Nature Environment & Pollution Technology

This is a peer-reviewed prepublished version of the paper

B-4217(26-04-2024)

# A Review on Biosurfactants with their Broad Spectrum Applications in Various Fields

**Nazim Uddin[1], Jyoti Sarwan[1], Sunny Dhiman[1], Kshitij[1], Komal Mittal[1], Vijaya Sood[1], Abu Bakar Siddiq[2] and Jagadeesh Chandra Bose K.[1]†**

[1]University Institute of Biotechnology (UIBT), Chandigarh University, Ludhiana Highway, Mohali, 140413, Punjab, India

[2]Nilphamari Government College, Ministry of Education, Bangladesh

†Corresponding author: Jagadeesh Chandra Bose K; jcboseuibltlab@gmail.com. Orchid ID: 0000-0002-4181-9675

Nazim Uddin-0009-0007-8544-029X

| | |
|---|---|
| Key Words | Glycolipid, Ecotoxicity, Biodegradability, Sophorolipids, Nanoparticles, Liposomes, Niosomes, SLAgNPs, SLAuNPS |
| DOI | https://doi.org/10.46488/NEPT.2024.v24i01.B4217 (DOI will be active only after the final publication of the paper) |
| Citation of the Paper | Nazim Uddin, Jyoti Sarwan, Sunny Dhiman, Kshitij, Komal Mittal, Vijaya Sood, Abu Bakar Siddiq and Jagadeesh Chandra Bose K. 2025. A Review on Biosurfactants with their Broad Spectrum of Applications is Various Fields. *Nature Environment and Pollution Technology*, 24(1), B4217. https://doi.org/10.46488/NEPT.2024.v24i01.B4217 |

## ABSTRACT

Because of the superior qualities of biosurfactants over their equivalents derived from fossil fuels, they have recently attracted more attention. Although production costs are still a major barrier to biosurfactants' superiority over synthetic surfactants, biosurfactants are expected to grow in market share over the next several decades. Glycolipids, a class of low-molecular-weight biosurfactants, are particularly sought-after for a variety of surfactant-related applications due to their effective reduction of surface and interfacial tension. Rhamnolipids, trehalose lipids, sophorolipids, and mannosyl erythritol lipids are the primary types of glycolipids. Glycolipids are made of hydrophilic carbohydrate moieties joined to hydrophobic fatty acid chains by ester bonds. This review addresses the unique glycolipid production and the wide range of goods available in the global market, as well as the present state of the glycolipid industry. Applications include food processing, petroleum refining, biomedical usage, bioremediation, and boosting agricultural productivity. With biosurfactants, their beneficial Ness in releasing oil encased in rock, a need for enhanced oil recovery (EOR). Another crucial biotechnological component in anti-corrosion procedures is biosurfactants, which stop Crude oil transportation in pipelines and are made easier by incrustations and the growth of biofilms on metallic surfaces. They are also employed in the production of emulsifiers and demulsifies and have other cutting-edge uses in the oil sector. Natural surfactants can be used to lessen pollution produced by chemical solvents or synthetic detergents without compromising the oil industry's financial gains. Consequently, it is imperative to invest in biotechnological processes. It is anticipated that natural surfactants will take over the global market in the not-too-distant future and prove to be economically feasible. It is likely possible to substitute synthetic surfactants used in agricultural product composition with biosurfactants. Because biosurfactants can benefit crops without harming the environment, they hold great potential as a useful tool in the fight against pesticide use. Furthermore, by making hazardous and leftover pesticides more soluble and thus accessible for biodegradation by other microbes, their potential as bioremediation agents can help to improve the health of soil systems. This article is based on the explanation of various applications of Biosurfactants.

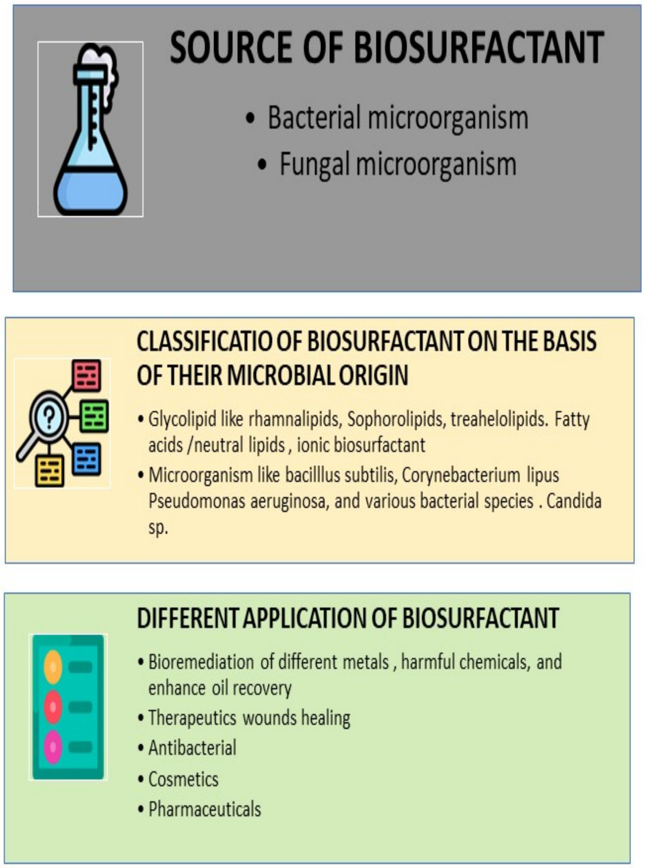
## INTRODUCTION

Sophorolipids are a type of biosurfactant widely used and produced exclusively by microorganisms such as fungi, bacteria, and yeasts. These biosurfactants usually have low molecular weight. Due to their eco-friendly properties, these Sophorolipids are widely accepted in the world market. Compared to chemical surfactants, biosurfactants offer several benefits. For example, biosurfactants are more environmentally friendly than synthetic surfactants because they are readily broken down by microbes in the environment. They are safer to use in a variety of applications since they are often non-toxic to people, animals, and the environment. In comparison to water alone, biosurfactants can penetrate and remove dirt and other impurities more efficiently by lowering the surface tension of liquids. Biosurfactants are also helpful in a variety of commercial processes, including the manufacturing of food, cosmetics, and pharmaceuticals, because they can create stable emulsions of immiscible liquids. The discovery of certain biosurfactants' antibacterial qualities makes them valuable for the creation of novel antibiotics and other antimicrobial agents (Tajabadi 2023, Bose & Sarwan 2023). When sophorolipids (SLs) made by the yeast *Starmerella bombicola* started to be sold, BS entered the market around 20 years ago, but they currently only account for a minor portion of the surfactant market. Innovation in all facets of BS research is crucial to boost the commercialization of BS. This includes discovering new compounds, creating genetically modified ones, characterizing novel microorganisms that produce BS, and enhancing scale-up and downstream BS production processes. Here, a few current instances of these reports will be shown (Seattle 2023). Surface-active compounds with biological origin, known as biosurfactants, are produced as secondary metabolites by filamentous fungi, bacteria, yeast, or plants. Their biological origin and lack of an additional chemical synthesis step during manufacture set them apart from conventional surfactants. When biosurfactants are in their natural condition, they are usually either neutral or anionic.

On the other hand, substances having amine groups are categorized as cationic. The microbiological source from which biosurfactants are formed, the substrates used for their production, and the particular growth conditions utilized can all be linked to the variations in their structures. Significant studies have been conducted on biosurfactants, such as surfactin, rhamnolipids, sophorolipids, and mannosyl-erythritol lipids (MELs) (Karnwal et al. 2023, Sharma et al. 2023). Among other things, they are used as detergents, foaming agents, wetting agents, emulsifiers, demulsifiers, spreading agents, and functional food ingredients. In the foodservice sector, BSs are used as antiadhesives, emulsion stabilizers, and antimicrobial/antibiofilm agents. Because of their possible benefits for the environment, there is a discernible increase in interest in the use of microbial emulsifying agents (Adetunji 2022).

### Structure of Sophorolipids

SLP are amphiphilic molecules, that are composed of a hydrophilic moiety a (head) sophorose disaccharide (2’-O-β-D-glucopyranosyl-β-D-glucopyranose), linked to the hydrophobic moiety (tail), a long chain of fatty acid, (Fig. 02) and partially acetylated, linked by a β-glycosidic bond to 17-L-hydroxy octadecanoic and 17-L-hydroxy-9-octadecanoic acid. These are produced as a combination of structurally allied molecules, reaching up to 40 patterns, and associated with isomers. The highest number of various structures originate from different possible combinations of (a) the β-glycosidic bond links the anomeric carbon of the head sophorose (C1’) to the ω-carbon (terminal/border) or ω-1 hydroxylated (sub-terminal) from the fatty acid (b) acetylation of the hydroxyl groups of the sugar moiety; sophorose C6’ and C6’’ carbons can be deacetylated, monoacetylated or diacetylated; (c) the appearance of acidic or lactonic forms; the *lactonic* form - carboxyl group of the fatty acid (tail) moiety is esterified to the sophorose in C4’’, C6’ or C6’’ (esterification in C4” is more frequent), acidic form – the carboxyl group of the fatty acid moiety is not esterified ; (d) the fatty acid chain might vary in size (mostly between C16 and C18), with the appearance of unsaturation (saturated, monounsaturated or polyunsaturated) -presence of stereo-isomers and sophorolipids can also consisted in the polymeric as dimeric or trimeric form Biosurfactants are produced from various sources as non-pathogenic microbial strains and they are classified based on their source (Fig. 1) with several oils as substrates and fatty acids sources, sugars, yeast extract used as carbon source, peptone, urea, and ammonium compounds are used for nitrogen sources during the synthesized (fermentation) period (Hernández et al. 2023, Bose & Sarwan 2023, Sharma et al. 2023). Glycolipids, lipopeptides, phospholipids, fatty acids, neutral lipids, polymeric surfactants, polysaccharides, lipopolysaccharides, proteins, and lipoproteins are examples of biosurfactants with a range of chemical structures. These are created by microorganisms grown on soluble (carbohydrates) and insoluble (hydrocarbons, oils, and oily residues) substrates. Vegetable oils and leftover fry oil are examples of substrate combinations that can be utilized to increase the production of biosurfactants. Biosurfactants have molar masses that range from 500 to 1500 Da on average. While biosurfactants with a higher molar mass are more frequently utilized for the stabilization of oil-in-water emulsions, low molar mass biosurfactants are more successful at lowering the surface tension at the air-water interface and the interfacial tension at the oil-water interface. While glycolipids, phospholipids, and lipopeptides have low molar masses and are traditionally referred to as biosurfactants, proteins, lipoproteins, polysaccharides, and lipopolysaccharides have high molar masses and are frequently referred to as emulsifiers (Augusto et al. 2023, Hernández et al. 2023, Seattle 2023).



SOURCE OF BIOSURFACTANT

- Bacterial microorganism
- Fungal microorganism

CLASSIFICATIO OF BIOSURFACTANT ON THE BASIS OF THEIR MICROBIAL ORIGIN

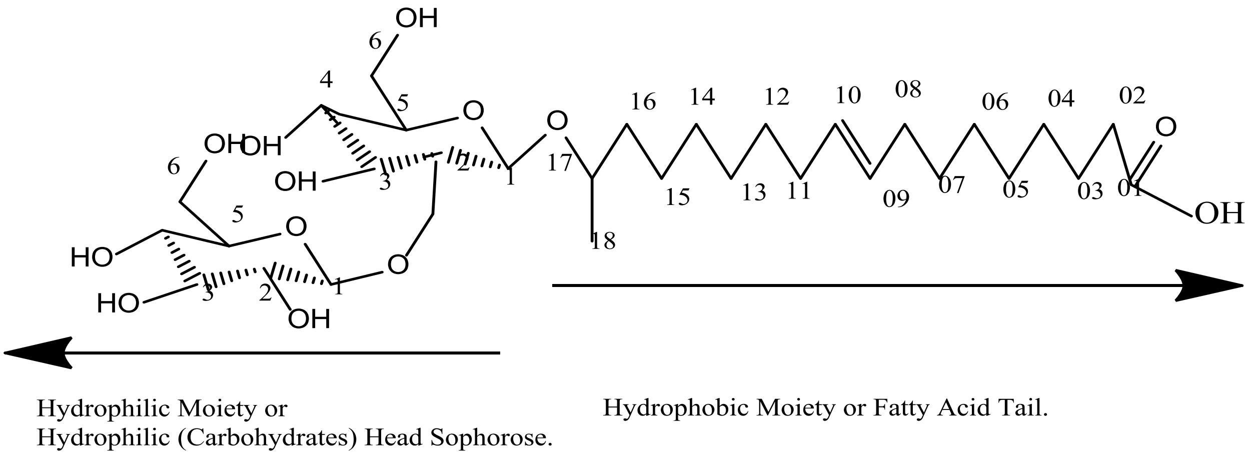
- Glycolipid like rhamnalipids, Sophorolipids, treahelolipids. Fatty acids /neutral lipids , ionic biosurfactant
- Microorganism like bacilllus subtilis, Corynebacterium lipus Pseudomonas aeruginosa, and various bacterial species . Candida sp.

DIFFERENT APPLICATION OF BIOSURFACTANT

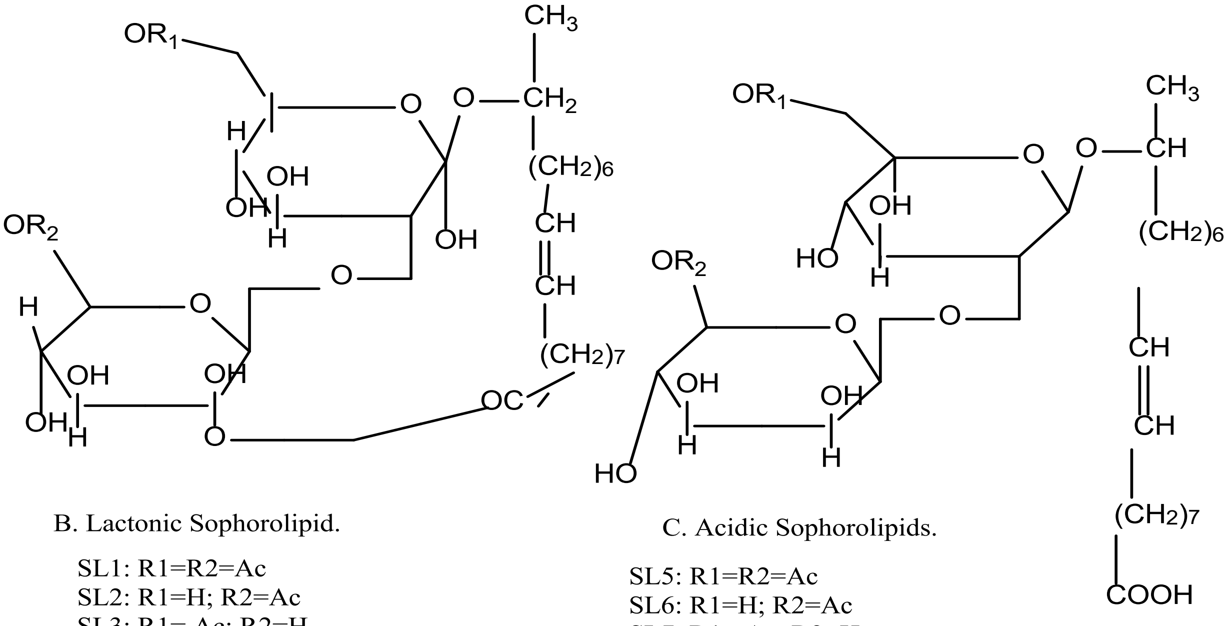
- Bioremediation of different metals , harmful chemicals, and enhance oil recovery
- Therapeutics wounds healing
- Antibacterial
- Cosmetics
- Pharmaceuticals

Fig. 1: Represent that the various biosurfactants originated from microorganisms.

Fig. 2. shows the molecular structure of biosurfactants and biosurfactants sophorolipids, and the molecular structure of lactonic and acidic forms of microbial-derived biosurfactants sophorolipids; the hexagonal-shaped part is the hydrophilic carbohydrate head sophorose, the hydrophobic part is the acid tail, where R = fatty acids.



A. Basic structure of Biosurfactants Sophorolipis.



B. Lactonic Sophorolipid.

SL1: R1=R2=Ac
SL2: R1=H; R2=Ac
SL3: R1= Ac; R2=H
SL4 : R1= R2 = Ac

C. Acidic Sophorolipids.

SL5: R1=R2=Ac
SL6: R1=H; R2=Ac
SL7: R1= Ac; R2=H
SL8: R1= R2 = Ac

Figure; A. Basic Structure of Sophorolipids, B. Lactonic Sophrolipids. C. Acidic Sophorolipids Wherease SL,is Sophorolipids, and R1...............Rn are Fatty acids.

Fig. 2: Glycolipids biosurfactants (Sophorolipids).

## Applications of Biosurfactants

This section explores some of the key applications of sophorolipids (Fig. 3).

## Antimicrobial Applications of Sophorolipids

**Organic active compounds sophorolipids with their applications in the healthcare field:** Sophorolipids biosurfactant is a bioactive compound capable of building active resistance against a variety of toxic activities such as carcinogenic agents. Due to their adaptable qualities, biosurfactants have garnered a lot of interest in recent decades from a variety of industries, including the environmental, oil, agriculture, textile, food, cosmetics, pharmaceutical, and medical (Karnwal et al. 2023). biosurfactants' biocidal and dispersion qualities are used in industrial water systems as anti-biofilm agents, as well as anti-fouling and anti-corrosion agents (Hausmann et al. 2024, McMahan et al. 2021).

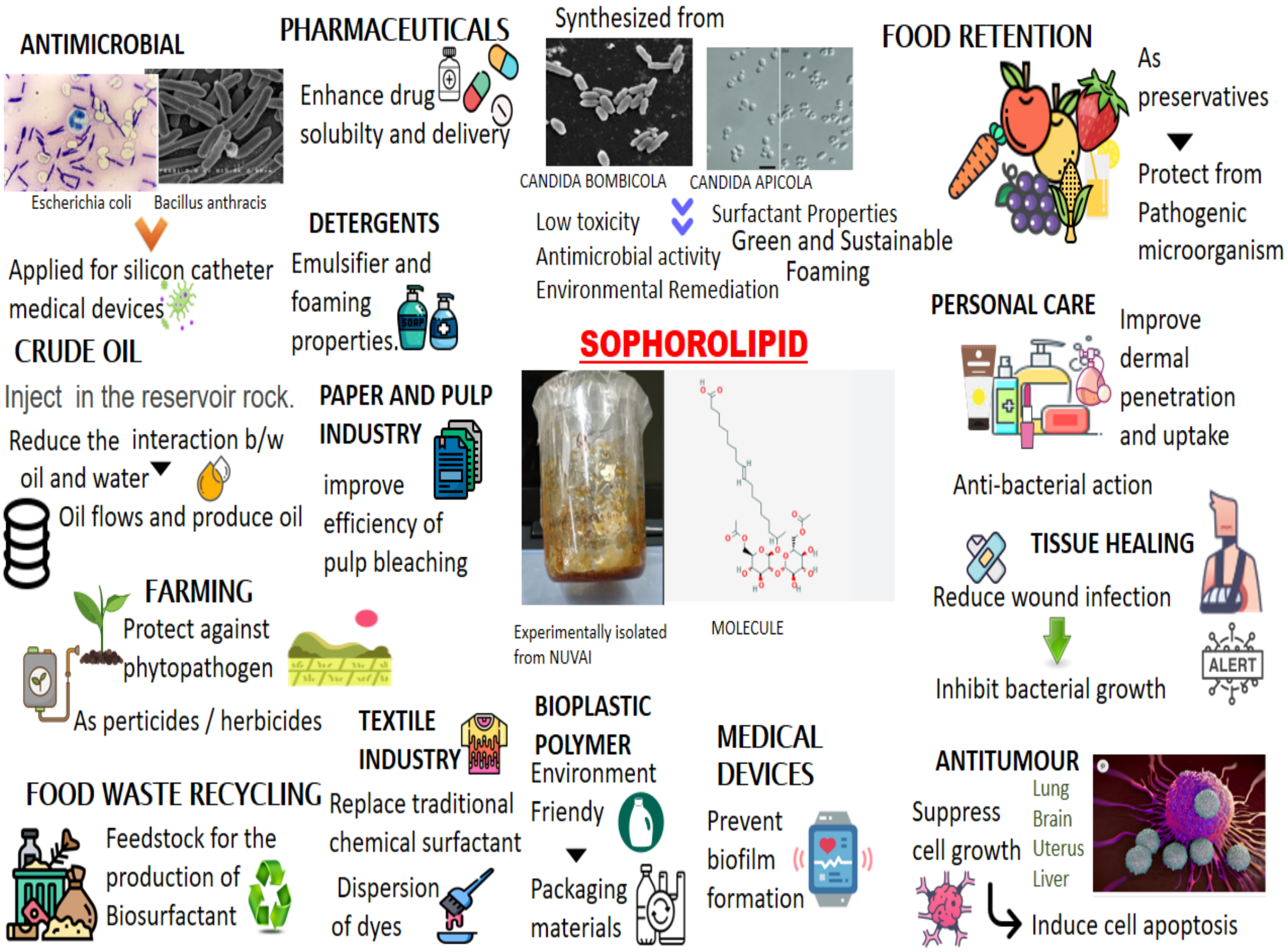


Fig. 3: Applications of biosurfactants sophorolipids in various fields.

**Anti-microbial applications of sophorolipids:** The growing prevalence of multi-resistant infections and the diminishing efficacy of traditional antimicrobials underscore the pressing need for new strategies. A broad spectrum of pathogenic microorganisms, including Gram-positive and Gram-negative bacteria and fungi, can be successfully inhibited by biosurfactants in their growth. Biosurfactants are a useful tool for developing environmentally conscious and sustainable approaches to combating microbial infections because, unlike synthetic drugs, they can offer unique antimicrobial mechanisms of action such as reducing cell surface hydrophobicity, disrupting membrane integrity, increasing its permeability, altering protein conformation and inhibiting membrane functions (transport and energy generation), or blocking the quorum-sensing system and down-regulating gene expression. Microorganisms find it difficult to overcome and develop resistance to these actions. It is also difficult for microorganisms to overcome and develop resistance to biosurfactants, which makes them a valuable tool for developing environmentally conscious and sustainable approaches to combating microbial infections. Moreover, unlike synthetic drugs, these molecules can offer unique antimicrobial mechanisms of action, such as reducing cell surface hydrophobicity, disrupting membrane integrity, increasing its permeability, altering protein conformation and inhibiting membrane functions (transport and energy generation), or blocking the quorum-sensing system and down-regulating gene expression. A multitude of microorganisms that have adapted to survive in harsh environments can be found in the vast and diverse marine ecosystem. These microorganisms may provide a rich source of unique bioactive compounds, some of which, like novel biosurfactants with strong antibacterial and antifungal properties, can effectively fight microbial infections.

Furthermore, using the biosurfactants that marine microorganisms make helps to preserve and investigate marine biodiversity, in addition to providing opportunities for the development of sustainable alternative antimicrobial agents (Ceresa et al. 2023). Surface tension cannot be further reduced by increasing surfactant concentration over a particular point, also referred to as the critical micellar concentration (CMC). Over the CMC, through a process known as micellization, surfactant molecules cluster in the bulk phase to form micelles that can have a variety of geometries, including spherical, cylindrical, discoidal, or even more complicated forms. The rheological and dynamic characteristics of the surfactant solution are influenced by the micelle form. In certain applications, the existence of micelles is essential to the surfactant's ability to operate; for instance, a study on a household cleaning solution found that foam production increased at concentrations higher than the CMC (Rossini et al. 2024, Karnwal et al. 2023). Table 1 shows the antimicrobial activity of biosurfactants against pathogens.

Table 1: Different microorganisms and their impacts on the environment and living beings.

| Microorganism | Strains | Harmful effects | Activity of SLP on Microorganisms | Ref |
|---|---|---|---|---|
| Bacteria (+ve) | Bacillus subtilis.<br>Staphylococcus aureus. | food contamination, skin infections, food-poisoning, | Bacteria cells rupture & disengage when treated with SLPiLA | (McMahan et al. 2021) |
| Bacteria (-ve) | Escherichia coli.<br>Pseudomonas aeruginosa. | Infections of the urinary tract, neonatal meningitis, gastroenteritis, and cross | The bacterial cell wall is severance or contraction or intercept when | (McMahan et al. 2021) |

| | | | | |
|---|---|---|---|---|
| | | infections in hospitals and clinics. | treated by SLPLA. | |
| Fungi | Food spoiled, various pathogenic fungi, like *Candida* sp., *Fusarium* sp. | Harmful to foods and creates different types of fungal diseases inside and outside of man, plants, and animals. | SLP- creates inhibition against spore germination and growth of mycelial of different fungal species. | (McMahan et al. 2021) |
| Algae | Creates water impurities, the dead zone in water, harmful to agriculture | The algal bloom changes water color and creates a barrier to entering the sunlight in water. Bloom releases toxins, which cause plants and animals to die. | The SLP has shown cell lysis and different inhibition against various algal species. | (Sun et al. 2004) |
| Actinomycetes | Dermatophillus congolensis. *Plasmobispora* and *Dactylosporangium.* | These strains are opportunistic. They are caused by dermatophilosis, actiomycosis, and other diseases in the mouth, lungs, and GIT in humans and wild and domestic animals. | The mode of action of SLP on actinomycetes as Cell lysis, cell disruption | (Sun et al. 2004) |

.

Except for the exhibition of the anti-bacterial properties, these SLs showed antifungal activities and antibiofilm (Table 2) that are produced by bacterial and fungal strains.

Table 2: Biosurfactant sophorolipids producing nonpathogenic yeast and fungal strains, produced SLs, and usage of different concentrations against various pathogenic microorganisms.

| Sources of Sophorolipids | Sophorolipids and their structures. | The lethal dosage of sophorolipids and their mode of action on | References |
|---|---|---|---|
| *Cryptococcus* sp. | Acidic and acetylated | 5 mg.mL$^{-1}$ has shown antimicrobial activity and inhibits cell growth against bacteria, and fungal strains like (*S. enterica, and C. albicans*), stabilizers for the production of functionalized NPs. | (Basak et al. 2014) |
| *Candida* sp. | Acidic ($C_{18:1}$ NASL)<br>Sophorolipids. | 5 to 20 mg.mL$^{-1}$ showed the highest antimicrobial activity against GBP, GNB *S. aureus, P. aeruginosa, and E faecalis.* Adjuvant activity with antibiotics and wound healing of skin | (Lydon et al. 2021) |

| | | | |
|---|---|---|---|
| *Candida tropicalis RA1* | Lactonic types sophorolipids | At 250 mg.mL$^{-1}$, the SLs have shown antibacterial against the cell growth of GPB higher than GNB. | (Ankulkar et al. 2022) |
| *Candida* sp. | AcSLs, L-SLs | These SLs have shown the MIC 100 µg.mL$^{-1}$ against GPB_GNB (*S. aureus, E. coli*) and adhesion to the abiotic surface of bacteria and inhibition of their biofilm. | (Youssef et al. 2004) |
| *Starmerella /Candida Bombicola* | Acidic and lactonic SLs | It shows anti-biofilm activity at 43.7% at the concentration of 50 µg.mL$^{-1}$ SLs against (*P. aeruginosa*) and other bacterial strains | (Gudiña et al. 2010) |
| | Acidic and lactonic SLs | The MIC of these SLs at the conc. 19.5 µg.mL$^{-1}$ Against the mutual environment of GPB-GNB, and used as surface cleaner and microbial control agents in industries. | (Youssef et al. 2004) |
| | Acidic: lactonic ratio is 3.8:6.2) | At the conc, 0.1 wt%, it has shown better bacterial anti-biofilm activity against GPB bacterial strains. | (Sun et al. 2004) |
| | Acidic and lactonic SLs. | At 50 µg.mL$^{-1}$ con. SLs have shown anti-bacterial and anti-biofilm activity and are safely used for silicon catheter medical devices as an antiseptic and biological control agent. | (Soberón-chávez et al. 2010) |
| | Acidic and lactonic | MIC >5% v/v of these SLs induces cell death of GPB-GNB class planktonic cells. | (Rossini et al. 2024) |
| | L-SLs | It has shown inhibitory activity at 1 mg.mL$^{-1}$ and 1.3 mg.mL$^{-1}$ conc. Against various oral cariogenic gram (+) bacteria like *L. fermentum and L. acidophilus.* | (Batista et al. 2006) |
| | L-SLs. | The MIC and MBC of it are at 97.5 mg.mL$^{-1}$, and 195 mg.mL$^{-1}$ conc. To the oral bacterial (*S. oralis*) strain. | (Muthusamy et al. 2008) |
| *Rhodotorula babjevae* | Lc-SLs. | 1 mg.mL$^{-1}$ of Sls has shown the MIC 75% on the growth of inhibition of dermatomycosis caused by *T. mentagrophytes* on the witty skin and feet, which are covered by Sox and cloth | (Vijayakumar & Saravanan 2015) |
| *Candida* sp. | Ac, -Lc-SLs. | 0.1% of these SLs have shown antifungal activity against *T. mentagrophytes*, and it prevents skin and athletes' foot dermatophytosis. | (McMahan et al. 2021) |

| | | | |
|---|---|---|---|
| *Starmerella bombicola* | Ac, - Lc-SLs. | 200 $\mu$g.mL$^{-1}$ of SLs has shown antifungal and antibiofilm activity as well as oral, skin, and vagainal candidiasis by *C. albicans*. | (McMahan et al. 2021) |
| | Ac, - Lc-SLs. | 50 $\mu$g.mL$^{-1}$ of it has shown inhibitory and preventive activities against various fungal and fungal infections. | (Heyd et al. 2008) |

Elshikh et al. 2017

**B. Anti-cancerous applications of biosurfactants:** Based on the results obtained through more than 1000 nonpathogenic yeast genome sequencing to date, it is certain that the glycolipid (sophorolipids), synthesized from the non-pathogenic yeast *Candida sp. Wickerhamiella Comercial* Y2A species belonging to the class of Saccharomycetales, trychomonascaceae, showed the highest cytotoxicity on various cancer cell lines. These types of cell lines include esophageal cancer cell lines such as KYSE, KYSE-30, KYSE-109, KYSE-150, and KYSE-450. Breast cancer cell line alcohol MDA-MB 231 or BCCL MDA-MB 231, Mouse Skin Cell Line B 16F 10, Lung Cancer Cell Line A 549, etc. A variety of glycolipid biosurfactants, such as lactonic-acidic sophorolipids, glucolipids, and bolalipids, are capable of building the immune system against cancer cells. Treatment with a lactonic sophorolipids-glucolipid combination has shown the highest levels of anticancer activity. This subject has been observed very closely through scratch assay and fluorescence microscopy. Glycolipid surfactants interfere with actin filaments. As a result, the tumor cell's displacement is hampered and inhibits migration, resulting in a change in the mitochondrial membrane potential centered around the SLP biosurfactant and its reactive oxygen species, leading to cell necrosis. Hence, cell death or apoptosis occurs. This means that in addition to two specific types of glycolipid surfactants, the combination of two differently formed glycolipids, such as acidic glycolipid or lactonic glycolipid or acidic-lactonic sophorolipids + glucolipid, acts as a potent anti-cancerous prescript. That is, the combination of two sophorolipids from a single sophorolipid is comparatively more effective. For example, the application of such combinations has shown synergistic interactions on the A549 cell line, as well as influencing the connection between the MDA-MB 231 and B16F10 cell lines. Similarly, fluorometric assay analysis shows that the combination application of G-500 ug.mL$^{-1}$ and L-SLP-50 ug.mL$^{-1}$ results in the application after 3 h of observation that all reactive oxygen species are stimulated to produce. However, by increasing the active potential of this glycolipid surfactant, it will be able to demonstrate its ability to produce 100% cell ROS of different cancer cell lines among the sophorolipids synthesized from the *Wickerhamiella* sp. Commercial species, Diacetylated lactonic sophorolipids human esophageal cancer cell line exhibits severe cytotoxic activity on both KYSE 109 and KYSE 450. That is, as much as monoacetylated lactonic SLP can obstruct in front of these two cell lines, Diacetylated lactonic SLP can create several times more obstruction. The ability of Di-unsaturated SLP in saturated hydroxyl fatty acid-rich sophorolipids to perform inhibition activity across cancer cell lines is much lower than that of monosaturated SLP. Cerasa et al. (2024) examined the mechanism of action of glycolipids, namely glucolipids, bolalipids, and acidic and lactonic sophorolipids, against cancer cells in a recent study. Three distinct cell lines were used in the experiments: A549, which is used for lung cancer, and MDA-MB 231 for breast cancer. And B16F10, which is used for mouse skin melanoma. The findings imply that glucolipids prevent the migration of tumor cells, potentially by interfering with actin filaments, and that reactive oxygen species are produced in cells by both glucolipids and lactonic sophorolipids. Furthermore, these biosurfactants changed the potential of the mitochondrial membrane, which ultimately led to necrosis and cell death. Moreover, pancreatic, breast, cervical, oral, colon, lung, and liver cancers are among the many tumors for which biosurfactants have lately become viable substitute compounds. Their capacity to control certain processes in mammalian cells, which stops the aberrant progression of cancer by inhibiting cell viability, proliferation, and migration, has shown promise for the treatment of cancer. Certain biosurfactants, such as glycolipids and lipopeptides, can decrease tumor cell proliferation and survival. (Ceresa et al. 2023)

**C. Anti-viral application of biosurfactants:** Females that are usually diagnosed with HIV need a female genitalia organ septic microbicidal activating agent for specific protection of their genitals. Sophorolipids synthesized from *Candida bombicola* may be the only promising microbicidal API to carry through the requirements. Individual experiments on the activity of structural analogs of synthesized sophorolipids, synthesized by *C. bombicola*, led to the conclusion that SLP has cytotoxicity activity as well as anti-HIV activity and exceptional spermicidal activity. Structural analysis of the series of derivatives of SLP shows that among the derivatives of SLP, Diacetate Ethyl ester SLP has virucidal and knock-down spermicide activity. Due to the antiviral activity of SLP derivatives, the outer protein lining of HIV-carrying sperm inside HIV is eroded due to the antiviral activity of SLP derivatives The derivative shows a lower application and shorter activity in less time than the contraceptive pill surfactant Nonoxynol'-9 (N-9) used in the vaginal cavity and rectum region. The sperm in the vaginal cavity and rectum region acts as an inactivating agent (Nagtode et al. 2023). Applying a mixture of Lactonic SLP and Natural SLP in a ratio of 1.0: 0.80 $mg.mL^{-1}$ and observing the sperm by Sander Cromer Assay system, it is seen that 50% of the sperm in just 120 seconds / 2 min. Synthesized Sophorolipids by pure species of non-pathogenic isolated yet also has antibacterial and antifungal activity. Due to the antifungal activity of SLP when applied as an Associate API with APIs used for the treatment of dermatitis, it multiplies the antifungal activity of the particular medicine. When SLP clotrimazole is applied to a certain dose of vaginal candidiasis treatment, the candidiasis patient recovers very quickly. Ethyl 17-L-[(2'-O-β-D-glucopyranosyl-β-D-glucopyranosyl)-oxy]-cis-9- octadecenoate. The pH of seminal fluid is treated with PH <5.0, SLP, which brings down the pH level of the fluid and produces anti-microbial activity against pre-post sexually transmitted pathogens in the female genitalia (Youssef et al. 2004). Analysis of the structural analog of acidic SLPs shows more anti-toxicity was expressed on HIV as a spermicide, but it cannot express the amount. Tests on the structural analogs of lactonic SLps again showed that L-SLps reveal higher virucidal activity (Aparna et al. 2012). Double-strand DNA viruses, such as the herpes simplex virus HSV-1 and HSV-2, infect people of almost ever age group, from infants to the elderly. More frequently acquired by HSV-1, faster than HSV-2. More HSV-2 is transmitted through sexual conjugation. Each year, about 23 million people worldwide are infected by the HSV-2 strain.

**D. Drug and drug delivery system and nanotechnology:** Surfactants are essential molecules in the creation of nanostructures because of their amphiphilic and self-assembly properties. They function as templates, modifiers, growth control agents, and stabilizers. The utilization of biological processes using plants, microorganisms, or their metabolites for the synthesis of nanomaterials is encouraged by the growing need for safe, environmentally friendly alternatives to dangerous chemicals (André et al. 2023). The literature has many papers on the microbial production of nanoparticles (NP). The enzymatic reduction of metal salts such as gold, iron, silver, platinum, and others is the usual process used to create metal nanoparticles (NPs). As a result, microbial metabolism offers an appropriate environment, either intracellularly or extracellularly, to support NP production. Silver NP was synthesized using a lipopeptide BS that was isolated from *Bacillus vallimortis*, and it showed antibacterial efficacy against Listeria monocytogenes, S. aureus, and E. coli. A different paper explains how a lipopeptide obtained from a Bacillus subtilis CN2 strain is used to prepare stable silver nanoparticles (NP).

In comparison to the NP made without the BS, the addition of the BS decreased the average size, homogeneity, and long-term stability of the NP and produced exceptional antibacterial activity against strains of Bacillus subtilis and *Pseudomonas aeruginosa. It* also described how biogenic synthesis by bacteria that produce BS is another method. In this instance, microbial growth is carried out, and after the addition of a metal precursor, the resultant cell-free medium is used as a starting material for NP synthesis. (Ceresa et al. 2023) In comparison to the NP made without the BS, the addition of the BS decreased the average size, homogeneity, and long-term stability of the NP and produced exceptional antibacterial activity against strains of Bacillus subtilis and *Pseudomonas aeruginosa.* It also described how biogenic synthesis by bacteria that produce BS is another method. In this instance, microbial growth is carried out, and after the addition of a metal precursor, the resultant cell-free medium is used as a starting material for NP synthesis. Although there isn't much research on the use of BS in the synthesis of natural organic NP, this method is thought to be more environmentally beneficial since it uses less metal and petrochemicals, both of which can build up in the environment. Recently reported the synthesis of a hybrid biopolymer-biosurfactant NP, which demonstrated that the addition of rhamnolipid increased the antibacterial activity against both planktonic and biofilm S. aureus and decreased the size and polydispersity of chitosan NP. The authors postulated that the hybrid NP's high density of polycationic chitosan enhances electrostatic interactions, promoting the release of RL at the bacterial surface and assisting in the breakdown of the cell membrane, which allows antimicrobials to reach their targets (Rossini et al. 2024, Shakeri et al. 2021, Hernández et al. 2023, Nouri et al. 2023) It was stated that bioactive peptide-loaded rhamnolipid liposomes might be used to create innovative antibacterial systems for use in agriculture and medicine. Nisin was incorporated into rhamnolipid-functionalized liposomes (rhamnosomes) to enhance the antibacterial and antibiofilm properties of the liposomes as well as the effectiveness of nisin. The resultant nanovesicles outperformed liposomes in terms of antibacterial activity, and they also increased nisin's ability to combat L. monocytogenes, S. aureus, E. coli, and P. aeruginosa. Because of its better adherence to the bacterial surface, there was an observed 80% reduction in biofilm biomass.

**E. Application of SLP to enhance immune activity**: Recent studies have also highlighted the potential benefits of biosurfactants for enhancing human health and well-being in the context of wound healing, where they have demonstrated the ability to speed up the healing process and encourage tissue regeneration. Moreover, their antibacterial characteristics provide them with appealing options for battling wound infections. Furthermore, biosurfactants have demonstrated anticancer properties by causing cancer cells to undergo apoptosis and by preventing the formation of tumors. Even with great advancements in cancer treatment, cancer continues to be the second greatest cause of death globally. In particular, the World Health Organization (WHO) released data for 2020 that projected 10 million fatalities and 19.3 million new cases. Over the years, numerous innovative cancer treatments have been created to tackle this deadly disease; nonetheless, chemotherapy and radiotherapy continue to be the primary options.

Notwithstanding several beneficial elements of these treatments, the rising death rates can be linked to anticancer medication's lack of specificity for cancer cells, which causes serious side effects, poor success rates, and the emergence of multidrug resistance in cancer cells. Moreover, they exhibit immuno-modulatory characteristics, which renders them prospective contenders for immunotherapy and immunomodulation tactics (Rossini et al. 2024, Shakeri et al. 2021, Ceresa et al. 2023). Because of its therapeutic qualities, the impact of biosurfactants on wound healing has been studied for more than 15 years. Cheffi et al. (2021) evaluation mentioned the impact of the lipopeptide molecule Bios-PHKT on HEK-293 cells and demonstrated that the migration and proliferation of cells driven by Bios-PHKT could be compared to the controls. It's interesting to note that lower Bios-PHKT concentrations were needed to promote wound healing than to cause cytotoxicity in HEK-293 cells. Regarding their ability to form emulsions, their antitumor and antibacterial qualities, and their impact on the immune system, lipopeptides are among the biosurfactants that have been investigated the most. Using an excision wound model, found that a lipopeptide produced by A. junii B6 can shield mouse cells from damage caused by free radicals, with signs of cell recovery (Ceresa et al. 2023)

Table 4 mentions some of the biosurfactants producing microorganisms to enhance immuno-modulatory activity in humans and animals. In the immune system, biosurfactants follow the path of immune-suppressive drugs, and these can increase wound healing in different inflammations.

Table 4: Acidic, Lactonic, acetylated, acidic, and lactonic Sophorolipids mobilized by microorganisms that keep a vital role in the immune system.

| Sources of Sophorolipids. | Sophorolipids and their structures. | The sophorolipids and their therapeutic action in the immuno-modulatory system. | References. |
|---|---|---|---|
| *Candida, W. Comercial,* and various fungi and bacteria. | C18:1DiAL, lactonic, and acidic SLs. | These types of Sophorolipids have shown anti-cancerous activity they showed inhibitory activity against various cancer cell lines at different concentrations. | (McMahan et al. 2021) |
| Some bacteria and fungi | DiAL, -SLs. | In the immune system, the SLs work as immuno-suppressive drugs; using 25 µg.mL$^{-1}$ of SLs showed the M1 macrophage polarization as an envelope to enhance the execution of typical wound rehabilitation and various inflammations. | (Vijayakumar & Saravanan 2015) |

**Application of sophorolipids for bioremediation:** Hydrophobic contaminants from the oil and gas sector can build up in soil. Soil contamination can result from various sources, including storage tank leaks, pipeline leaks, and spills caused by mishaps that occur during the discovery, refining, and transportation of oil. In addition to being hazardous, these contaminants are also recalcitrant and insoluble. Soil remediation techniques include mechanical, chemical, biological, and physical approaches. The biological approach makes use of low-tech materials and renewable resources, such as plants, microbes, and surfactants. Surfactants facilitate the desorption of pollutants from soil particles and promote their mineralization and microbial degradation by reducing the surface and interfacial tensions of the pollutants. Biosurfactants can help in the process of phytoremediation, which is the absorption of toxins by plants to remove contaminants from the environment. Many aspects must be taken into account to effectively use biosurfactants in the bioremediation of petroleum hydrocarbons, particularly in soil systems. Greater efficiency is achieved when low quantities of biosurfactants are administered during the early phases of biodegradation, particularly when the hydrocarbon content is high. High quantities of biosurfactants, on the other hand, cause the bacteria to absorb the biomolecules rather than the pollutant to biodegrade. The oil degradation rate was improved by 10 to 20% by the biosurfactants generated by Bacillus sp. and C. sphaerica UCP0995, showing an improvement in the biodegradation of hydrocarbons in soil. Researchers looked into how well the biosurfactant alasan broke down polyaromatic hydrocarbons in soil. In the presence of the surfactant, it was discovered that fluoranthene was more than 50% and that *Sphingomonas paucimobilis* EPA505 significantly increased the mineralization of phenanthrene. The biosurfactant generated by P. cepacia CCT6659, which was grown in industrial waste, showed promise for use in soil bioremediation. 95% of the contaminants in soil contaminated by hydrophobic organic compounds were degraded in 35 to 60 days by an Indigenous consortia and biosurfactant (Augusto et al. 2023, Fernandes & Dias, 2023, Miao et al. 2024, Rossini et al. 2024)

The following table (Table 5) presents the biodegradation potential of various types of hydrocarbons. Biosurfactant sophorolipids showed their highest biodegradation activity than chemical surfactants by their same concentration on different hydrocarbons.

Table 5: Biodegradation rates of various hydrocarbon compounds by sophorolipids.

| S no | Model Compound | Time | SLP | Activity | Reference |
|---|---|---|---|---|---|
| 1 | Pristan | 6 days | 10g.L$^{-1}$ -2 ml | 85% | (Shekhar et al. 2015) |
| 2 | 2-Methylnaphthalene | 2 days | 10g.L$^{-1}$ -2 ml | 95% | (Shekhar et al. 2015) |
| 3 | Hexadecane | 6 days | 10g.L$^{-1}$ -2 ml | 97% | (Priya & Usharani 2009) |

| | | | | | |
|---|---|---|---|---|---|
| 4 | Crude oil | 56 days | 10g.L$^{-1}$ -2 ml | 80% | (Priya & Usharani 2009) |
| 5 | Saturates | 56 days | 10g.L$^{-1}$ -2 ml | 80% | (Priya & Usharani 2009) |
| 6 | Phenanthrene | 4 days | 10g.L$^{-1}$ -2 ml | 71% | (Jimoh & Lin 2019) |
| 7 | Aromatics. | 56 days | 10g.L$^{-1}$ -2 ml | 72% | (Jimoh & Lin 2019) |

**Oil recovery:** Water, gas, and the organic components, together with the proper thermochemical conditions present in sedimentary rock, make up crude oil. There are three processes in the extraction of crude oil. Natural pressure and produced pressure (injection of gas and water) are the first and second processes. Roughly 40% of the trapped oil is extracted by these procedures. Recovering the leftover oil is the third stage. Although it is challenging to remove this oil from rock, enhanced oil recovery, or EOR, uses thermal methods (injection of hot water and carbon dioxide ($CO_2$), non-thermal methods (flooding with solvents and chemical surfactants), and biological approaches. In this procedure, synthetic surfactants pollute the environment and demand capital. On the other hand, the application of biosurfactants in EOR can create advantageous circumstances and address issues related to environmental contamination. The process known as "Microbial Enhanced Oil Recovery" (MEOR) uses microorganisms or the byproducts of their metabolism to extract leftover oil. Typically, this process entails injecting nutrients into the reservoir first, then injecting microorganisms that make biosurfactants (in situ biosurfactant production). Industrial bioreactors can also be used to produce ex-situ biosurfactants, which can then be directly injected into the reservoir using $CO_2$ (Augusto et al. 2023). According to one study, bacteria produce biosurfactants and can degrade crude oil extracted from an Assamese oil field's reservoir. B. Tequilensis demonstrated optimal biosurfactant synthesis and good oil degradation characteristics. Ex-situ. After obtaining an interfacial tension of 0.32 mN.m$^{-1}$ and eliminating 80% of the oil during washing operations, the crude biosurfactant was determined to be a surfactin.

The microbes' emulsifiers/surfactants cause the surface tension to drop, which releases the contained oil. Biosurfactants change the interfacial behavior of $CO_2$-brine-rock and the wettability of injected $CO_2$, improving the flushing efficiency of the injected fluid and $CO_2$ (Augusto et al. 2023, Hausmann et al. 2024, Miao et al. 2024, Eras-muñoz et al. 2022, Shaikhah et al. 2024, Andreolli et al. 2023, Nagtode et al. 2023, André et al. 2023, Sarwan et al. 2024a, 2024b, )

A list of biosurfactants sophorolipids produced by microorganisms for enhancing oil recovery/bioremediation is listed in Table 6 below. Feedstocks used in the production of biosurfactants and their bioconversion mechanisms in the environment are summarized.

Table 6: Sophorolipids and their antimicrobial and oil recovery activity.

| Microorganisms | SLs-Biosurfactants. | Density and productivity /Litr<br>And feedstock | SLs, and their mechanisms, bioconversions activity on the environment. | References |
|---|---|---|---|---|
| *Candida floricola* | Ac-SLs. | 3.5 g.L$^{-1}$ by feed batch fermentation using splurge glycerol as feedstock. | In the future, the SLs will facilitate the broad-spectrum use fields for SLs. | (Nasser et al. 2024) |
| *Starmerella bombicola* | DiAc- Lc-LSL (C18:1). | 1 g.L$^{-1}$ SLs by solid-state fermentation Winterization oil cake as feedstock | It showed Emulsifying properties, and CMC: 40.1 mg.L$^{-1}$, it has been used in the displacement of crude oils. | (Aparna et al. 2012, McMahan et al. 2021) |
| | Ac, -Lc- SLs | 41.6 g.L$^{-1}$ by shake flask and 51.5 g.L$^{-1}$ SLs by submerged fermentation, using sunflower oil refinery waste as feedstock. | It has shown emulsifier activity. It is used for various crude oil displacements as bioremediations. | (Sharma et al. 2023) |
| | Ac, -Lc- SLs. | 15.25 g.L$^{-1}$ by feed batch- resting cell methods- using jatropha oil as feedstock. | Its CMC value is 3: 9.5 mg.L$^{-1}$, so the SLs have been used as a replacement for the synthetic surfactant in detergents, and MIC90 4 value is 300 µg.mL$^{-1}$. It is used as an antibacterial against GPB. | (Hausmann et al. 2024) |
| | Lc- SLs. | 115.2 g.L$^{-1}$ by feed batch fermentation, using hydrolysate food wastage as feedstock for enhancing SLS production. | The SLS is used for the bioconversion of food and various environmental and industrial waste oils. | (Sun et al. 2004) |
| | Lc- SLs. | 3.7 g.L$^{-1}$ SLs produced by fed-batch fermentation processes using food waste | It is used for bioconversions of food waste and waste streams. | (Sharma et al. 2023) |

**Agricultural application of sophorolipids:** It has been shown that biosurfactants can be used to remediate contaminated soil. Achromobacter sp. TMB1 was isolated by Lin (1996) from soils surrounding nearby gas pumps. This bacterium produced ten distinct forms of mono- and dirhamnolipid congeners, with fatty acid carbon lengths ranging from C8 to C12. Subsequent tests revealed that these biosurfactants were stable between 20°C and 100°C in temperature and between 2 and 12 in pH, retaining their structural integrity up to 550°C, suggesting their potential for use in bioremediation. *Gordonia alkanivorans* W33 was shown to be more effective in bioremediating petroleum-contaminated soil when sophorolipids and rhamnolipids were added. Significant breakdown of the petroleum in the soil was seen when the bacteria were combined with sophorolipids and rhamnolipids at a weight ratio of 9:10. With a 20,000 $mg.kg^{-1}$ petroleum content, about 56.3% of the petroleum was broken down, with an average degradation rate of 250.2 $mg.d^{-1}$ (Vandana & Singh 2018)). Sophorolipid and rhamnolipid combination is thought to boost the capacity to create microemulsions from a variety of hydrocarbons; this is supported by a study on the remediation of co-contaminated soil with phenanthrene (PHE) and cadmium (Cd) utilizing enhanced soil washing with biosurfactant. In contrast to soils polluted with a single chemical, the presence of both contaminants altered the rhamnolipid micelle and soil structure, resulting in varying clearance rates. The outcomes showed that PHE was successfully ensnared in the rhamnolipid micelles and that Cd complexed with the micelle's exterior carboxyl groups. After the settings were optimized, the removal rates of PHE and Cd were 87.8% and 72.4%, respectively (Miao et al. 2024, Eras-muñoz et al. 2022, Industries et al. 2023, Silva et al. 2024)

The highest number of microorganisms is given below in Table 7. Non-pathogenic yeast strains, not only yeast strains but also bacterial strains, are produced biosurfactants. Both sophorolipids can show antimicrobial, larvicidal, insecticidal, and herbicidal activities against a lot of bacterial and fungal pathogens that are responsible for causing plant disease.

Table 7: Agricultural applications of sophorolipids**.**

| Sl. No | Sources of Sophorolipids | Sophorolipids and their structures. | The lethal dosage of sophorolipids and their mode of action in cancer cell lines. | References |
|---|---|---|---|---|
| 01 | *Candida bombicola* | Acidic and lactonic | 1 $mg.mL^{-1}$ destabilization, membrane permeability or cell lysis, and inhibition of phytopathogen. 5% v/v of it is capable of disrupting of biofilm of comingle of Staphylococcus aureus ATCC 9144 and Bacillus subtilis BBK006 | (Miao et al. 2024) |
| 02 | *Candida kuoi* | Acidic SLs | For the emulsification properties, 1% v/v of SLP has shown phytotoxicity and herbicidal activity against sicklepod and *Senna obtusifolia* | (Miao et al. 2024) |
| 03 | *Stermerella bombicola* | Lactonic SLs | It has shown antimicrobial activity against *Pythium ultimum* and *Moesziomyces sp*. as pesticides and fungicides at 2 $mg.mL^{-1}$ and 1 $mg.mL^{-1}$ concentration. | (Miao et al. 2024) |
| 04 | *Wickerhamiella domercqiae* | Lactonic SLs | The SLs have shown anti-fungal activity against various fungal strains like *F. oxysporum, F. solani P. ultimum* at 10 | (Miao et al. 2024) |

| | | | | |
|---|---|---|---|---|
| | | | mg/mL conc. It creates inhibition against the growth of mycelia and germination of spores of fungal strains. | |

**Application in poultry industries**: In the poultry industry, there is a widespread influence of artificial emulsifiers and natural sophorolipids biosurfactants on the feed process and quality of pelletized feeds in the broiler diet. In the poultry industry, natural biosurfactant sophorolipids and artificial biosurfactant sophorolipids are being used as natural antibiotics as well as immunoregulators and immunomodulators, along with increasing food quality control and quality(Zhao et al. 2021). In the prescribed ratio of 2 1, oil and water and two types of emulsifiers, such as glycerol polyethylene glycol ricinolate synthetic emulsifiers and lyso-phosphatidylcholine with natural biosurfactant basal diet, mixed with water and emulsifier and natural biosphere. The experiment was performed through 4 treatment processes to determine the effect of unchanged levels of water, oil, natural biosurfactant, and synthetic emulsifiers' compounds with the basal diet, with different ingredients, in water, oil, natural biosurfactant, and synthetic emulsifiers. The effect of emulsifiers on energy consumed and actual torque displayed in food production has been determined, as the application of emulsifiers as a supplement has been shown to increase the biostability and other quality of poultry and fish feed. Simultaneously, the effect of the emulsifier on mail temperature, moisture, and water activity is determined. The main goals and objectives of conducting this experiment were to determine the quality of the feed palette produced by the application of emulsifiers and biosurfactants based on how the quality of the product is controlled (Zajic et al. 1983). Based on physical (hardness, thickness by pressure ability test of Fr = (Initial weight–Final weight)/Initial weight × 100 = x.xx%), chemical, biostability, bioavailability, buoyancy, etc., quality of feed palette used in the poultry industry (Adebajo et al. 2020, Nouri et al. 2023, Industries et al. 2023).

Among the microbial strains that have played a role in the production of biosurfactants, *Candida bombicola or Starmerella bombicola* (Table 8) is one of them.

Table 8: Applications of biosurfactants sophorolipids in poultry and poultry feed industries.

| Sources of Sophorolipids | Sophorolipids and their structures. | The lethal dosage of sophorolipids and their mode of action on poultry and poultry industries. | References |
|---|---|---|---|
| *Starmerella bombicola* | Lc-SLs | 0.0015%, and 0.5% conc. Using the SLs has shown antimicrobial activity to protect from the effects of Clostridium perfringens and Campylobacter jejune poultry food pathogens in poultry industries. | (Vandana & Singh 2018) |
| | Lc- SLs | 31.25 $\mu g.mL^{-1}$, and 62.5 $\mu g.mL^{-1}$ conc. SLs have been used to give protectants the poultry food affected by different | (Vandana & Singh 2018) |

| | | | |
|---|---|---|---|
| | | bacterial S. aureus and L. monocytogenes pathogens in poultry. | |
| | Ac- SLs | The conc of SLs has been tested at 15.6 to 2,000 $\mu g \cdot mL^{-1}$ and 78.1 to 10,000 $\mu g \cdot mL^{-1}$ To protect the poultry food from the harmful effects of gram-positive and gram-negative bacteria. | (Vandana & Singh 2018) |

**Applications in food industries:** Microbial surfactants provide a flexible way to improve a range of food qualities, such as texture improvement, thickening, foaming, emulsification, and preservation. Rhamnolipids, for instance, have been shown to improve the volume, form, and stabilities of dough, therefore improving bread products. Additionally, Ribeiro et al. (2020). investigated the use of biosurfactants from Saccharomyces cerevisiae URM 6670 in place of egg yolk in cookie formulation, with no discernible changes to the dough's physical or physicochemical properties. Cookies with more linoleic acid (C18:2), a source of advantageous polyunsaturated fatty acids (PUFAs) with the potential to reduce cardiovascular disease, were produced as a result of the addition of biosurfactants (Miao et al. 2024, Sundaram et al. 2024, Vigil et al. 2024). Biosurfactants play a vital role in the food business by preventing food spoiling because of their natural antibacterial and antiadhesive properties. Their versatility in handling many environmental conditions, such as temperature, pH, and salinity, and their biodegradable, non-toxic nature render them appropriate for a range of uses, including food surface cleaning, packaging, coating, transportation, and storage procedures. In light of the possibility of food contamination during food preparation, Listeria monocytogenes is a bacterium that is particularly known to cause serious disease (Sun et al. 2021) examined the potential inhibitory effects of two commercial glycolipid products on L. monocytogenes in milk and cheese, specifically NagardoTM and rhamnolipids. Their research showed that NagardoTM was a better addition to milk at concentrations below 1100 $mg.L^{-1}$, whereas rhamnolipids caused unwanted color changes and coagulation in whole milk. The minimum bactericidal concentration (MBC) and minimum inhibitory concentration (MIC) values for NagardoTM were 1100 $mg.L^{-1}$ and 800 $mg.L^{-1}$, respectively. Notably, at a dosage of 1,000 $mg.L^{-1}$, NagardoTM dramatically reduced cell counts in skim milk, demonstrating more powerful antibacterial actions. Furthermore, it has been shown that glycolipids are excellent at preventing spore germination. The effect on spore-forming bacteria, such as *Viridibacillus arenosi, Bacillus weihenstephanensis*, and *Paenibacillus odorifer*, which are known to withstand pasteurization and induce spoiling during refrigerated storage, was evaluated by Sun et al. (2021a). Their research showed that whereas dosages of 400 and 200 mg L-1 greatly inhibited the growth of *P. odorifer* and *B. weihenstephanensis* in whole milk, larger concentrations (400 $mg.L^{-1}$) of glycolipids were required to suppress the germination of *Viridibacillus arenosi* spores. According to), this implies that adding 400 $mg.L^{-1}$ of glycolipids to whole milk may be able to stop spoiling brought on by spore-forming bacteria (Miao et al. 2024, Rossini et al. 2024, Vieira 2023, Nouri et al. 2023)

Below is a list of different microorganisms (bacterial and fungal) in (Tables 9 and 10). With their lethal activity as the applications of sophorolipids bio-surfactant in the food industries. These sophorolipids have shown lethal activity against a lot of bacterial and fungal strains.

Table 9: Applications of sophorolipids in food industries against a lot of gram-positive and gram-negative bacterial strains**.**

| % Of SLP | Microorganisms | Gram Activity | Lethal time | Rates of Lethality. | References |
|---|---|---|---|---|---|
| 1% v/v | *Salmonella typhimurium*<br>*ATCC 23564,* | -ve | 10 min | 90% | (Vieira, 2023) |
| 1% v/v | *Escherichia coli*<br>*ATCC 8739* | -ve | 10 min | 99% | 50 |
| 1% v/v | *Erwinia*<br>*chrysanthemi ATCC 11663* | -ve | 10 min | 100% | 50 |
| 1% v/v | *Xanthomonas*<br>*campestris ATCC 13951* | -ve | 10 min. | 100% | 50 |
| 1% v/v | *Shigella dysenteriae.* | -ve | 30 seconds | 100% | (Abu-Ruwaida et al. 1991) |
| 1% v/v | *Salmonella typhi* | -ve | 30 seconds | 100% | (Abu-Ruwaida et al. 1991) |
| 1% v/v | *Escherichia coli* | -ve | 30 seconds | 100% | (Abu-Ruwaida et al. 1991) |
| 5% v/v | *Bacillus subtilis* | +ve | 30 seconds | 100% | (Abu-Ruwaida et al. 1991) |

Table 10: Applications of sophorolipids in food industries against a lot of fungal strains.

| Microorganisms | Sophorolipids | Types of bioactivities or properties. | Use and their mode of action on the body. | Reference |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| *Rhodotorula babjevae YS3* | Ac, - Lc- SLs | Antimicrobial (Antifungal) | A con$^{c}$. of 125 µg.mL$^{-1}$ (MIC) of SLs has been used to protect food from food-borne fungal pathogens such as *F. oxysporum* and *F. solani*. | (Sharma et al. 2023a) |
| *Wickerhamiella domercqiae* | Lc - SLs | Antimicrobial<br>(Antifungal) | A con$^{c}$. of 10 mg.mL$^{-1}$ of SLs has been used to inhibit fungal spore formation and block the mycelial growth of *F. oxysporum* and *P. ultimum*. | (Youssef et al. 2004) |
| *Metschnikowia churdharensis* | Ac, - Lc- SLs | Antimicrobial<br>(Antifungal) | SLs at con$^{c}$ of 49 µg.mL$^{-1}$ and 98 µg.mL$^{-1}$ have been used to protect food from spoilage caused by fungal pathogens such as *F. oxysporum* and *F. solani*. | (Youssef et al. 2004) |
| *Candida glabrata* | Ac, - Lc- SLs | Antimicrobial<br>(Antifungal and Antibacterial) Emulsifier. | SLs at con$^{c}$ of 60 µg.mL$^{-1}$ and 125 µg.mL$^{-1}$ have been used to protect food from spoilage caused by *B. subtilis* (bacteria) and *F. oxysporum* (fungus). | (Youssef et al. 2004) |

**Application in cosmetic products of biosurfactants**: Another type of glycolipid biosurfactant called sophorolipids is made from the yeast Candida species and is applied to cosmetics. Because of their remarkable ability to reduce surface tension and their emulsifying qualities, sophorolipids are now a necessary component of many cosmetic products. Natural sophorolipids have been shown to lower surface tension from 72 mNm-1 at 25°C to values in the range of 30 to 40 mN m$^{-}$1 at a water-air interface (Develter & Lauryssen 2010). For a certain amount of time, between 500 and 5000 nm, the mean droplet diameters of sophorolipid emulsions show an increase as the percentage of almond oil in an almond oil-water emulsion grows. Pratap et al. looked at the surfactant's presence in face wash formulations (Nagtode et al. 2023). These authors concentrated on using non-edible jaggery, maize oil, oleic acid from *Starmerella bombicola*, and waste syrup from a jaggery facility to produce sophorolipids sustainably. It was established that waste-derived sophorolipids could be utilized in face wash formulations in place of chemically generated sodium lauryl sulfate since they exhibited good foam height stability and emulsification index. All skin types, including fair, medium, and dark skin tones, have been demonstrated to experience mild to minimal allergic reactions while using a face wash based on sophorlipids. These results demonstrate the sophorolipids' ability to stabilize emulsions in formulations used in cosmetics. Additionally, sophorolipids exhibit benefits for skin compatibility and moisture that are consistent with important consumer requirements for contemporary cosmetics. The results of this research indicate that biosurfactants derived from renewable feedstocks have potential use in personal care products, providing a substitute for conventional chemical surfactants. In toothpaste formulations, biosurfactants and chitosan were investigated as potential natural substitutes for sodium lauryl sulfate (Resende et al. 2019, Nasser et al. 2024). It was found that the combination of fungal chitosan and biosurfactants produced by Pseudomonas aeruginosa, Bacillus methylotrophicus, and Candida bombicola showed antibacterial efficacy against Streptococcus mutans without causing cytotoxicity. Similar to commercial fluoride toothpaste, these biosurfactant-chitosan combinations decreased the survival of Streptococcus mutans biofilms. Making use of the complementary properties of chitosan and biosurfactants could offer a viable, long-term strategy for creating toothpastes that work well without the use of artificial surfactants. This shows that rhamnolipid biosurfactants have the potential to function as biocompatible detergents and foaming agents in oral hygiene formulations, albeit more clinical research is necessary (Karnwal et al. 2023, Miao et al. 2024, Nasser et al. 2024, Vigil et al. 2024, Adu et al. 2023)

Below is the information in a table of some microorganisms that produced acidic and lactonic sophorolipids (Table 11) with their different bioactive properties in beauty care products and promoting wound healing activity.

Table 11: Sophorolipids and their applications in cosmetics industries to produce beauty care products to use and enhance the beauty of the body.

| Microorganisms | Sophorolipids | Types of bioactivities or properties. | Use and their mode of action on the body. | References |
|---|---|---|---|---|
| *Starmerella bombicola.* | Ac- SLs | It reduces S T. | CAC 2 0.083% showed the highest penetration enhancer. | |
| | Acidic (C18001 - NASL) 3 | Antimicrobial (antibacterial) | Using 4 $mg.mL^{-1}$ with kanamycin or cefotaxime as a synergist has shown MIC against the wounds of *E. faecalis, P. aeruginosa,* and cosmetics. | (McMahan et al. 2021) |
| *Candida bombicola* | Lactonic-SLP | Emulsifier | Preparation of cream and lotions by the SLP at the 50 $\mu g.mL^{-1}$ conc. For use in cosmetology. | (Fernandes & Dias 2023) |
| *Candida kuoi* | Acidic-SLP | Emulsifier | Pharmaceuticals are formulated drugs for external use. | (Fernandes & Dias 2023) |

| | | | | |
|---|---|---|---|---|
| *Pseudohyphozyma bogoriensis.* Rhodotorula bogoriensis | Long chain C22-SL 1 SLP. | Antimicrobial<br>(anti-bacterial) | Long-chain SLP has shown antibacterial growth or growth of inhibition against *P. acne as skin care.* | (Fernandes & Dias 2023) |
| *Rhodotorula bogoriensis* | Long chain C22-SL 1 sophorolipids | Antimicrobial (anti-bacterial) | At 100 mg.mL$^{-1}$ of the SLP, the colony showed the growth of inhibition against P acne. | (Fernandes & Dias 2023) |

**Sophorolipids and biosurfactants in the detergent industry:** The detergents used in the market have various applications in daily life. In detergent industries, surfactant compounds have been formulated by using byproducts of petrochemical industries. For example, MERS has occurred over the past years and decades during epidemics like COV-1, Evola-V, and ASARCH COV-2, the most commonly used synthetic formed surfactants as detergents, disinfectants, and various antiseptics for preventing the spread of viruses in personal care, households, offices, factories, and populated areas are from various types of petroleum industries derived from by-products. The biodegradation potential of these byproducts is very low, and these synthetic byproducts are the main cause of creating severe toxicity in the ecosystem. To avoid environmental toxicity, instead of petroleum-derived synthetic surfactants, the production and substitution of biodegradable and non-toxic bio-waste or microorganisms-derived molecules (biosurfactants) has become a growing and acceptable commercial option at present. Therefore, by microorganisms, short-length carbon-chained, biodegradable organic compounds should be synthesized and considered to be alternatives to synthetic surfactants and environmentally friendly detergents and disinfectants. Or replacing synthetic surfactants, through technological and product development, with green and biosurfactants (effective in hard water and low temperatures) synergistically. Biosurfactants, due to their emulsifying properties, are capable of exhibiting their activity as detergents, and in addition, due to their unique properties of detergents, they will be popular as laundry and various cleaning agents detergents (Helmy et al. 2020)

**In heavy metal binding:** Some biosurfactants, such as rhamnolipids, can remove specific components from soil, including Pb, Zn, and Cd. By modifying Cd absorption through their interactions with the cell surface and Cd complexation, rhamnolipids can lessen the toxicity of metals. High-molecular-weight (HMW) polysaccharides in emulsifiers link metals, as demonstrated by the emulsifier Acinetobacter calcoaceticus's ability to link uranium (Shakeri et al. 2021). Lead (Pb), chrome (Cr), mercury (Hg), zinc (Zn), copper (Cu), nickel (Ni), and cobalt (Co) are among the heavy metals that can be found in soil and sediments. To precipitate and be removed from the soil, the heavy metals must form stable complexes with anionic biosurfactants (22). Heavy metal-contaminated soils can be cleaned up by washing with a surfactant solution. Additionally, the biosurfactant can be used repeatedly to remediate polluted soil, allowing the metals to be used again in the battery sector (Augusto et al. 2023).

**In pharmaceutical industry:** Early neonates experience lung surfactant-related respiratory problems, which can be shown to be normal by a protein-phospholipid complex (PPC). Because this protein is produced fermentatively by cloning the relevant genes into bacteria, it may have therapeutic qualities. One treatment and management option for tobacco mosaic virus (TMV), which mostly affects *Nicotiana glutinosa* and potato virus X (PVX), is 1% rhamnolipid emulsion (Shakeri et al. 2021).

**Anti-corrosion activities of biosurfactants:** The process of corrosion causes basic qualities used in the application of various materials, including rubber, plastic, wood, cement, and metals, to deteriorate.

Metals corrode due to chemical and electrochemical processes, which are influenced by their surroundings. The oxidation of metal atoms on a metal surface leads to corrosion, a natural process that weakens the surface's mineralized structure. This kind of corrosion starts with protons adhering to the metal atoms and progresses through an electrochemical reaction. Surface corrosion can occur when metallic cations react with anions or dissolve in the aqueous phase (Augusto et al. 2023).

## CONCLUSIONS

The exceptional qualities of biosurfactants-high biodegradability, low toxicity, and resistance to harsh pH and temperature conditions-have recently attracted more attention, surpassing those of their equivalents derived from fossil fuels. Glycolipids are a type of low molecular weight biosurfactants that are particularly effective at reducing interfacial tension and surface tension among these versatile biomolecules. Particularly, the most notable representations are rhamnolipids, trehalose lipids, sophorolipids, and mannosyl erythritol lipids. Glycolipids have several uses, such as bioremediation, food processing, petroleum refining, biomedical applications, and agriculture, but their production costs continue to be the main barrier to them outperforming synthetic surfactants. While the incorporation of secondary feedstocks offers a viable approach to augmenting the sustainability of glycolipid production, the application of these feedstocks in industrial environments is restricted because of their uneven composition. The incorporation of secondary feedstocks offers a promising approach to augmenting the sustainability of glycolipid production; nevertheless, the uneven composition of these feedstocks hinders their widespread use in industrial environments. It will take significant work to improve productivity and streamline process flow to address this problem. The appropriate optimization of secondary feedstocks in biosurfactant production is thought to be able to strike a balance between the advantages for the environment, the economy, and society. These developments could lead to more ecologically friendly and sustainable glycolipid synthesis, which would benefit the surfactant sector.

## REFERENCES

Abu-Ruwaida, A.S., Banat, I.M., Haditirto, S., Salem, A. and Kadri, M., 1991. Isolation of biosurfactant-producing bacteria, product characterization, and evaluation. *Acta Biotechnologica*, 11(4), pp.315–324. https://doi.org/10.1002/abio.370110405

Adebajo, S.O., Akintokun, P.O., Ojo, A.E., Akintokun, A.K. and Badmos, O.A., 2020. Recovery of biosurfactant using different extraction solvents by rhizospheric bacteria isolated from rice-husk and poultry waste biochar amended soil. *Egyptian Journal of Basic and Applied Sciences*, 7(1), pp.252–266.

Adetunji, C.O., 2022. *Applications of Next Generation Biosurfactants in the Food Sector.* Academic Press.

Adu, S.A., Twigg, M.S., Naughton, P.J., Marchant, R. and Banat, I.M., 2023. Glycolipid biosurfactants in skincare applications: challenges and recommendations for future exploitation. *Plos One,* 11, pp.1–22.

André, M., Dias, M. and Nitschke, M., 2023. Bacterial-derived surfactants: an update on general aspects and forthcoming applications. *Brazilian Journal of Microbiology*, 54(1), pp.103–123.

Andreolli, M., Villanova, V., Zanzoni, S., Onofrio, M.D., Vallini, G., Secchi, N. and Lampis, S., 2023. Characterization of trehalolipid biosurfactant produced by the novel marine strain Rhodococcus sp. SP1d and its potential for environmental applications. *Journal of Cleaner Production,* 5, pp.1–15.

Ankulkar, R., Chavan, S., Aphale, D., Chavan, M. and Mirza, Y., 2022. Cytotoxicity of di-rhamnolipids produced by Pseudomonas aeruginosa RA5 against human cancerous cell lines. *3 Biotech*, 12(11), p.323.

Aparna, A., Srinikethan, G. and Smitha, H., 2012. Production and characterization of biosurfactant produced by a novel Pseudomonas sp. 2B. *Colloids and Surfaces B: Biointerfaces*, 95, pp.23–29. https://doi.org/10.1016/j.colsurfb.2012.01.043

Augusto, A., Filho, P.S., Converti, A., C.R.De, Soares, F. and Sarubbo, L.A., 2023. Biosurfactants as multifunctional remediation agents of environmental pollutants generated by the petroleum industry, *Bioresource Technology,* 81, p.56.

Basak, B., Bhunia, B. and Dey, A., 2014. Studies on the potential use of sugarcane bagasse as carrier matrix for immobilization of Candida tropicalis PHB5 for phenol biodegradation. *International Biodeterioration and Biodegradation*, 93, pp.107–117. https://doi.org/10.1016/j.ibiod.2014.05.012

Batista, S.B., Mounteer, A.H., Amorim, F.R. and Tótola, M.R., 2006. Isolation and characterization of biosurfactant/bioemulsifier-producing bacteria from petroleum-contaminated sites. *Bioresource Technology*, 97(6), pp.868–875. https://doi.org/10.1016/j.biortech.2005.04.020

Bose, K.J. and Sarwan, J., 2023. Multi-enzymatic degradation potential against wastes by the novel isolate of Bacillus. *Biomass Conversion and Biorefinery*, 23, p.789. https://doi.org/10.1007/s13399-023-04620-z

Ceresa, C., Fracchia, L., Sansotera, A.C. and Alejandra, M., 2023. Harnessing the potential of biosurfactants for biomedical and pharmaceutical applications. *Science,* 21, p.81

Cheffi, M., Maalej, A., Mahmoudi, A., Hentati, D., Marques, A.M., Sayadi, S. and Chamkha, M., 2021. Lipopeptides production by a newly Halomonas venusta strain: Characterization and biotechnological properties. *Bioorganic Chemistry*, *109*, p.104724.

Develter, D.W.G. and Lauryssen, L.M.L., 2010. Properties and industrial applications of sophorolipids. *European Journal of Lipid Science and Technology*, 112(6), pp.628–638.

Eras-Muñoz, E., Farré, A., Sánchez, A., Font, X., Gea, T., Farré, A., Sánchez, A., Font, X. and Gea, T., 2022. Microbial biosurfactants: A review of recent environmental applications. *Bioengineered*, 13(5), pp.12365–12391. https://doi.org/10.1080/21655979.2022.2074621

Fernandes, N. and Dias, D.R., 2023. Biosurfactants and their benefits for seeds. *PLos One,* 16, pp.1412-1423. https://doi.org/10.1007/978-3-031-21682-4

Gudiña, E.J., Teixeira, J.A. and Rodrigues, L.R., 2010. Isolation and functional characterization of a biosurfactant produced by Lactobacillus paracasei. *Colloids and Surfaces B: Biointerfaces*, 76(1), pp.298–304. https://doi.org/10.1016/j.colsurfb.2009.11.008

Hausmann, R., Déziel, E. and Soberón-Chávez, G., 2024. Editorial: Microbial biosurfactants: updates on their biosynthesis, production and applications. *Science,* 11, pp.1–2. https://doi.org/10.3389/fbioe.2024.1433035

Helmy, Q., Gustiani, S. and Mustikawati, A.T., 2020. Application of rhamnolipid biosurfactant for bio-detergent formulation. *IOP Conference Series: Materials Science and Engineering*, 823(1), pp. 12104. https://doi.org/10.1088/1757-899X/823/1/012014

Hernández, M.L., Pedersen, J.S. and Otzen, D.E., 2023. Proteins and biosurfactants: Structures, functions, and recent applications. *Current Opinion in Colloid & Interface Science*, 68, p.101746. https://doi.org/10.1016/j.cocis.2023.101746.

Heyd, M., Kohnert, A., Tan, T.H., Nusser, M., Kirschhöfer, F., Brenner-Weiss, G., Franzreb, M. and Berensmeier, S., 2008. Development and trends of biosurfactant analysis and purification using rhamnolipids as an example. *Analytical and Bioanalytical Chemistry*, 391(5), pp.1579-1590. https://doi.org/10.1007/s00216-007-1828-4.

Jagadeesh Chandra Bose, K. and Sarwan, J., 2023. *Nanovaccinology*. Springer, pp. 79–99. https://doi.org/10.1007/978-3-031-35395-6_5.

Jimoh, A.A. and Lin, J., 2019. Biosurfactant: A new frontier for greener technology and environmental sustainability. *Ecotoxicology and Environmental Safety*, 184(June), p.109607. https://doi.org/10.1016/j.ecoenv.2019.109607.

Karnwal, A., Shrivastava, S., Rahman, A., Said, M., Kumar, G., Singh, R., Kumar, A. and Mohan, A., 2023. Microbial biosurfactant as an alternate to chemical surfactants for application in cosmetics industries in personal and skin care products: A critical review. *Journal of Applied and Environmental Microbiology*, 2023. https://doi.org/10.1155/2023/2375223.

Lin, S.C., 1996. Biosurfactants: Recent advances. *Journal of Chemical Technology and Biotechnology*, 66(2), pp.109–120.

Lydon, K.A., Kinsey, T., Le, C., Gulig, P.A. and Jones, J.L., 2021. Biochemical and virulence characterization of *Vibrio vulnificus* isolates from clinical and environmental sources. *Frontiers in Cellular and Infection Microbiology*, 11, p.637019.

McMahan, K., Yu, J., Mercado, N.B., Loos, C., Tostanoski, L.H., Chandrashekar, A., Liu, J., Peter, L., Atyeo, C., Zhu, A., Bondzie, E.A., Dagotto, G., Gebre, M.S., Jacob-Dolan, C., Li, Z., Nampanya, F., Patel, S., Pessaint, L., Van Ry, A. and Barouch, D.H., 2021. Correlates of protection against SARS-CoV-2 in rhesus macaques. *Nature*, 590(7847), pp.630–634. https://doi.org/10.1038/s41586-020-03041-6.

Miao, Y., To, M.H., Siddiqui, M.A., Wang, H., Chopra, S.S., Kaur, G., Roelants, S.L.K.W., Sze, C. and Lin, K., 2024. Sustainable biosurfactant production from secondary feedstock—recent advances, process optimization, and perspectives. *Frontiers in Chemistry*, 17, p.16. https://doi.org/10.3389/fchem.2024.1327113.

Muthusamy, K., Gopalakrishnan, S., Ravi, K., Sivachidambaram, P., Muthusamy, K. and Gopalakrishnan, S., 2008. Biosurfactants: Properties, commercial production and application. *Current Science*, 94(6), pp.736–747.

Nagtode, V.S., Cardoza, C., Khader, H., Yasin, A., Tambe, S.M., Roy, P., Singh, K., Goel, A., Amin, P.D., Thorat, B.R., Cruz, J.N. and Pratap, A.P., 2023. Green surfactants (biosurfactants): A petroleum-free substitute for sustainability—comparison, applications, market, and prospects. *ACS Omega*, 11, p.591. https://doi.org/10.1021/acsomega.3c00591.

Nasser, M., Sharma, M. and Kaur, G., 2024. Advances in the production of biosurfactants as green ingredients in home and personal care products. *Frontiers in Chemistry*, 3, pp.1–9. https://doi.org/10.3389/fchem.2024.1382547.

Nouri, H., Moghimi, H. and Lashani, E., 2023. Fungal biosurfactants and their applications. *Fungal Biosurfactants and Their Applications*, 16, pp.1–14. https://doi.org/10.1007/978-3-031-31230-4.

Priya, T. and Usharani, G., 2009. Comparative study for biosurfactant production by using *Bacillus subtilis* and *Pseudomonas aeruginosa*. *International Journal of Microbiological Research*, 2(4), pp.284–287.

Resende, A.H.M., Farias, J.M., Silva, D.D.B., Rufino, R.D., Luna, J.M., Stamford, T.C.M. and Sarubbo, L.A., 2019. Application of biosurfactants and chitosan in toothpaste formulation. *Colloids and Surfaces B: Biointerfaces*, 181, pp.77–84.

Ribeiro, B.G., Guerra, J.M.C. and Sarubbo, L.A., 2020. Biosurfactants: production and application prospects in the food industry. *Biotechnology Progress*, 36(5), p.e3030.

Rossini, C., Willian, M., Fernandes, R., Souza, D., Hacha, R.R. and Silvas, C., 2024. Biosurfactants: An overview of their properties, production, and application in mineral flotation. *Minerals Engineering*, 15, pp.1–23.

Sarwan, J., Bose, J.C., Kumar, S., Bhargav, S.S., Dixit, S.K., Sharma, M., Mittal, K., Kumar, G. and Uddin, N., 2024a. Biodegradation of cellulosic wastes and deinking of colored paper with isolated novel cellulolytic bacteria. *Nature Environment and Pollution Technology*, 23(2), pp.761–773. https://doi.org/10.46488/nept.2024.v23i02.013.

Sarwan, J., Uddin, N. and Bose, J.C., 2024b. Enhanced production of microbial cellulases as an industrial enzyme: A short review. *Journal of Microbial Biotechnology*, 2(1), pp.59–70.

Seattle, W., 2023. *Biosurfactants and their Role in Environmental Sustainability*. Springer, pp.1–14. https://doi.org/10.1016/B978-0-323-91697-4.00002-8.

Shaikhah, D., Loise, V., Angelico, R., Porto, M., Calandra, P., Abe, A.A., Testa, F., Bartucca, C., Rossi, C.O. and Caputo, P., 2024. New trends in biosurfactants: From renewable origin to green enhanced oil recovery applications. *Current Trends in Chemical Engineering*, 41, pp.1–34.

Shakeri, F., Babavalian, H., Amoozegar, M.A., Ahmadzadeh, Z., Zuhuriyanizadi, S. and Afsharian, M.P., 2021. Production and application of biosurfactants in biotechnology. *Biotechnology Reports*, 11(3), pp.10446–10460.

Sharma, H., Rana, N., Sarwan, J., Bose, J.C., Devi, M. and Chugh, R., 2023. Nano-material for wastewater treatment. *Materials Today: Proceedings*, 16, p.258. https://doi.org/10.1016/j.matpr.2023.02.258.

Sharma, H., Rana, N., Sarwan, J., Bose, J.C., Devi, M. and Chugh, R., 2023. Nano-material for wastewater treatment. *Materials Today: Proceedings*, xxxx. https://doi.org/10.1016/j.matpr.2023.02.258

Shekhar, S., Sundaramanickam, A. and Balasubramanian, T., 2015. Biosurfactant producing microbes and their potential applications: A review. *Critical Reviews in Environmental Science and Technology*, 45(14), pp.1522–1554. https://doi.org/10.1080/10643389.2014.955631

Silva, C., Medeiros, A.O., Converti, A., Almeida, F.C.G. and Sarubbo, L.A., 2024. Biosurfactants: Promising biomolecules for agricultural applications. *Biosurfactants,* 19, p.54

Soberón-chávez, G., Abdel-mawgoud, A.M., Hausmann, R. and Le, F., 2010. Biosurfactants and bioengineering of production. *International Journal of Scientific Research,* 17, p.1–11. https://doi.org/10.1007/978-3-642-14490-5

Sun, S., Zeng, H., Robinson, D.B., Raoux, S., Rice, P.M., Wang, S.X. and G.L., 2004. Controlled synthesis of $MFe_2O_4$ (M = Mn, Fe, Co, Ni and Zn) nanoparticles. *Journal of Chemical Science,* 126(1), pp.273–279.

Sun, W., Zhu, B., Yang, F., Dai, M., Sehar, S., Peng, C., Ali, I. and Naz, I., 2021. Optimization of biosurfactant production from Pseudomonas sp. CQ2 and its application for remediation of heavy metal contaminated soil. *Chemosphere*, 265, p.129090.

Sundaram, T., Govindarajan, R.K., Vinayagam, S., Krishnan, V., Nagarajan, S., Gnanasekaran, G.R., Baek, K., Kumar, S. and Sekar, R., 2024. Advancements in biosurfactant production using agro-industrial waste for industrial and environmental applications. *Plos One,* 12, p.36. https://doi.org/10.3389/fmicb.2024.1357302

Tajabadi, M.T., 2023. Review article: Biosurfactant-producing microorganisms: Potential for bioremediation of organic and inorganic pollutants. *Journal of Bioremediation,* 2(2), pp.18–23. https://doi.org/10.58803/rbes.v2i2.13

Vandana, P. and Singh, D., 2018. Review on biosurfactant production and its application. *International Journal of Current Microbiology and Applied Sciences*, 7(08), pp.4228–4241. https://doi.org/10.20546/ijcmas.2018.708.443

Vieira, R.S., 2023. Biosurfactant production by Acinetobacter venetianus and its application in bioremediation. *Bioremediation*, 91, pp.456-467. https://doi.org/10.1002/ceat.202200540

Vigil, T.N., Felton, S.M., Fahy, W.E., Kinkeade, M.A., Visek, A.M., Janiga, A.R., Jacob, S.G. and Berger, B.W., 2024. Biosurfactants as templates to inspire new environmental and health applications. *Journal of Cleaner Production,* 71, pp.1–9. https://doi.org/10.3389/fsybi.2024.1303423

Vijayakumar, S. and Saravanan, V., 2015. Biosurfactants-types, sources and applications. *Research Journal of Microbiology*, 10(5), pp.181–192. https://doi.org/10.3923/jm.2015.181.192

Youssef, N.H., Duncan, K.E., Nagle, D.P., Savage, K.N., Knapp, R.M. and McInerney, M.J., 2004. Comparison of methods to detect biosurfactant production by diverse microorganisms. *Journal of Microbiological Methods*, 56(3), pp.339–347. https://doi.org/10.1016/j.mimet.2003.11.001

Zhao, F., Zhu, H., Cui, Q., Wang, B., Su, H. and Zhang, Y., 2021. Anaerobic production of surfactin by a new Bacillus subtilis isolate and the in situ emulsification and viscosity reduction effect towards enhanced oil recovery applications. *Journal of Petroleum Science and Engineering*, 201, p.108508.