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BIOSURFACTANTS: POSSIBLE ROLES IN ENVIRONMENTAL MANAGEMENT -A REVIEW

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ABSTRACT

Recent years have seen a rise in interest in biosurfactants, which are surface-active compounds produced by microorganisms that affect surfaces, particularly the surface tension of liquid-vapor interfaces. Due to their ability to emulsify and solubilize hydrophobic compounds as result of their amphipathic nature, biosurfactants are useful in degradation of hydrocarbon and are therefore applicable in oil spill management. Because they are biodegradable, have low toxicity, work well at high or low pH levels, and are more environmentally friendly than their chemical equivalents, biosurfactants have merits over their chemical counterparts. Biosurfactants are adaptable materials with a wide range of uses in the biodegradation and bioremediation of environmental contaminants. In addition, they have uses in pharmaceutical, food, and other industries. The continuous interest in biosurfactants results from these benefits and their vast variety of applications. Hydrophobic pollutants such as hydrocarbons and their derivatives are the major environmental issues due to their poor degradation but the use of biosurfactants can enhance their microbial degradation. When microorganisms try to use substrates like hydrocarbon as a source of carbon, they produce a variety of compounds called biosurfactants that help the diffusion into the cell. This review discusses the roles of these microbial products as veritable tools in environmental management with particular emphasis on the roles of biosurfactants in the sanitation of petroleum pollution and bioremediation of soils contaminated by pesticides.

Keywords: Biosurfactants, biodegradation, bioremediation, environmental management, environmental pollution, microorganisms

INTRODUCTION

The alarming rate of the release of different substances which have deleterious effect on the environment has been the major drive for environmental management. Petroleum spills are an inevitable byproduct of oil extraction and refining, especially in oil-producing nations like Nigeria, and more notably in the Niger Delta region of the country, due to the rising demand for petroleum and related goods during the past 10 years. (Adetunji et al., 2023). Since a trustworthy substitute has not yet been discovered, crude petroleum will continue to be a significant source of energy for some time to come despite its exorbitant cost. As a result, the issue of pollution by petroleum and its associated ecological effects would continue to be a serious environmental problem. Also, the non-biodegradable matters released as industrial wastes as well contribute to the environmental degradation. Therefore, it appears that microbial biodegradation of hydrocarbons is a potential method for reducing petroleum pollution. Low yields in production procedures and expensive recovery and purification costs have prevented large-scale synthesis of these compounds (Sarubbo et al., 2006; Salihu et al., 2009). One way that microbes absorb hydrocarbons is by the formation of metabolites, or specific compounds that promote the dispersion of liquid hydrocarbons as hydrocarbons in aqueous emulsions, microdroplets, or micelles, which are subsequently carried into the cell. These metabolites are known as biosurfactants (Jayabarath et al., 2009).

Environmental pollution

This is pollution of the earth's physical and biological systems to the point where it has a negative impact on the environment as a whole (Nayak et al., 2009). Environmental pollution happens when a system's ability to efficiently handle and eliminate hazardous consequences of human activity without suffering structural or functional harm is compromised. Environmental contamination has been and will continue to be a problem. There is a greater emphasis on the need to create creative solutions to address the issue as public knowledge of the issue grows and more stringent environmental laws is established. Growing public awareness has an impact on the search for and development of relevant technologies that will aid in the cleanup of environmental toxins, both organic and inorganic, such as hydrocarbons (Pacwa-Plociniczak et al., 2011).

Sources of environmental pollution

The sources of environmental contamination are classified into two broad categories, viz; fossil fuel and non-fossil fuel sources.

Fossil fuel sources

Fossil fuel (oil, gas, coal) are very much important as they are needed in our everyday activities such as in power generating industries, for filling our cars, they also occur in products such as lubricating oils, plastics, detergents, asphalt, solvents, many other chemicals of industrial relevance, etc. Extremely high amounts of air pollution are produced during the burning of fossil fuels, which is widely acknowledged as one of the most crucial areas to focus on in order to control and reduce environmental pollution (Onwukwe and Nwakaudu, 2012). Additionally, fossil fuels are responsible for soil and water pollution. For instance, when oil is transported via pipelines from its production site to a final destination, an oil spill from the pipeline may happen and contaminate the soil, which then contaminates the groundwater. An oil leak that contaminates the ocean's water can happen when oil is transported by tankers over water. The manufacture and distribution of fossil fuels, petrochemical plants, other manufacturing facilities, power generating facilities, and transportation systems like air travel, shipping, and road transportation are all common sources of pollution from fossil fuels.

Non-fossil fuel sources

Livestock farming: Agriculture also uses chemicals like fertilizers and pesticides, which can contaminate the soil and water.

Trading activities: The excessive packaging of goods sold in supermarkets and other retail establishments creates a lot of solid trash that is either disposed of in landfills or burned in urban incinerators, which pollutes the soil and the air.

Residential areas: This is yet another important polluter, producing solid municipal garbage that could wind up in landfills or incinerators, contaminating the soil and polluting the air (Brockhaus et al., 2017).

Biosurfactants versus synthetic chemical surfactants

Biosurfactants are molecules with surface activity that are created by microorganisms. These molecules, which are amphiphilic and contain hydrophilic and lipophilic moieties, are preferentially partitioned at the interface between fluid phases with varying degrees of polarity and hydrogen bonding, such as oil/water or air/water interfaces, lowering the liquid's surface tension (Salihu et al., 2009; Pacwa-Plociniczak et al., 2011; Santos et al., 2016). A glycosidic ester or amide link binds the hydrophilic group to the lipophilic group. The hydrocarbon (alkyl) tail of one or more fatty acids, which might be unsaturated, saturated, hydroxylated, or branched, normally makes up the lipophilic moiety. The majority of them are neutral or negatively charged, and the carboxylate groups that give them their anionic nature (Mukherjee et al., 2009). They are non-toxic biomolecule that are biodegradable. They strongly emulsify hydrocarbons and produce powerful emulsions. Contrary to conventional surfactants, which are frequently sourced from feed stock, biosurfactants are manufactured by microbial fermentation using less expensive agro-based substrates and waste materials (Rahman and Gakpe, 2008).

Chemical surfactants can be used in the same way as the biosurfactant for environmental management. For instance, by an affinity for a binding that exists between the grease and the detergent, surfactants assist in the release of organic and metal pollutants from soils in a manner similar to that of a detergent eliminating grease from textiles. Molecules with a surfactant have a polar head and a nonpolar tail. They ease the tension on the surface and aid in the creation of emulsions between various liquids. When oil is present, the molecules group together with their heads pointing outward, trapping oil droplets in the core where they can be broken down and flushed through. Due to their stubborn and persistent character, common chemical surfactants but their derivatives can pose major environmental risks. They have a long history of use and are still widely utilized today. As a result, with the current advancements in biotechnology, attention has been focused on the use of biosurfactants, an alternative ecologically friendly technique. (Whang et al., 2008).

Inconsistent findings were obtained when chemical surfactants were tested for their impact on the bio-stimulation of native microorganisms to improve the elimination of organic contaminants. Therefore, switching to biosurfactants from chemical surfactants can reduce all of the risks those latter entail (Haba et al., 2003). Despite all of these negative effects, chemical surfactants are used in a variety of processes, including drilling, the manufacture of cement, demulsification, slurries, acidulation, corrosion prevention, fracturing, transportation, water flooding, chemical, foam, cleaning, and steam flooding, and safeguarding the environment as dispersing agents for oil spills (Wei et al., 2018).

Biosurfactants also provide a major resource-use advantage over their chemical counterparts, which are said to contribute to the depletion of non-renewable petrochemical resources (Henkel et al., 2012). Additionally, these synthetic substitutes accumulate in biological systems and endanger the ecosystem (Rahman and Gakpe, 2008). Due to their superior surface action, biosurfactants exhibit improved efficiency and effectiveness in comparison with conventional surfactants. They produce reduced surface tension at less concentration, demonstrating the effectiveness of biosurfactants (Sobrinho et al., 2013). A product is deemed sustainable, according to Gavrilescu and Chisti (2005), if it outperforms its conventional counterparts in terms of performance, toxicity, durability, recyclability, and biodegradability once its useful life has passed. Biosurfactants meet each of these criteria and more. However, due to the high cost of production of these microbial surfactants, their use in bioremediation is not really competing with the use of their chemical counterpart, their advantages over them notwithstanding (Das and Mukherjee, 2007; Sobrinho et al., 2013).

Classification of biosurfactants

Contrary to chemically produced surfactants, which are often classified based on the features of their polar grouping, biosurfactants are frequently categorized largely by their chemical composition and microbiological origin (Whang et al., 2008). Biosurfactants fall into two categories: molecules with low molecular mass, which efficiently lower surface and interfacial tension, and polymers with higher molecular mass, which perform better as emulsion stabilizers. Glycolipids, phospholipids and lipopeptides are among the primary classes of low-mass surfactants, while polymeric and particulate surfactants are among the major classes of high-mass surfactants. Numerous biosurfactants contain hydrophobic regions made of long-chain fatty acids or their derivatives, and hydrophilic regions made of amino acids, carbohydrates, phosphates, and cyclic peptides (Souza et al., 2014; Ramírez et al., 2015; Varjani and Upasani, 2017). According to Desai and Banat (1997) and Mulligan (2007), biosurfactants can be divided into six types depending on their chemical makeup: fatty acids, neutral acids, lipopeptides/lipoproteins, glycolipids, phospholipids, polymeric/particulate surfactants, and so on (Souza et al., 2014; Ramírez et al., 2015) Rhamnolipids produced by *Acetinobacter calcoaceticus* and sophorolipid by *Candida bombicola* and *pseudomonas aeruginosa* are some examples of microbial derived surfactants.

Table 1: Major biosurfactant classes and microorganisms involved

S/No	Biosurfactant class	Microorganism involved in biosynthesis
1	**Glycolipids**	
	Sophorolipids	*Candida apicola, C. bombicola*
	Rhamnolipids	*Pseudomonas aeruginosa*
	Mannosylerythritol lipids	*C. antartica*
	Trehalose lipids	*Arthobacter* sp., *Rhodococcus erithropolis*
2	**Phospholipids**	*Corynebacterium lepus, Acinebacter* sp.

3	**neutral lipids/ Fatty acids**	
	Corynomicolic acids	*Corynebacterium insidibasseosum*
4	**Lipopeptides**	
	Lichenysin	*B. licheniformis*
	Surfactin/fengycin/ iturin	*B. subtilis*
	Serrawettin	*Serratia marcescens*
	Viscosin	*P. fluorescens*
5	**Surface-active antibiotics**	
	Gramicidin	*Brevibacterium brevis*
	Antibiotic TA	*Myxococcus xanthus*
	Polymixin	*B. polymyxa*
6	**Polymeric/ Particulate surfactants**	
	Polymeric surfactants	
	Emulsan	*Acinetobacter calcoaceticus*
	Lipomanan	*C. tropicalis*
	Alasan	*A. radioresistens Liposan*
	Particulate biosurfactants	
	Whole microbial cells	*Cyanobacteria*
	Vesicles	*A.calcoaceticus*

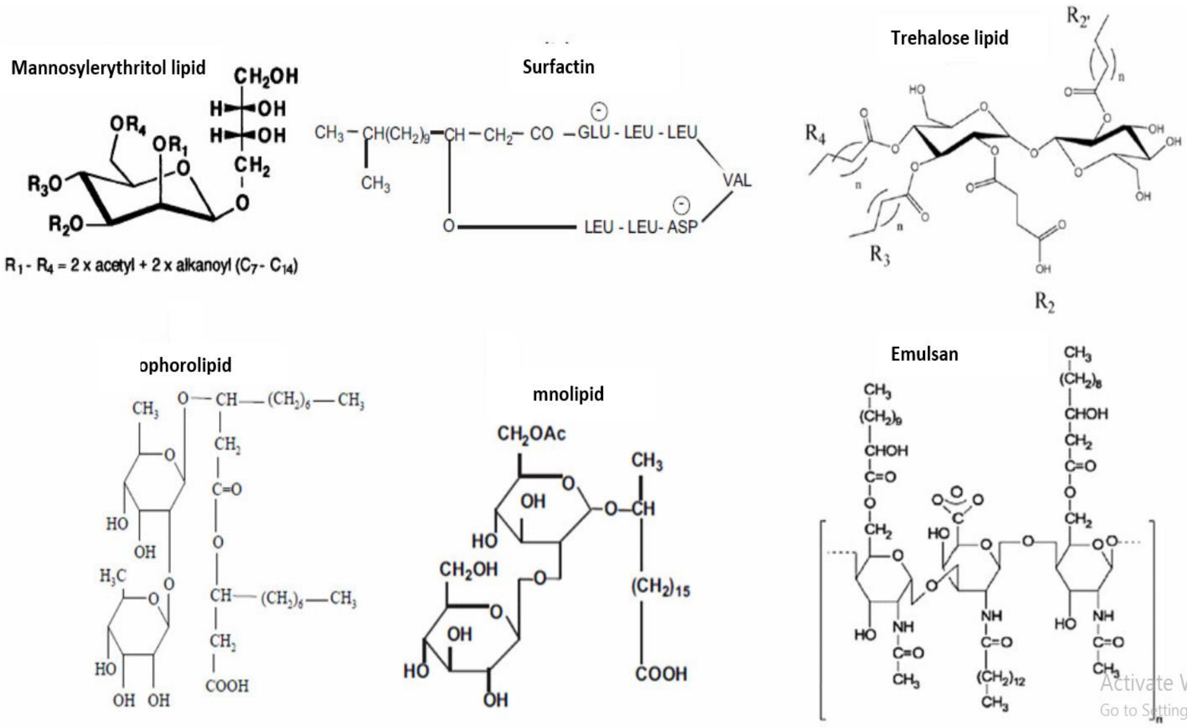

Figure 1. Some common biosurfactants with their chemical structures (Ghojavand et al., 2008).

Production of biosurfactant

The production of biosurfactants involves: first isolating the microorganism and then inoculate the organisms into the blood agar media contained in pre-sterilized Petri plates. Then incubate the medium at $37^{0}C$ for 24hrs (Wei et al., 2018). Several renewable substrates have been discovered to date for the experimental manufacture of surfactants and microorganisms from a variety of sources, including industrial wastes. Examples of these recyclable substrates are frying oil, soap stock, animal fat, and olive oil mill effluent. For instance, Pseudomonas sp. isolates can synthesize rhamnolipid from water-insoluble or water-soluble substrates, while the latter case results in increased synthesis of surface-active agents (Wei et al., 2018). This study addressed the creation of biosurfactant utilizing a water-insoluble substrate that contained 1.5% (V/V) cooked vegetables. A number of additional nutrients, including peptone, MgSO4.7H2O, KH2PO4, NaNO3, and yeast extract were added to the medium. 100ml of medium and 500ml Erlenmeyer flasks were used to cultivate the cultures. The medium that had been autoclaved and allowed to cool received the trace element solution after being filtered, sterilized, and added. The culture medium was then incubated at 300C for 48–72 hours with around 2ml. (Desai and Banat, 1997; Wang and Mulligan, 2008).

Extraction of rhamnolipid**:** Surfactants were created and released into the media while the cells were being incubated. The acid precipitation method was used to extract this. The medium was first centrifuged at 5000 rpm for 15 min, collecting the cell-free broth with surfactant in a separate tube. By adding HCl, the surfactant in the broth precipitated at pH 2.0. The broth was once more centrifuged for 15 minutes at 5000 rpm to remove the surfactant using dichloromethane. Additionally, recrystallization was used to achieve purity. Distilled water that contained enough NaOH to produce a pH of 7.0 was used to dissolve the dichloromethane extract. Whattman No. 4 filter paper was used to filter this solution, and HCl was added to lower the pH to 2.0. After centrifugation, a pellet of the white material was obtained (Ramírez et al., 2015; Varjani and Upasani, 2017).

Factors that affect the production biosurfactants

***Culture condition*:** The condition of the culture such as the elements present in the media, the components of the media and the precursors have been discovered to affect the production of biosurfactants both in quality and in quantity (Das and Mukherjee, 2007). According to reports, such elements as nitrogen, iron, and manganese have an impact on the production of biosurfactants. For instance, P. aerugionsa Bs-2 is said to produce more biosurfactants when nitrogen is limited (Salihu et al., 2009). Similar to this, it has been observed that adding iron and manganese to the culture medium causes *B. subtilis* to produce more biosurfactant (Wei et al., 2018).

***Downstream recovery from the culture*:** The recovery of the biosurfactant from the medium can be accomplished in a number of practical ways, including solvent extraction, ammonium sulphate precipitation, acid precipitation, crystallization and centrifugation (Ghojavand et al., 2008). The use of ion exchange chromatography, foam fractionation, ultrafiltration, adsorption-desorption on polystyrene resins, and other novel and intriguing recovery techniques have all been discovered recently in an effort to increase quantitative production. One processing method has reportedly been found to be insufficient for the recovery and purification of the product in the biosurfactant recovery process (Coimbra et al., 2009; Radzuan et al., 2017). However, a multistep recovery for biosurfactants is necessary if a product with high degree of purity must be obtained (Hazra et al., 2017).

***The microbial strains*.** Use of highly productive microbial strains is frequently necessary for industrial production. A production method cannot be made commercially feasible and profitable even with affordable raw materials, an effective recovery procedure, and optimal medium/culture conditions until the producer organism has a high yield of the final product by nature (Banat et al., 2014).

Furthermore, if the natural production strains are not producing enough, the industrial production process depends on an adequate supply of recombinant and mutant hyperproducers. Table 2 presents a few mutant and recombinant types with improved biosurfactant production traits in addition to the natural biosurfactant producer strains.

Table 2: Some typical biosurfactants and the microbes that produce them

Biosurfactant	Microorganism	Source	References
Rhamnolipids	*Pseudomonas aeruginosa*	Soils and waste water contaminated by petroleum,	Wei et al., (2008), Varjani and Upasani, (2017); Thakur et al., (2021)
Mannosylerythritol lipids	*Candida antartica*	Wastes from soybean and vegetable oils	Coelho et al., 2020; Matosinhos et al., 2023
Trehalose lipids	*Rhodococcus erythropolis* 517T	Polluted soils from oil and hydrocarbon gas station	Franzetti et al., 2010; Gayathiri et al., 2022
Bioemulsan	*Gordonia* spp BS29	Soils contaminated by diesel	Rosenberg and Ron, 1997; Amoabediny et al., 2010
Surfactin	*Bacillus subtilis* ATCC 21332	Waste from soybean and petroleum sludge	Chen et al., 2022; Xia and Wen, (2022).

These mutant types were created by a variety of methods, including transposons, chemical mutagens like nitrosoguanidine, radiation, and other methods (Nayak et al., 2009). Numerous recombinant strains that produce biosurfactants in higher yields and with enhanced production characteristics have been created recently as well to these mutant hyper-producing kinds.

Biosurfactants and environmental management

Environmental management is the process by which the health of the environment is regulated. Environmental management refers to a set of activities aimed at finding answers to the practical issues that humans face when interacting with nature, exploiting resources, and producing trash (Kitamoto et al., 2001). The environmental issues we face are numerous and varied. Many scientists predict that in the future decades, a number of issues—including global warming, depletion of the ozone layer, the devastation of the world's rain forests, and oil spills—will reach critical levels (Gayathiri et al., 2022). Petroleum hydrocarbons have contaminated both soil and priceless groundwater supplies as a result of their extensive use (Xia and Wen, 2022). The primary source of energy is still petroleum hydrocarbon, which is a significant global environmental pollution.

Microbial degradation eliminates these toxins from the environment which are petroleum hydrocarbons. Innovative methods have been created that use biosurfactants to speed up the microbial decomposition of hydrocarbons because such biological degradation is known to take a long period. According to Rahman and Gakpe (2008) and Matosinhos et al. (2023), biosurfactants play a significant role in lowering atmospheric carbon dioxide emissions, a major greenhouse gas. For example, the inclusion of biosurfactants encourages the microorganism to break down hydrocarbons at rates that are higher than those that could be reached by the addition of nutrients alone. The first study to demonstrate that hydrocarbon culture medium encouraged the growth of a *P. aeruginosa* strain that produces rhamnolipids was Franzetti et al. (2010). Recent investigations have established the impact of biosurfactants on the biological degradation of hydrocarbons by enhancing microbial accessibility to insoluble substrates (Chen et al., 2022; Xia and Wen, 2022; Matosinhos et al., 2023). Numerous studies have demonstrated how biosurfactants affect hydrocarbons, improving their water solubility and causing oily compounds to be displaced from soil particles. Therefore, biosurfactants boost these organic molecules' apparent solubility at doses above the threshold of critical micelle concentration, which increases their availability for microbe absorption (Verstraete, 2002; Coimbra et al., 2009). These factors make the incorporation of biosurfactants in a process of bioremediation for a hydrocarbon-polluted atmosphere particularly promising, as it will facilitate microorganism uptake.

Applications of biosurfactants in bioremediations

Environmental bioremediation constitutes one of the main fields where biosurfactant is used. A biological method or procedure called "bioremediation" is utilized to lessen environmental pollutants. It entails the mineralization or modification of organic pollutants by living things into less dangerous ones (Sobrinho et al., 2013). Through the procedure of bioremediation, pollutants are broken down naturally by microorganisms into water as well as carbon dioxide (CO_2) (Lai et al., 2009). Substances created are then incorporated into numerous biogeochemical cycles (Cameotra and Bollag, 2003). Although the constituents of hydrocarbon pollutants are often bonded to soil particles, they are not necessarily easily accessible to microorganisms. They become less bioavailable as a result, the process of biodegradation is less effective (Ron and Rosenberg, 2002; Kuyukina et al., 2005). In light of this, microorganisms make biosurfactants as secondary metabolites (Varjani and Upasani, 2017), especially when they are growing on substrates that are insoluble in water (Luna et al., 2011) such as hydrocarbons. Biosurfactant production can occur extracellularly or as cell-bound compounds (Satpute et al., 2010). The majority of organic synthetic chemicals found in polluted soil are either totally or just weakly soluble in water (Jayabarath et al., 2009). Therefore, they are a concern to the environment since they exist in the subsurface as a different liquid phase, also known as a non-aqueous liquid phase. Before microbial cells may digest hydrophobic contaminants found in petroleum hydrocarbons, soil, and water environments, they must first be solubilized. Pesticides and other hydrophobic compounds can have their surface area increased by biosurfactants, enhancing their water solubility (Adetunji et al., 2022). Biosurfactants produced extracellularly cause the substrate (a hydrocarbon) to emulsify. Contrarily, the cell membrane of microbes produces biosurfactants that serve to make it easier for substrates to flow through the membrane (Mulligan, 2005). To this purpose, the biological breakdown of hydrocarbons and the preparation of contaminated areas using biosurfactant-producing microbes is thought to be an efficient microbiological remedy for environmental contaminants (Pacwa-Plociniczak et al., 2011).

The potential of biosurfactants to increase the bioavailability of contaminants to microorganisms through bioremediation enhanced with the addition of biosurfactants and to solubilize and mobilize hydrocarbons in soils through biosurfactant-enhanced washing, resulting in the removal of the contaminants, have been the main topics of research on the use of biosurfactants for the cleanup of environmental pollutants (Banat et al., 2010; Luna et al., 2011). Such biosurfactant applications vary in their modes of operation and biosurfactant characteristics. Usage is either focused on how biosurfactants affect the metabolic activity of microbes or on the physicochemical characteristics of the biosurfactants themselves (Coelho et al., 2020). Thus, Mazaheri et al. (2010) and De Silva et al. (2014) confirmed that understanding the chemical and physical characteristics of the polluted area is necessary for the successful application of biosurfactants in petroleum bioremediation. The biosurfactants utilized should also be appropriate in terms of the chemical and physical properties of the polluted locations in order to enable the commercialization of biosurfactants (Sobrinho et al., 2013). Therefore, the application of biosurfactants for bioremediation both in soil and aquatic ecosystems has gained relevance in recent researches (Adetunji et al., 2023).

Microbial engineered oil recovery (MEOR)

The utilization of biosurfactants in microbial-engineered oil recovery has significant promise. MEOR lowers interfacial tension at the oil-rock contact by stimulating reservoir microbes to create macromolecules and surfactants (De Silva et al., 2014). The microbes within the reservoir are often supplied with inexpensive substrates, including inorganic source of fertilizers and molasses to encourage growth and the synthesis of biosurfactant in order to generate it in situ (Joshi et al., 2008; Freitas et al., 2016). Bacteria must have the ability able to thrive under the harsh circumstances found in oil reservoirs, which include high temperatures, salinity, inadequate oxygen supply and pressure in order to be beneficial for MEOR in situ. In the laboratory, many anaerobic and aerobic thermophiles that can withstand moderate salinity and pressure have been isolated (Ilori et al., 2005). Field investigations conducted in Hungary, the US, Romania, USSR, Poland, Czechoslovakia, and the Netherlands have reported on the usefulness of MEOR. In some situations, a substantial boost in oil recovery was seen (Whang et al., 2008).

Removal of oil spill in aquatic environment

When oil is spilled in an aquatic setting, the lighter hydrocarbon elements volatilize and the polar hydrocarbon components dissolve in water. However, the majority of the oil constituents will stay on the water's surface due to the oil's low solubility. evaporation, microbial degradation and Photo oxidation are the main techniques for removing hydrocarbons. Since saltwater contains creatures that can break down hydrocarbons, biological degradation may be one of the more effective ways to remove pollutants (Souza et al., 2014). Through the emulsification and dispersion of hydrocarbons, surfactants promote degradation. Hydrocarbon-degrading microorganisms have been isolated from watery environments. Aquatic environments may benefit from the usage of microorganisms with emulsifying functions and soil microbes that create biosurfactants. According to Haba et al. (2003), *P. aeruginosa* SB30-produced emulsifiers may swiftly emulsify oil into tiny droplets, making them suitable for removal from contaminated beaches. Oil-degrading bacteria may produce biosurfactants that are helpful for cleaning oil storage tanks. After 4 days of aeration in an oil tanker compartment containing K_2HPO_4, oily blast, urea, and water, the substantial layer of sludge that was still present in the control tanker was completely eliminated. This was most likely caused by the biosurfactant created, which promoted the growth of the local bacterial population (Haba *et al*., 2003).

Oil recovery, transportation, and pipelining have all been made easier by using surfactants, which have been explored for their potential to reduce the viscosity of heavy oils (Kumar et al., 2006Emulsan, a highly molecular-weight lipopolysaccharide produced by *A. calcaoceticus* RAG-1, has been suggested for use in the petroleum industry for a number of uses, such as cleaning oil and sludge from tanks and barges, reducing the viscosity of heavy oils, improving oil recovery, and stabilizing water-in-oil emulsions in fuels. (Jayabarat et al., 2009). According to Frenzetti et al. (2009), prokaryotic organisms proliferate when specific hydrocarbon types are solubilized. EDTA severely reduced the specific solubilization of hydrocarbons, whereas sufficient Ca++ overcame this. It was determined that a key process in the microbial uptake of hydrocarbons is the selective solubilization of hydrocarbons (Freitas et al., 2016).

Action of Biosurfactant in water

At concentrations over the critical concentration of micelle, the biosurfactant molecule is preferentially oriented at the oil-water interface to form surfactant-stabilized droplets and to reduce the surface tension of water. Microbial degradation and assimilation of the surfactant stabilized droplets thereby sanctifying the water (Sánchez, 2022; Li et al., 2023)

Removal of oil spill on the soil environment

Degradation depends on the presence of microbes that break down hydrocarbons in the soil, the composition of the hydrocarbons, the availability of oxygen, the presence of water, the temperature, the pH, and the inorganic nutrients (Lee et al., 2008; Sánchez, 2022). The biological breakdown of a hydrocarbon can also be impacted by its physical state. Increased hydrocarbon movement and solubility due to the addition of biosurfactants or synthetic surfactants is necessary for efficient microbial breakdown (Adetunji et al., 2022). Results from the use of biosurfactants in the breakdown of hydrocarbons have been inconsistent. According to Kitamoto et al.'s (2001) research, the fungus *Cladosporium resiuae* generated phospholipids and extracellular fatty acids, primarily dodecanoic acid and phosphatidylcholine, when cultured on alkane mixtures. Phosphatidylcholine supplementation increased the alkane decomposition rate by 30% (Bodour et al., 2004 According to a report, when mixed bacterial cultures were utilized, the emulsifier Emulsan slowed the breakdown process while stimulating aromatic mineralization in pure bacterial cultures (Kim et al., 2002; Amoabediny et al., 2010).

Naphthalene was used in the first step of hydrocarbon degradation in a mixed soil population to evaluate hydrocarbon breakdown in model oil; additional oil constituents were broken down during the second phase following the production of biosurfactants by the relevant bacteria reducing the interfacial tension (Jayabarath et al., 2009). The amount of degradation and final production of biomass were both boosted by the addition of biosurfactants, such as certain sophorolipids. Method to detoxify waste waters, industrial sludges, and soils was disclosed in Biodetox (Germany) (Maneerat et al., 2005). In situ biological reclamation of polluted surface, deep ground, and groundwater was also discussed.

Increasing the mobility of hydrocarbons in polluted soil by adding biosurfactants is another way to get rid of oil contamination. Using a production well, the emulsified hydrocarbon may then be retrieved and degraded above ground in a bioreactor. Adsee 799 and Hyonic NP-90: two synthetic surfactants, were used to study in situ soil washing (Nayak et al., 2009). It has been somewhat successful to remove petroleum hydrocarbon from the soil through the addition of surfactants to the wash water (Pornsunthorntawee et al., 2009). Biosurfactants enhance the microbial degradation of recalcitrant hydrophobic compounds contained in industrial waste water by dispersion and solubilization (Paria, 2008).

Bioremediation of pesticide contaminated soil

The most common insecticide still used in Nigeria and several other nations is hexa-chlorocyclohexane (HCH). The alpha-form of HCH, which is not just non-insecticidal but also thought to be carcinogenic, makes up over 70 percent of the technical product out of the eight known isomers of HCH (Neitsch et al., 2016). Pseudomonas Ptm+ strain was one among the strains effective at degrading HCH (Usman et al., 2016). In a mineral medium with HCH, the strain isolate developed extracellular biosurfactant. Although this biosurfactant emulsified the solid organochlorine HCH more thoroughly than it did other solid organochlorines like DDT and cyclodienes (Olivera et al., 2009), this suggests that the biosurfactant is only effective at dispersing HCH. Additionally, it was shown that *Pseudomonas* growing in liquid culture reached its peak in emulsifier synthesis prior to the start of HCH breakdown (Neitsch et al., 2016). An enormous macromolecule with lipid, carbohydrate, and protein components made up the extracellular biosurfactant. Rhamnose was recognized as the carbohydrate component by various analytical techniques. The biosurfactant's stable rhamnose component was essential for the substance's action. Investigative work showed that the protein fraction contained the HCH metabolism's proximal enzymes. HCH was transformed into tertachlorohexenes and then chlorophenols in the presence of biosurfactant by the actions of isomerase and dechlorinase (Tuleva et al., 2002; Adetunji et al., 2023).

This change was sped up by the biosurfractant's action, which increased HCH's surface area. Therefore, it is clear that extracellular biosurfactant plays a crucial part in how the *Pseudomonas* Ptm+ strain degrades HCH (Rikalovic et al., 2015).

Attention has also been paid to the production of biosurfactant for the liquid pesticide Fenthion. The biosurfactant was secreted by Bacillus subtilis in both a liquid and solid state fermentation system (Sarubbo et al., 2006). These two organisms' microbial surfactant exhibits the qualities of a potent cleaning agent for removing pesticides from old containers, mixing tanks, freight docks, etc., (Liu et al., 2015).

The setbacks of Large-Scale usage of Biosurfactants

Despite the many benefits that have been identified for biosurfactants, it is a well-known fact in most research works that these substances cannot commercially compete with their synthetic counterparts because of the production cost, low yields, safety concerns, and production of a variety of congener molecules with varying surface and interfacial properties (Radzuan et al., 2017; Sarubbo et al., 2922; Zargar et al., 2023). The substrates are the first place to look for solutions to this constraint. The expense associated with the substrate choice made during the production process emphasizes the necessity for economical substrates in the production of biosurfactants. One must create a procedure that is economical and makes use of inexpensive materials.

CONCLUSION

Due to their eco-friendly makeup and extensive applications, the manufacture of biosurfactants has recently attracted interest. These microbial products' versatility and recognized benefits will help them succeed in industrial applications. Manufacturers must concentrate on product development to compete in a fiercely competitive market in the near future. In the end, the net economic equilibrium between their manufacturing costs and functional advantages will determine the fate of biosurfactants. Finding an economical procedure that uses inexpensive ingredients and, on the other hand, producing goods with a high yield and activity are necessary to achieve a delicate balance between the two. The finding of novel lower temperatures biosurfactants also presents a fascinating field for research in the possible role in the utilization of biosurfactants in cold areas and the development of low-energy production procedures. This is due to the numerous, environmental, medical, and industrial applications of biosurfactants and the microorganisms which produce them, many of which necessitate their exposure to extremes of temperature, pressure, pH, and other variables. Even more urgently, it will be necessary to isolate extremophiles or create super-active, genetically altered microbes that can survive in harsh environments.

REFERENCES

Adetunji, C. O., Jeevanandam, J., Selvam, J. D., Inobeme, A., Thangadurai, D., Michael, O. S., ... & Olaniyan, O. T. (2022). Production and commercialization of biosurfactants for plant pest management. In Applications of biosurfactant in agriculture (pp. 69-92). Academic Press.

Adetunji, C. O., Morumda, D., Dauda, W. P., Abraham, P., Glen, E., Abraham, M. P., ... & Nnyanzi, L. A. (2023). In silico approaches for xenobiotic polymers and their degradation mechanism. In In-Silico Approaches to Macromolecular Chemistry (pp. 479-501). Elsevier.

Amoabediny, G. H., Rezvani, M., Rashedi, H., Jokari, S., Chamanrokh, P., Mazaheri, M., ... & Yazdian, F. (2010). Application of a novel method for optimization of bioemulsan production in a miniaturized bioreactor. Bioresource technology, 101(24), 9758-9764.

Banat, I. M., Franzetti, A., Gandolfi, I., Bestetti, G., Martinotti, M. G., Fracchia, L., ... & Marchant, R. (2010). Microbial biosurfactants production, applications and future potential. Applied microbiology and biotechnology, 87, 427-444.

Banat, I. M., Satpute, S. K., Cameotra, S. S., Patil, R., & Nyayanit, N. V. (2014). Cost effective technologies and renewable substrates for biosurfactants’ production. Frontiers in microbiology, 5, 697.

Bodour, A.A., Gerrero-Barajas, C., Jiorle, B.V., Malcomson, M.E., Paull, A.K., Somogyi, A., Trinh, L.N., Bates, R.B. and Maier, M.R. (2004). Structure and Characterization of Flavolipids, a Novel Class of Biosurfactants Produced by *Flavobacterium sp*. Strain MTN11: Applied and Environmental Microbiology. 70, 114-120.

Brockhaus, S., Fawcett, S. E., Knemeyer, A. M., & Fawcett, A. M. (2017). Motivations for environmental and social consciousness: Reevaluating the sustainability-based view. Journal of Cleaner Production, 143, 933-947.

Cameotra, S. S., & Bollag, J. M. (2003). Biosurfactant-enhanced bioremediation of polycyclic aromatic hydrocarbons. Critical Reviews in Environmental Science and Technology, 33(2), 111-126.

Chen, X., Lu, Y., Shan, M., Zhao, H., Lu, Z., & Lu, Y. (2022). A mini-review: Mechanism of antimicrobial action and application of surfactin. World Journal of Microbiology and Biotechnology, 38(8), 143.

Coelho, A. L. S., Feuser, P. E., Carciofi, B. A. M., de Andrade, C. J., & de Oliveira, D. (2020). Mannosylerythritol lipids: antimicrobial and biomedical properties. Applied microbiology and biotechnology, 104(6), 2297-2318. https://doi.org/10.1007/s00253-020-10354-z

Coimbra, C. D., Rufino, R. D., Luna, J. M., & Sarubbo, L. A. (2009). Studies of the cell surface properties of Candida species and relation to the production of biosurfactants for environmental applications. Current Microbiology, 58, 245-251.

Das, K., & Mukherjee, A. K. (2007). Comparison of lipopeptide biosurfactants production by Bacillus subtilis strains in submerged and solid state fermentation systems using a cheap carbon source: some industrial applications of biosurfactants. Process Biochemistry, 42(8), 1191-1199.

Desai, J. D., & Banat, I. M. (1997). Microbial production of surfactants and their commercial potential. *Microbiology and Molecular biology reviews*, *61*(1), 47-64.

Franzetti, A, Caredda, P, Ruggeri, C, La Colla P, Tamburini, E, Papacchini, M and Bestetti, G. Potentia (2009). Applications of Surface Active Compounds by Gordonia sp. strain BS29 in Soil Remediation Technologies: Chemosphere. 27, 1000-1012.

Franzetti, A., Gandolfi, I., Bestetti, G., Smyth, T. J., & Banat, I. M. (2010). Production and applications of trehalose lipid biosurfactants. European Journal of Lipid Science and Technology, 112(6), 617-627.

Freitas, B. G., Brito, J. G., Brasileiro, P. P., Rufino, R. D., Luna, J. M., Santos, V. A., & Sarubbo, L. A. (2016). Formulation of a commercial biosurfactant for application as a dispersant of petroleum and by-products spilled in oceans. Frontiers in Microbiology, 7, 1646.

Gavrilescu, M., & Chisti, Y. (2005). Biotechnology—a sustainable alternative for chemical industry. Biotechnology advances, 23(7-8), 471-499.

Gayathiri, E., Prakash, P., Karmegam, N., Varjani, S., Awasthi, M. K., & Ravindran, B. (2022). Biosurfactants: potential and eco-friendly material for sustainable agriculture and environmental safety—a review. Agronomy, 12(3), 662.

Ghojavand, H., Vahabzadeh, F., Mehranian, M., Radmehr, M., Shahraki, K. A., Zolfagharian, F., ... & Roayaei, E. (2008). Isolation of thermotolerant, halotolerant, facultative biosurfactant-producing bacteria. *Applied microbiology and biotechnology*, *80*, 1073-1085.

Haba, E., Abalos, A., Jauregui, O., Espuny, M. J., & Manresa, A. (2003). Use of liquid chromatography-mass spectroscopy for studying the composition and properties of rhamnolipids produced by different strains of Pseudomonas aeruginosa. Journal of Surfactants and Detergents, 6, 155-161.

Hazra, C., Kundu, D., Ghosh, P., Joshi, S., Dandi, N., & Chaudhari, A. (2011). Screening and identification of Pseudomonas aeruginosa AB4 for improved production, characterization and application of a glycolipid biosurfactant using low-cost agro-based raw materials. Journal of Chemical Technology & Biotechnology, 86(2), 185-198.

Hazra, C., Kundu, D., Ghosh, P., Joshi, S., Dandi, N., & Chaudhari, A. (2011). Screening and identification of Pseudomonas aeruginosa AB4 for improved production, characterization and application of a glycolipid biosurfactant using low-cost agro-based raw materials. Journal of Chemical Technology & Biotechnology, 86(2), 185-198.

Henkel, M., Müller, M. M., Kügler, J. H., Lovaglio, R. B., Contiero, J., Syldatk, C., & Hausmann, R. (2012).

Rhamnolipids as biosurfactants from renewable resources: concepts for next-generation rhamnolipid production. Process Biochemistry, 47(8), 1207-1219.

Hommel, R., Stiiwer, O., Stuber, W., Haferburg, D., & Kleber, H. P. (1987). Production of water-soluble surface-active exolipids by Torulopsis apicola. Applied microbiology and biotechnology, 26, 199-205.

Ilori, M. O., Amobi, C. J., & Odocha, A. C. (2005). Factors affecting biosurfactant production by oil degrading Aeromonas spp. isolated from a tropical environment. Chemosphere, 61(7), 985-992.

Jayabarath, J., Shyam, S. S., Arulmurugan, R., & Giridhar, R. (2009). Bioremediation of heavy metals using biosurfactants. Int J Biotechnol Appl, 1(2), 50-54.

Joshi, S., Bharucha, C., Jha, S., Yadav, S., Nerurkar, A., & Desai, A. J. (2008). Biosurfactant production using molasses and whey under thermophilic conditions. Bioresource technology, 99(1), 195-199.

Kim, H. S., Jeon, J. W., Lee, H. W., Park, Y. I., Seo, W. T., Oh, H. M., ... & Yoon, B. D. (2002). Extracellular production of a glycolipid biosurfactant, mannosylerythritol lipid, from Candida antarctica. Biotechnology letters, 24, 225-229.

Kitamoto, D., Ikegami, T., Suzuki, G. T., Sasaki, A., Takeyama, Y. I., Idemoto, Y., ... & Yanagishita, H. (2001). Microbial conversion of n-alkanes into glycolipid biosurfactants, mannosylerythritol lipids, by Pseudozyma (Candida antarctica). Biotechnology Letters, 23, 1709-1714.

Kumar, M. A. N. O. J., Leon, V. L. A. D. I. M. I. R., & Ilzins, O. A. (2006). Enhancement of oil degradation by co-culture of hydrocarbon degrading and biosurfactant producing bacteria. Polish journal of microbiology, 55(2), 139.

Kuyukina, M. S., Ivshina, I. B., Makarov, S. O., Litvinenko, L. V., Cunningham, C. J., & Philp, J. C. (2005). Effect of biosurfactants on crude oil desorption and mobilization in a soil system. Environment international, 31(2), 155-161.

Lai, C. C., Huang, Y. C., Wei, Y. H., & Chang, J. S. (2009). Biosurfactant-enhanced removal of total petroleum hydrocarbons from contaminated soil. Journal of hazardous materials, 167(1-3), 609-614.

Lee, S. C., Lee, S. J., Kim, S. H., Park, I. H., Lee, Y. S., Chung, S. Y., & Choi, Y. L. (2008). Characterization of new biosurfactant produced by Klebsiella sp. Y6-1 isolated from waste soybean oil. Bioresource Technology, 99(7), 2288-2292.

Li, H., Fang, C., Liu, X., Bao, K., Li, Y., & Bao, M. (2023). Quantitative analysis of biosurfactants in water samples by a modified oil spreading technique. RSC advances, 13(15), 9933-9944.

Liu, Q., Lin, J., Wang, W., Huang, H., & Li, S. (2015). Production of surfactin isoforms by Bacillus subtilis BS-37 and its applicability to enhanced oil recovery under laboratory conditions. Biochemical engineering journal, 93, 31-37.

Luna, J. M., Rufino, R. D., Jara, A. M. A., Brasileiro, P. P., & Sarubbo, L. A. (2015). Environmental applications of the biosurfactant produced by Candida sphaerica cultivated in low-cost substrates. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 480, 413-418.

Luna, J. M., Rufino, R. D., Sarubbo, L. A., Rodrigues, L. R., Teixeira, J. A., & de Campos-Takaki, G. M. (2011). Evaluation antimicrobial and antiadhesive properties of the biosurfactant Lunasan produced by Candida sphaerica UCP 0995. Current Microbiology, 62, 1527-1534.

Maneerat, S. (2005). Production of biosurfactants using substrates from renewable-resources. Songklanakarin J. Sci. Technol, 27(3), 675-683.

Matosinhos, R. D., Cesca, K., Carciofi, B. A. M., de Oliveira, D., & de Andrade, C. J. (2023). Mannosylerythritol lipids as green pesticides and plant biostimulants. Journal of the Science of Food and Agriculture, 103(1), 37-47.

Mazaheri Assadi, M., & Tabatabaee, M. S. (2010). Biosurfactants and their use in upgrading petroleum vacuum distillation residue: a review. International Journal of Environmental Research, 4(4), 549-572.

Mukherjee, S., Das, P., & Sen, R. (2009). Rapid quantification of a microbial surfactant by a simple turbidometric method. Journal of Microbiological Methods, 76(1), 38-42.

Mulligan, C. N. (2005). Environmental applications for biosurfactants. Environmental pollution, 133(2), 183-198.

Mulligan, C. N., & Gibbs, B. F. (2004). Types, production and applications of biosurfactants. Proceedings-Indian National Science Academy Part B, 70(1), 31-56.

Nayak, A. S., Vijaykumar, M. H., & Karegoudar, T. B. (2009). Characterization of biosurfactant produced by Pseudoxanthomonas sp. PNK-04 and its application in bioremediation. International Biodeterioration & Biodegradation, 63(1), 73-79.

Neitsch, J., Schwack, W., & Weller, P. (2016). How do modern pesticide treatments influence the mobility of old incurred DDT contaminations in agricultural soils?. Journal of agricultural and food chemistry, 64(40), 7445-7451.

Olasanmi, I. O., & Thring, R. W. (2018). The role of biosurfactants in the continued drive for environmental sustainability. Sustainability, 10(12), 4817.

Olivera, N. L., Nievas, M. L., Lozada, M., Del Prado, G., Dionisi, H. M., & Siñeriz, F. (2009). Isolation and characterization of biosurfactant-producing Alcanivorax strains: hydrocarbon accession strategies and alkane hydroxylase gene analysis. Research in microbiology, 160(1), 19-26.

Onwukwe, S. I., & Nwakaudu, M. S. (2012). Drilling wastes generation and management approach. International Journal of Environmental Science and Development, 3(3), 252.

Pacwa-Płociniczak, M., Płaza, G. A., Piotrowska-Seget, Z., & Cameotra, S. S. (2011). Environmental applications of biosurfactants: recent advances. International journal of molecular sciences, 12(1), 633-654.

Paria, S. (2008). Surfactant-enhanced remediation of organic contaminated soil and water. Advances in colloid and interface science, 138(1), 24-58.

Pornsunthorntawee, O., Arttaweeporn, N., Paisanjit, S., Somboonthanate, P., Abe, M., Rujiravanit, R., & Chavadej, S. (2008). Isolation and comparison of biosurfactants produced by Bacillus subtilis PT2 and Pseudomonas aeruginosa SP4 for microbial surfactant-enhanced oil recovery. Biochemical engineering journal, 42(2), 172-179.

Pornsunthorntawee, O., Maksung, S., Huayyai, O., Rujiravanit, R., & Chavadej, S. (2009). Biosurfactant production by Pseudomonas aeruginosa SP4 using sequencing batch reactors: Effects of oil loading rate and cycle time. Bioresource technology, 100(2), 812-818.

Radzuan, M. N., Banat, I. M., & Winterburn, J. (2017). Production and characterization of rhamnolipid using palm oil agricultural refinery waste. Bioresource Technology, 225, 99-105.

Rahman, P. K., & Gakpe, E. (2008). Production, characterisation and applications of biosurfactants-Review. Biotechnology.

Ramírez, I. M., Tsaousi, K., Rudden, M., Marchant, R., Alameda, E. J., Román, M. G., & Banat, I. M. (2015). Rhamnolipid and surfactin production from olive oil mill waste as sole carbon source. Bioresource technology, 198, 231-236.

Rikalović, M. G., Vrvić, M. M., & Karadžić, I. M. (2015). Rhamnolipid biosurfactant from Pseudomonas aeruginosa: from discovery to application in contemporary technology. Journal of the Serbian Chemical Society, 80(3), 279-304.

Ron, E. Z., & Rosenberg, E. (2001). Natural roles of biosurfactants: Minireview. *Environmental microbiology*, *3*(4), 229-236.

Ron, E. Z., & Rosenberg, E. (2002). Biosurfactants and oil bioremediation. Current opinion in biotechnology, 13(3), 249-252.

Rosenberg, E., & Ron, E. Z. (1997). Bioemulsans: microbial polymeric emulsifiers. Current opinion in biotechnology, 8(3), 313-316.

Salihu, A., Abdulkadir, I., & Almustapha, M. N. (2009). An investigation for potential development on biosurfactants. Biotechnol Mol Biol Rev, 3(5), 111-7.

Sánchez, C. (2022). A review of the role of biosurfactants in the biodegradation of hydrophobic organopollutants: production, mode of action, biosynthesis and applications. World Journal of Microbiology and Biotechnology, 38(11), 216.

Santos, D. K. F., Rufino, R. D., Luna, J. M., Santos, V. A., & Sarubbo, L. A. (2016). Biosurfactants: multifunctional biomolecules of the 21st century. International journal of molecular sciences, 17(3), 401.

Sarubbo, A. L., Moura de Luna, J., & de Campos-Takaki, G. M. (2006). Production and stability studies of the bioemulsifier obtained from a new strain of Candida glabrata UCP 1002. Electronic journal of Biotechnology, 9(4), 0-0.

Sarubbo, L. A., Maria da Gloria, C. S., Durval, I. J. B., Bezerra, K. G. O., Ribeiro, B. G., Silva, I. A., ... & Banat, I. M. (2022). Biosurfactants: Production, properties, applications, trends, and general perspectives. Biochemical Engineering Journal, 181, 108377.

Satpute, S. K., Banat, I. M., Dhakephalkar, P. K., Banpurkar, A. G., & Chopade, B. A. (2010). Biosurfactants, bioemulsifiers and exopolysaccharides from marine microorganisms. Biotechnology advances, 28(4), 436-450.

Silva, R. D. C. F., Almeida, D. G., Rufino, R. D., Luna, J. M., Santos, V. A., & Sarubbo, L. A. (2014). Applications of biosurfactants in the petroleum industry and the remediation of oil spills. International journal of molecular sciences, 15(7), 12523-12542.

Sobrinho, H. B., Luna, J. M., Rufino, R. D., Porto, A. L. F., & Sarubbo, L. A. (2013). Biosurfactants: classification, properties and environmental applications. Recent developments in biotechnology, 11(14), 1-29.

Souza, E. C., Vessoni-Penna, T. C., & de Souza Oliveira, R. P. (2014). Biosurfactant-enhanced hydrocarbon bioremediation: An overview. International biodeterioration & biodegradation, 89, 88-94.

Tuleva, B. K., Ivanov, G. R., & Christova, N. E. (2002). Biosurfactant production by a new Pseudomonas putida strain. Zeitschrift für Naturforschung C, 57(3-4), 356-360.

Usman, M. M., Dadrasnia, A., Lim, K. T., Mahmud, A. F., & Ismail, S. (2016). Application of biosurfactants in environmental biotechnology; remediation of oil and heavy metal. AIMS Bioengineering, 3(3), 289-304.

Varjani, S. J., & Upasani, V. N. (2017). Critical review on biosurfactant analysis, purification and characterization using rhamnolipid as a model biosurfactant. Bioresource technology, 232, 389-397.

Verstraete, W. (2002). Environmental biotechnology for sustainability. Journal of biotechnology, 94(1), 93-100.

Wang, S., & Mulligan, C. N. (2009). Rhamnolipid biosurfactant-enhanced soil flushing for the removal of arsenic and heavy metals from mine tailings. Process Biochemistry, 44(3), 296-301.

Wei, Y. H., Cheng, C. L., Chien, C. C., & Wan, H. M. (2008). Enhanced di-rhamnolipid production with an indigenous isolate Pseudomonas aeruginosa J16. Process Biochemistry, 43(7), 769-774.

Whang, L. M., Liu, P. W. G., Ma, C. C., & Cheng, S. S. (2008). Application of biosurfactants, rhamnolipid, and surfactin, for enhanced biodegradation of diesel-contaminated water and soil. Journal of hazardous materials, 151(1), 155-163.

Xia, L., & Wen, J. (2022). Available strategies for improving the biosynthesis of surfactin: a review. Critical reviews in biotechnology, 1-18.

Zargar, A. N., Kumar, M., & Srivastava, P. (2023). Biosurfactants: Challenges and Future Outlooks. In Advancements in Biosurfactants Research (pp. 551-576). Cham: Springer International Publishing.