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The Multifaceted Role of Microbial Biosurfactants in Various Fields

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Abstract

This review paper aims to explore the multifaceted roles and applications of microbial surfactants, also known as biosurfactants. These amphiphilic compounds, synthesized by various microorganisms such as *Acinetobacter sp.*, *Bacillus sp.*, *Candida antarctica*, and *Pseudomonas aeruginosa*, exhibit both hydrophobic and hydrophilic properties. Through lowering surface tension and interfacial tension, biosurfactants facilitate fluid phase aggregation, imparting organisms with unique physiological and ecological advantages. The synthesis of biosurfactants in bacteria not only contributes to antimicrobial activity but also enhances substrate availability for cellular absorption, particularly in challenging environmental conditions. Categorized based on molecular weight and chemical composition, biosurfactants offer numerous benefits including biodegradability, reduced toxicity, and versatile applications in agriculture, detergent production, biopesticides, and microbial oil enhancement processes. This review synthesizes current knowledge on microbial surfactants, elucidating their diverse roles and promising applications across various industries.

Keywords: Biosurfactant, Rhamnolipids, Surfactin, Glycolipids, Lipopeptides, Interfacial tension, Emulsification.

1. Introduction

Biosurfactants are amphiphilic substances made in living surfaces, primarily on microbial cell surfaces or excreted extracellular hydrophobic and hydrophilic moieties that confer the ability to accumulate between fluid phases, reducing surface and interfacial tension at the surface and interface, respectively (Abbot et al., 2022). To the same principles as chemical surfactants, they have the distinctive ability of lowering surface and interfacial tension (Singh et al., 2007). Bio Surfactants, which are the active ingredients in soaps and detergents and have the ability to concentrate at the air-water interface, are frequently used to separate oily materials from specific media because they can increase the aqueous solubility of Non-Aqueous Phase Liquids (NAPLS) by lowering their surface/interfacial tension at air-water and water-oil interfaces (Khordagui et al., 2021). Chemical composition and microbial origin are the main categories used to group biosurfactants. Glycolipids, phospholipids, polymeric biosurfactants, and lipopeptides (surfactin) are the four main categories of biosurfactants. Rhamnolipids, sophorolipids, and trehalolipids are the best-known glycolipids (Saranraj et al., 2022). It is well known that biosurfactants with typically low molecular weight can improve oil recovery by lowering the surface tension and interfacial tension

(IFT) between oil and water. While emulsan, a high molecular weight biosurfactant, is well known for its emulsifying abilities, which improve the mobility and recovery of heavy oil (Onaizi et al., 2021). Surfactants are widely used in industrial, agricultural, food, cosmetic, and pharmaceutical applications; however, because they are chemically synthesized, the majority of these compounds have the potential to have negative environmental and toxicological effects (Mahmoud et al., 2020).

The choice of raw materials varies from nation to nation depending on how readily accessible they are. Due to its low cost and easy availability, date molasses was recommended as a carbon source in Oman (Sarwer et al., 2022). Because of their large surface activities and other unique characteristics, the *Bacillus spp*. bacterial group is well known for their capacity to create strong lipopeptide biosurfactants like surfactin and substances (Nitschke and Pastore, 2006). The use of biosurfactants in the petrochemical sector and for environmental protection are the key drivers of this expanding interest. Their applications in the environment are mostly connected to the bioremediation of petroleum hydrocarbons in soil and groundwater as well as the degradation of dangerous compounds (Elijah, 2022). The use of thermal, chemical, physical, and other enhanced oil recovery (EOR) methods is currently frequently seen (Gbadamosi et al., 2019). These methods are effective, but they are also costly and damaging to the environment. (MEOR), commonly known as a physiologically based EOR method, is an alternative. MEOR can be applied in numerous different ways, such as an in-situ process that uses local microorganisms or an ex-situ method that produces bioproducts outside of oil wells and then immediately injects them to improve oil recovery (Traudel, K., and Merten., 2017). To perform in situ MEOR, it is necessary to recognize the indigenous microbial population (Patel et al., 2007) and feed it with the proper nutrient media for growth and the synthesis of bioproducts that will ultimately increase the recovery factor.

2. Classification and chemical nature of biosurfactant

Based on their microbiological origin and chemical structure, biosurfactants can be categorized. (Markande et al., 2021). divided them into two groups: high molecular weight molecules and low molecular weight molecules. Low-mass surfactants consist of lipopeptides, glycolipids and phospholipids, while polymeric and particle surfactants are examples of high-mass surfactants. Based on the ionic charge in the polar portion of the molecule, synthetic surfactants are categorized. Surfactants are classified as anionic, cationic, non-ionic, or amphoteric based on whether they have an electrical charge or not (Maneerat, 2005; Ron and Rosenberg, 2001). Only a small percentage of biosurfactants those with amine groups, for example—are cationic, while the majority are neutral or anionic. Long chain fatty acids are the hydrophobic moiety, while alcohol, phosphate, carboxyl acid, cyclic peptides, carbohydrates, and amino acids are the hydrophilic moiety (Tato et al., 2021).

Typically, biosurfactants are categorized according to the microbial producer species or their biochemical makeup. These compounds can be divided into five main categories based on their structural similarities (Fenibo et al., 2019).

- **Glycolipids: the** hydrocarbons utilized as substrate determine the degree of polarity; examples include rhamnolipids produced by *Pseudomonas aeruginosa* and sophorolipids produced by species of *Candida*.
- **Lipopolysaccharides** – which normally have a high molecular mass and are soluble in water; example: emulsan, an extracellular emulsifier produced from hydrocarbons by the bacteria *Acinotobacter calcoaceticus.*

- **Lipopeptides** – example: surfactin produced by *Bacillus subtilis* (one of the most potent biosurfactants reported in the literature).
- **Phospholipids** – structures common to many microorganisms; example: biosurfactant from *Corynebacterium lepus*; Fatty acids, neutral lipids (some classified as glycolipids) and hydrophobic proteins.

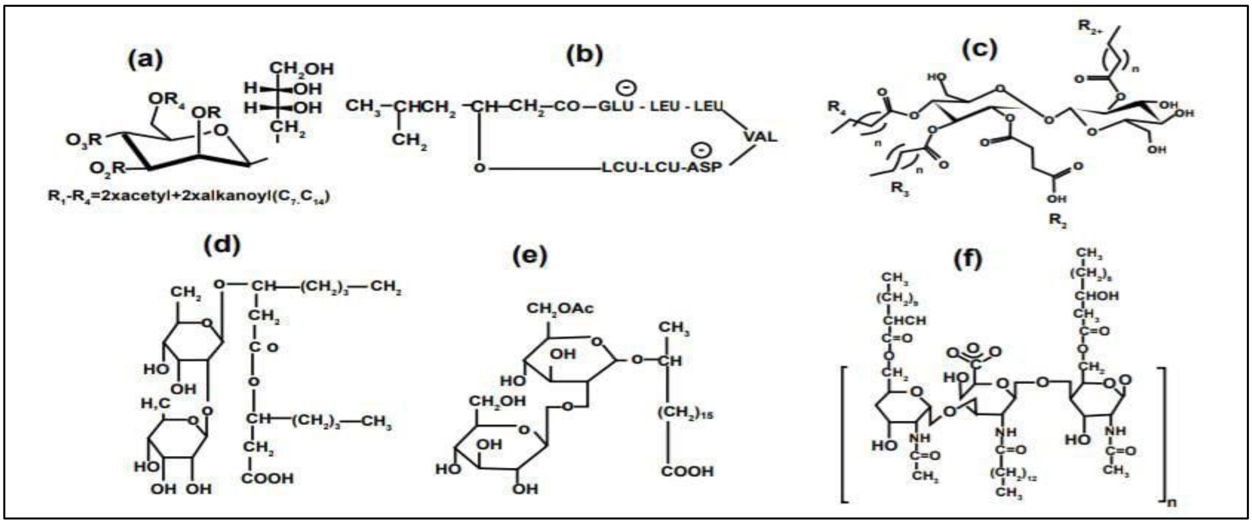

Figure 1: Chemical structures of some common biosurfactants (a) Mannosylerythritol lipid (b) Surfactin (c) trehalose lipid (d) Sophorolipid (e) Rhamnolipid (f) Emulsan. (Md, F., 2012).

3. Application of biosurfactant in various fields

Biosurfactants are multipurpose substances obtained from microbial sources that are used in a wide range of industries. They are essential to improving oil recovery efficiency, reducing environmental effects, and promoting the biodegradation of hydrocarbons in the petroleum industry. Biosurfactants are used in agriculture to improve soil fertility, stimulate plant growth, and support disease and pest biocontrol. In the food business, biosurfactants function as emulsifiers, stabilizing agents, and antibacterial agents, guaranteeing product quality and safety. In washing products, they help remove oil and persistent stains. They have potential applications in medicine, including antibacterial treatments, wound healing, and drug delivery systems. Biosurfactants also play a key role in environmental bioremediation processes, helping to break down contaminants and restore contaminated areas. The vast range of uses of biosurfactants highlights their significance in tackling a range of issues in different industries while encouraging environmental stewardship and sustainability. Below is a discussion of these various applications.

3.1 Application of Biosurfactants in the Petroleum Industry

One of the main energy sources is petroleum. Between 2000 and 2030, the global energy demand predicts a 1.7% increase in the amount of oil produced annually, with annual consumption rising to 15.3 billion tons. If current consumption levels are maintained, oil reserves may satisfy global demand for about 40 years (Effendi et al., 2018). Throughout the entire chain of petroleum processing (extraction, transportation, and storage), biosurfactants have been used successfully in the petroleum industry for the exploration of heavy oil. Biosurfactants are employed in the cleaning of contaminated vessels, the microbially enhanced (Nikolova et al., 2021).

3.2 Extraction of Crude Oil from Reservoirs

Utilizing microorganisms and the byproducts of their metabolic product, Microbially-Enhanced Oil Recovery (MEOR) is a significant method for the recovery of residual oil. It is generally acknowledged that about 30% of the oil in a reservoir may be extracted utilizing the most recent Enhanced Oil Recovery (EOR) technology (Quraishi et al., 2021). Around the world, a variety of enhanced oil recovery techniques are now being used. These procedures, meanwhile, are not only costly, but also damaging to the environment. Thus, it is vital to look for different, more affordable, and environmentally friendly improved oil recovery techniques than those that use chemicals and heat. To improve oil recovery in the current energy crisis, several biotechnology-based techniques have been explored (Das and Mukherjee, 2007). MEOR is a method of recovering residual oil that uses microorganisms or byproducts of their metabolism. The polymers and biosurfactants that microorganisms create lessen the capillary pressures that prevent oil from passing through the pores of rock, hence lowering the surface tension between the two materials. The emulsification and disintegration of oil film in rock is also facilitated by biosurfactants. MEOR employs a variety of techniques, such as the introduction of biosurfactant-producing microorganisms into the reservoir and subsequent spread in situ, the addition of nutrients to the reservoir to promote the growth of biosurfactant-producing wild microorganisms, or the continued production of biosurfactants in reactors and subsequent injection into the reservoir (Perfumo et al., 2010). These procedures improve oil recovery from a depleted reservoir, hence extending the reservoir's life. MEOR is less expensive than chemically enhanced oil recovery because microorganisms produce effective products from inexpensive substrates or raw materials (Al-Bahry et al., 2013). Poor recovery in oil producing wells that are currently in operation may be caused by limited permeability in some reservoirs or excessive oil viscosity, which impairs mobility. People's interest in tertiary recovery strategies since most of the oil is kept in the reservoir by using primary and secondary recovery techniques (Yuan and Wood, 2018). According to Shennan and Levi (2017) there are several methods for using biosurfactants in MEOR. For example, injecting bacteria that produce biosurfactants via a well into a reservoir and then watching One mechanism involves propagation in situ through the reservoir rock (Ukwungwu, 2017). Another involves injecting specific nutrients into a reservoir to encourage the growth of native microorganisms that produce biosurfactants; a third mechanism involves producing biosurfactants ex situ in bioreactors and then injecting them into the reservoir. Although the industry now uses a wide variety of surfactants, it is crucial to create even more novel compounds to increase the range of specific qualities and applications (Cameotra and Makkar, 2004).

3.3 Application of Biosurfactants in Agriculture

Applying surfactants as mobilizing agents is one technique to improve the solubility of chemical biohazards like PAH. Hydrophobic Organic Contaminants (HOC) become more evident solubilized because of is. Surfactants are also thought to shorten the distance between the location of absorption and the site of the microorganisms' bio-uptake by aiding bacteria in adhering to soil particles containing contaminants (Xia, 2017). Surfactants are employed in agriculture as well for the hydrophilization of heavy soils to produce good wettability and ensure even fertilizer distribution in the soil. Additionally, they encourage the distribution and penetration of the toxicants in pesticides and stop some fertilizer from caking during storage. Rhamnolipid biosurfactant, which is mostly produced by the genus *Pseudomonas*, is known to have strong antibacterial activity. Additionally, cumulative exposure to rhamnolipid biosurfactants is not expected to have any negative effects on people or the environment. Fengycins are reportedly also antifungal, which means they could be used in biocontrol of plant diseases (Traudel and Merten, 2017).

3.4 Applications of biosurfactants in commercial laundry detergent.

Cleaning and washing applications employ over half of all surfactants produced (Farias et al., 2021). Anionic and nonionic chemical surfactant classes have been utilized as detergent compounds for many years (Hall et al., 1996). Traditionally, detergent formulations have included a variety of additional components together with one or more detergent active elements.as fragrances, bleaches, fluoresces, and detergency builders. Cleaning cloth, dishes, kitchenware, and hard surfaces including glass, glazed surfaces, plastics, metals, and enamels are the main uses for detergent formulations (Bouassida. et al., 2018). Interest in select and including "green" components into detergent formulations is growing as environmental protection, the use of substances with low toxicity, low carbon footprints, and high biodegradability become more prominent (Jessop, et al., 2015). The final usage of the detergent determines which surfactant is best for the composition. For instance, laundry detergents need a surfactant with high washing power and the capacity to dissolve fabric, yet face washing products only need a surfactant with strong foaming power and skin-friendly properties. Create readily removable foam (Giagnorio et al., 2017). Surfactants, a vital ingredient in contemporary commercial laundry detergents, are usually chemically synthesized and hazardous to freshwater living things. The search for environmentally friendly, natural alternatives to chemical surfactants in laundry detergents has been prompted by growing public awareness of the risks and environmental problems connected with chemical surfactants. When heated at high temperatures, biosurfactants like Cyclic Lipopeptide (CLP) retain all their surface-active properties since they are stable throughout a wide pH range (7.0-12.0) (Mukherjee, 2007). They demonstrated high compatibility and stability with conventional laundry detergents and demonstrated good emulsion forming capability with vegetable oils, both of which encourage their inclusion in the formulation of laundry detergents (Das and Mukherjee, 2007). Crude petroleum-oil biodegradation efficiency of *Bacillus subtilis* and *Pseudomonas aeruginosa* strains isolated from a petroleum-oil contaminated soil from North-East India.

3.5 Biosurfactants as Biopesticide

variety of ways. For example, they can be hazardous to cell membrane permeability in a way that is comparable to that of detergents (Zhao et al., 2010). According to Gharaei-Fathabad (Gharaei-Fathabad, 2011), several biosurfactants have high antibacterial, antifungal, and antiviral activity. These surfactants function as anti-adhesive agents, providing them beneficial. for both medicinal and probiotic purposes, as well as the treatment for various diseases. One such is the marine *B. circulans* biosurfactant, which shown strong antibacterial efficacy against semi-pathogenic microbial strains, including MDR strains, as well as Gram positive and Gram-negative pathogens. Broad-spectrum insecticides and pesticides, which can also have unfavorable side effects, are applied as part of traditional arthropod control strategies. Additionally, the rise of insect populations that are resistant to pesticides and the rising cost of new chemical pesticides have sparked a hunt for new eco-friendly vector control methods. It is possible to use lipopeptide biosurfactants as biopesticides since they have insecticidal effect against fruit in Drosophila melanogaster (Das and Mukherjee., 2007). Important products for agriculture, including insecticides, that have been produced with the help of biosurfactants are frequently used in agricultural areas. As an adjuvant to herbicides, insecticides, and fungicides, surfactants are important. The synthetic surfactant currently used in the pesticide industry serves as a spreading, emulsifying, dispersing, and wetting agent and boost pesticide effectiveness. Due to their defensive qualities, these surfactants are also utilized in insecticides nowadays in agriculture. *Pseudomonas* and *Burkholderia sp.* bacteria from paddy fields have been reported to breakdown surfactants (Karamchandani et al., 2023). Various surfactant types, including cationic, amphoteric, nonionic, and anionic ones, are currently employed in a number of pesticide manufacturing sectors. Therefore, surfactants are frequently utilized in pesticide formulation.

3.6 Biosurfactants in the food industry

As biocompatible, biodegradable, and/or nontoxic substances, biosurfactants combine specific qualities that show a range of beneficial qualities for the food industry, particularly as emulsifiers, foaming, wetting, solubilizers, adhesives, and antimicrobial agents (Sarubbo et al., 2022). The application of glycolipid biosurfactants in the food industry is proposed. Indeed, they are frequently referred to as food additives due to their low toxicity and biodegradability. They are also widely known for having antibacterial activity against numerous types of bacteria. The marine actinobacterium *Brachy bacterium paraconglomeratum* developed a glycolipid biosurfactant that has strong antibacterial properties against *Streptococcus* species (Citarasu et al., 2021). The food industry is very concerned about biofilms because they can be a source of lingering contamination that causes food to degrade and disease transmission. An approach to preventing bacterial adhesion and biofilm formation is pre-conditioning surfaces with biosurfactants, microorganisms that can affect the physicochemical properties of surfaces, modifying bacterial interactions and, as a result, adhesion.

- **3.6.1 Food Emulsifier**

Biosurfactants have several qualities, including the ability to generate emulsion-based formulations, which has enormous potential for use in the food sector. An emulsion is a heterogeneous system with a dispersed and continuous phase that consists of up of at least one immiscible liquid that is deeply distributed in another in the form of droplets. Emulsifiers are especially beneficial for low-fat goods (Romero et al., 2021). Because they enhance the creaminess and texture of dairy products. Conversely, polymeric surfactants wrap the oil droplets and create emulsions that are incredibly stable and never coalesce. This characteristic is particularly helpful for creating food and cosmetics-grade oil/water emulsions (Stock, S., and von Klitzing., 2022).

- **3.6.2 Food stabilizer:**

Biosurfactants regulate consistency in ice cream and bread recipes. Additionally, they are used while cooking oil and fats as an anti-spattering agent and fat stabilizer (Sonawane et al., 2021). Rhamnolipid surfactants are added during food preparation to enhance the texture and alter the stability of wheat dough, the rheological characteristics, and the shelf life of items containing starch (Gudiña and Rodrigues, 2019). According to (Traudel and Merten, 2017) surfactants can also be used to regulate the texture of fat-based products, stabilize aerated systems, and prevent fat globule aggregation. The process of hydrolyzing rhamnolipid surfactants made by *P. aeruginosa* yields L-rhamnose, which is already used in industry as a precursor to premium flavor components like Furaneol (a trademark of Firmenich SA, Geneva) (Pardhi et al., 2022).

- **3.6.3 Antiadhesive activity:**

Utilizing biosurfactant's antiadhesive properties, several bacterial groups may develop biofilms on surfaces that get into contact with food, which can be inhibited and disrupted. The bacteria observed on surfaces used in the food companies, known as bacterial biofilms, have colonized these environments

(Silva et al., 2021). Regulate the adherence of microbes to food contact surfaces is a crucial step in supplying consumers with safe and high-quality products since they are possible sources of contamination, which can result in food spoiling and the transmission of disease (Masotti et al., 2019).

3.7 Application of biosurfactants in medicine

(Shekhar et al., 2015) elucidated on the wide range of applications of biosurfactants in medicine they include:

- **3.7.1 Antimicrobial Activity:**

It is essential to discover novel antimicrobials and devise a strategy for the rehabilitation of currently prescribed antibiotics has become evident in light of the growth in antibiotic resistance. The fight against antibiotic resistance has prompted a global call to action (WHO, 2017) in terms of national (Díaz de Rienzo et al. (2016a) and international (CDC, 2015) measures. In terms of their uses, biosurfactants are well-suited for all of the following: bactericidal, bacteriostatic, biofilm disruption, biofilm formation inhibition, and adjuvant and synergistic actions with antibiotics. According to (Fenibo et al., 2019). *Klebsiella pneumonia, Escherichia coli, Vibrio cholera, Bacillus subtilis, and Staphylococcus aureus* were all susceptible to the antibacterial action of biosurfactants produced by Staphylococcus saprophyticus SBPS 15 (Mani et al., 2016). (Sabarinathan et al., 2021). Discovered that rhamnolipid shows the ability to breakdown biofilms against *Bacillus pumilus*. Listeria monocytogenes in food and some Gram-positive bacteria like *B. pumulis* and *M. flavus* can be inhibited by the biosurfactant SUR (Das et al., 2007).

- **3.7.2 Anti-cancer activity:**

In the human promyelocytic leukemia cell line, several microbial extracellular glycolipids cause cell differentiation rather than proliferation (Guerfali et al., 2019). Additionally, PC 12 cells exposed to MEL increased acetylcholine esterase activity and stopped the cell cycle at the G1 phase, leading to neurite overgrowth and partial cellular differentiation. These findings imply that MEL stimulates neuronal differentiation in PC 12 cells and lay the foundation for the use of microbial extracellular glycolipids as novel therapeutic agents for the treatment of cancer cells (Krishnaswamy et al., 2009).

- **3.7.3 Anti adhesive activity:**

Biosurfactants have been found to prevent pathogenic organisms from adhering to solid surfaces or infection sites (Rodrigues et al., 2006) showed that pre-coating vinyl urethral catheters with a surfactin solution before inoculating them with media decreased the amount of biofilm that *Proteus mirabilis, Salmonella enterica, E. coli*, and *Salmonella typhimurium* formed. According to (Muthusamy et al., 2008). Pretreatment of silicone rubber with *S. thermophilus* surfactant inhibited 85% of *C. albicans* adhesion, and surfactants from *L. fermentum* and *L. acidophilus* adsorbed on glass decreased the quantity of Enterococcus faecalis adhering uropathogenic cells by 77%. According to (Rivardo et al., 2009), adhesion of biosurfactants to solid surfaces may represent a novel and efficient strategy to prevent the colonization of harmful microorganisms. It has been discovered that biosurfactants prevent pathogenic organisms from adhering to the infection site (Das et al., 2009). In addition to being beneficial as therapeutic and probiotic agents, these surfactants can play a key role as anti-adhesive agents, making them useful for treating several problems. In addition, biosurfactant is utilized in the pharmaceutical industry as a means of promoting stem fibroblast metabolism. In prematurely born infants, an absence of pulmonary surfactant, which is a phospholipid protein complex, also results in respiratory failure. However, the production of these surfactant molecules through fermentation has been made possible by the isolation of their genes from bacteria and their cloning (Rodrigues et al., 2006).

3.8 Application on bioremediation:

Bioremediation involves the capacity of living organisms to metabolize or degrade organic pollutants, resulting in the production of less toxic byproducts that can be assimilated into natural biogeochemical cycles. Nonetheless, the rate and extent of biodegradation are subject to various environmental factors, including oxygen availability, pH levels, the presence of essential nutrients (macronutrients and micronutrients), as well as the physicochemical properties of both the contaminants and the substrates or particles with which they interact. These factors collectively influence the efficacy of bioremediation processes (Tyagi and Kumar, 2021). Because biosurfactants are derived from biological sources, they are considered to have improved biocompatibility and microbial biodegradability, which allows up a broad spectrum of possible uses. This biological origin is very interesting, particularly when there is important environmental interference, like in cases of tertiary petroleum recovery, crop protection, decontamination of oil-polluted areas, and the pharmaceutical and cosmetic industries (Gayathiri, et al., 2022). The production of biosurfactants in situ or by addition may successfully encourage the biodegradation of hydrocarbons in soil. Microbes are known to have a distinctly shorter degradation time and, in particular, adaption time (Koshlaf., 2017). The specific arrangement of soil particles, referred to as soil structure, dictates the soil's capacity to deliver nutrients and water to the bioactive regions. Therefore, the presence of biosurfactants in soil may have a beneficial effect by increasing the rates of hydrocarbon dissolution or desorption, solubilization, or even emulsification. It was successfully shown conclusively by (Bustamante et al., 2016). That rhamnolipids promote many mechanisms involved in the degradation of organic substrates. According upon how the substrate is presented, the biodegradation process's effectiveness and the specific mode of action of rhamnolipid may change (Chebbi et al., 2022). In this way, the researchers discovered that when hexadecane was trapped in matrices with pore-sizes larger than 300 nm, as opposed to matrices with lower pore-sizes or in sea sand, rhamnolipid and a number of other surfactants enhanced the degradation of hexadecane to a greater extent (Mariaamalraj et al., 2016). State that surfactants can only accelerate hydrocarbon the decomposition in situations when the process confronts rate limitation.

4. Conclusions

Biosurfactants offer diverse solutions across industries, from enhancing oil recovery in the petroleum sector to aiding soil remediation in agriculture. Their ability to reduce interfacial tension and promote emulsification makes them valuable in commercial laundry detergents, where they provide effective cleaning while minimizing environmental impact. In medicine, biosurfactants exhibit antimicrobial and anticancer properties, contributing to drug delivery and tissue engineering applications. Additionally, they play a crucial role in bioremediation by enhancing the degradation of organic pollutants in soil and water environments. Overall, biosurfactants represent versatile tools for addressing industrial challenges while promoting sustainability and environmental stewardship. Further research and technological advancements are essential to fully harness their potential and maximize their impact across various fields, ultimately advancing global efforts in sustainability and environmental protection.

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