factors including temperature, salinity, and pH affect how well they work. An important benefit in industrial applications is that natural surfactants frequently maintain their action in harsh conditions. Biosurfactants, such lipopeptides and rhamnolipids, exhibit superior foaming and emulsification properties in a variety of mediums[54, 57, 53]

| Surfactant | CMC (mg/L) | Surface Tension (mN/m) | Optimal pH | Stability Conditions |
|---|---|---|---|---|
| **Rhamnolipids** | 10-200 | 25-30 | 6–8 | High salinity, heat stable |
| **Sophorolipids** | 40-100 | 35-40 | 5–7 | Stable across pH 4–10 |

**Table 4 : Physicochemical Properties of Common Natural Surfactants**

2) Reduction of Surface and Interfacial Tension : Reducing the surface tension of water (usually 72 mN/m at 25°C) and the interfacial tension between water and oil is one of the main roles of surfactants. Surface tension can be reduced by natural biosurfactants to as low as 25–30 mN/m. Surface tension is reduced by surfactin to around 27 mN/m, whereas rhamnolipids can reach about 30 mN/m. In applications involving emulsification, foaming, detergency, and wetting, this characteristic is essential.

3) Emulsification Index (E24) and Emulsification Activity: The ability of a surfactant to stabilise emulsions over a 24-hour period is gauged by the emulsification index (E24). When emulsifying hydrocarbons, biosurfactants such as sophorolipids and rhamnolipids have high E24 values (often >50%). Pharmaceutical suspensions, food texture stabilisation, and oil spill cleanup all depend on effective emulsification.[56,60,3]

4) Stability of Heat : Over a wide temperature range, many natural surfactants retain their structural integrity and activity. Biosurfactants such as surfactin and sophorolipids are thermostatable, which allows them to be used in high-temperature industrial operations (up to 100–120°C). This is especially helpful for detergent compositions, food processing, and petroleum recovery.

5) Stability of pH and Ionic Strength: Natural surfactants can work in a variety of salinity and pH ranges because rhamnolipids and lipopeptides are still active at pH values between 4 and 10, they are advantageous for better oil recovery, cleaning products, and agriculture. Many biosurfactants are essential for industrial and marine applications because they can withstand salt concentrations of up to 10–12% NaCl without losing their functionality.[58,34]

6) Properties of Foaming: In cleaning and cosmetic products, foam durability and foaming capability are crucial. Plants like Quillaja saponaria contain saponins, which create a thick, stable foam that works well in shampoos and drinks.Microbial surfactants are more stable in harsh environments but typically have smaller foam volumes.

7) Behaviour of Rheology and Viscosity

Certain biosurfactants improve texture and increase solution viscosity, particularly polymeric forms like emulsan. When thickening or gelling is sought in paint, culinary products, and personal care items, this is beneficial.[59,60]

## 5. PRODUCTION AND EXTRACTION TECHNIQUES

Production is influenced by the surfactant's source. For microbial biosurfactants, fermentation with carbon-rich substrates (such as glucose, oils, and waste glycerol) is commonly employed. Consideration must be given to variables like temperature, pH, and aeration in order to increase yield. Ultrafiltration, solvent extraction, and foam fractionation are common recovery methods. Plant-derived surfactants are extracted using aqueous, alcoholic, or supercritical fluid extraction techniques, and purified using chromatography or precipitation. Hence the selection of proper production and extraction method is necessary for obtaining high quality surfactant from the natural sources otherwise it will lead to change in their properties and actions.[55]

The production and extraction oultines of the natural surfactant is:

Step 1: Purification Step 2: Drying Step 3: Cell Seperation Step 4: Solvent Extraction Step 5: Innoculum Preperation Step 6: Fermentation

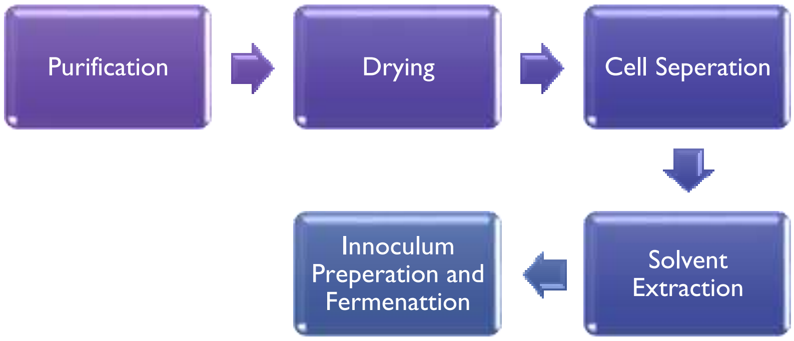


**Fig 16. Process of Processing & Production**

In the purification step we purify all the biosurfactants so that it can be used for industrial applications and must be free from any type of contamination. Purification process helps in maintaining the standard and quality of the products so as to ensure it's high efficacy at the time of industrial application. After the process of purification, drying of surfactants is done so that it can be stored properly and further used for the process of development. Hence drying is a crucial step in the production process. Cell separation is the proce3ss of separating the microbial cells from the fermentation broth. Then solvent extraction is carried out so as to extract the biosurfactants with the help of solvents. This is a crucial step as any change or mistake will hamper the overall quality of the biosurfactant being extracted. Innoculum Preparation is done i.e the microbal cultures are prepared so as to cultivate the microbes which are required for the process of production of biosurfactant. Then fermentation is carried out so as to cultivate the micrroragnisms which are required for production of biosurfactants.[34,29,58]

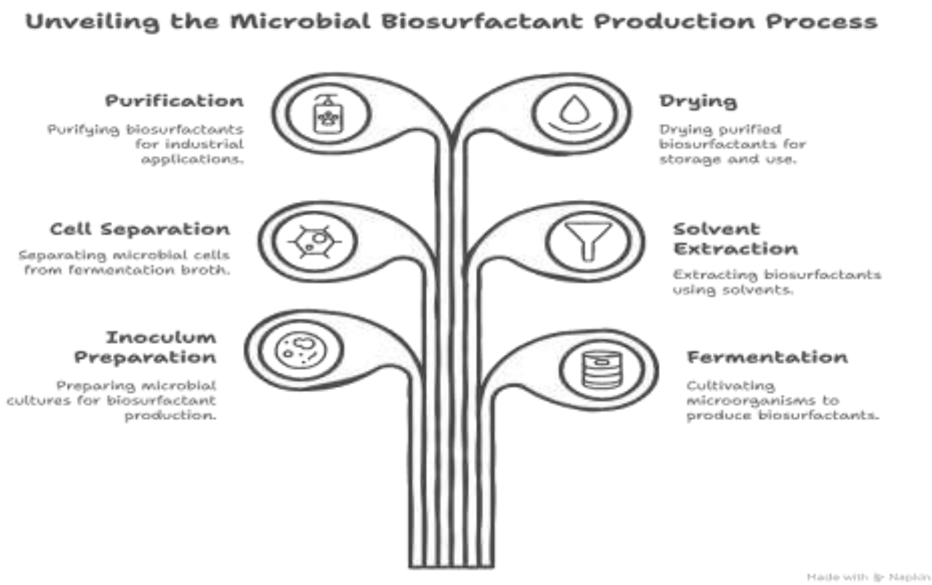


**Fig. 17: The microbial based biosurfactant development process**

## 6. APPLICATIONS OF BIO-SURFACTANTS

There are various application of using biosurfactants over synthetic based surfactants as they are environment friendly. They also helps in increasing the bioavailability of the drugs. Surfactants not only have application in the pharmaceutical industry but as well as in the cosmetic and food industry.

A. **Environmental Applications:** Natural surfactants are those which employed in oil spill cleanup, soil cleaning, and as well as the promotion of hydrophobic contaminants(biodegradation). Rhamnolipids are those which make hydrocarbons more soluble and improves the microbial access to them. Further, they used in the removal of heavy metals from wastewater, hence they are safe for environment as in comarision to the synthetically prepared biosurfactants.[60,32,53]

B. **Pharmaceutical and Biomedical Applications:** As the properties of Biosurfactants is immunomodulatory, antibacterial, and antiadhesive. They act as nanocarriers in drug delivery as well as increase the bioavailability of medications that are poorly soluble. Surfactants are widely used in the preparation of medications as they mask up the poor absorption process of the drugs and increase the overall bioavailability and therapeutic efficacy of the drug products. For instance, surfactin promotes wound healing.[46,52,44]

C. **Food Industry:** In food industry, Lecithin and saponins enhance texture, prolong shelf life, and stabilize emulsions. Additionally, natural surfactants lowers the fat level in baked food and they also utilized as foaming agents in beverages. Surfactants are widely used in the preparation of emulsion as it reduces the surface tension between the components and helps in the preparation of emulsions

D. **Cosmetics:** The usage of surfactants generated from plants and microbes in shampoos, lotions, and face cleansers is growing because of their mild and non-toxic properties. They reduce irritation, emulsify oils, and improve skin moisture. Surfactants have it's wide applicability in the production of shampoos and face cosmetics. Nowadays, natural surfactants are more preferred as compared to the synthetic one. The users are being more attracted towards the benefits of natural surfactants[60]

E. **Agriculture**: In agriculture, Biosurfactants enhance soil permeability, encourage nutrient uptake, and act as biocontrol agents in agriculture. To increase effectiveness and lower chemical residues, they are added to biopesticides and biofertilizers.*[5]*.

| Industry | Applications | Surfactant Type |
|---|---|---|
| **Environment** | Oil spill dispersant | Rhamnolipids |
| **Food** | Emulsifier in bakery products | Lecithin |
| **Cosmetics** | Moisturizing agent in lotions | Saponins |
| **Pharma** | Drug delivery systems | Lipopeptides |
| **Agriculture** | Biopesticide formulation | Sophorolipids |

**Table 5: Applications of Biosurfactants**

Advantages of Natural Surfactants:

1) Eco-friendly: It made from renewable resources as well as it completely biodegradable
2) Low toxicity: safer for ecosystems and is low toxic to the skin and the people.
3) Functional diversity: Works well throughout a broad temperature and pH range.
4) Selective activity: Certain contaminants or diseases may be targeted by biosurfactants.[1,9,53]

## 7. RECENT ADVANCES AND TRENDS

Current advancements in the synthesis of biosurfactants focus on enhancing the productivity of microbial strains via metabolic pathway optimization and genetic engineering. To lower production costs, low-cost and renewable substrates like molasses, leftover frying oil, and agricultural leftovers are being investigated. To improve biosurfactant distribution, stability, and functional performance, nano-formulations are being created. To learn more about biosynthetic pathways and regulatory networks, omics technologies such as proteomics, metabolomics, and genomes are being used more and more. These resources support the identification of important genes and enzymes for specific alterations. Higher yields and scalability are also being facilitated by developments in fermentation technology and bioprocess engineering. Innovations in upstream and downstream processing are fuel by the continued emphasis on environmental sustainability and economic viability. Research is advancing towards cost-effective scale-up, green chemistry integration, and development of multi-functional surfactants. The rise in consumer demand for natural and safe products across industries supports the transition to natural surfactants[7,28,49,53].

## 8. CONCLUSION

Natural surfactants are less toxic than synthetic and can be used by the people without any consequences and it represent a promising solution to the limitations of synthetic counterparts. It is gentle on the skin and used for the personal care products. In Nautral surfactant, it uses safe ingredients. They are wide applicable as well as eco-friendliness, and versatility position them as vital agents in the move toward sustainable industrial practices. Ongoing research and technological improvements will be key to overcoming production barriers and unlocking their full commercial potential. Also the higher yields and scalability are also being facilitated by developments in fermentation technology and bioprocess engineering. Innovations in upstream and downstream processing are fuel by the continued emphasis on environmental sustainability and economic viability. In a much larger sense, modern natural surfactants are surface-active substances made from natural source ingredients, as was previously indicated. Furthermore, a natural surfactant, whether hydrophilic or hydrophobic, may only contain one component derived from a renewable resources. Natural surfactants can effectively clean or emulsify things, produce micelles, and lower surface tension thanks to their amphiphilic structure. They are perfect for use in personal care because of their natural origin, which also improves biodegradability, lowers toxicity, and lessens skin irritation. Hence natural surfactants are more preferred as compared to the synthetically derived surfactants.[55,53,4,9]

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