MSc Program
Engineering Management

ACADEMY FOR CONTINUING EDUCATION

Exploring the Effectiveness of Biosurfactant in Enhancing Oil Recovery and Reducing Environmental Impact in Oil and Gas Industry

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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Vienna, 18.03.2024

Affidavit

I, **JUSTIN JOSEPH ARUMANATHARAYIL, BENG TECH**, hereby declare

1. that I am the sole author of the present Master's Thesis, "EXPLORING THE EFFECTIVENESS OF BIOSURFACTANT IN ENHANCING OIL RECOVERY AND REDUCING ENVIRONMENTAL IMPACT IN OIL AND GAS INDUSTRY", 79 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Signature

I dedicate this thesis to honour the legacy of Professor Peter Kopacek, a brilliant mind, compassionate mentor, and true pioneer in the field of automation and robotics.
Professor Peter Kopacek was a pivotal figure in forming our understanding of the world. He brought unmatched passion, insight, and inventiveness to each lecture. For me and many other students, his commitment to pushing the boundaries of technology innovation motivated us to aim high and achieve success in our academic and professional endeavours.
In addition to his extensive experience, Professor Peter Kopacek will always be remembered for his engaging lectures and his special fusion of humour and intelligence. His ability to humbly and charmingly explain difficult ideas made learning enjoyable for everyone who had the privilege of sitting in his classroom.
Even though Professor Peter Kopacek is no longer with us, his influence lives on in the memories and hearts of everyone who had the good fortune to know him. For future generations, his teachings will serve as a source of inspiration and guidance.
Let's honour Professor Peter Kopacek extraordinary life while we also grieve the loss of an incredible teacher. May his legacy serve as an inspiration to all those who come after him to be innovative, curious, and passionate about learning.

Rest in peace, dear Professor. Your wisdom, kindness, and laughter will be deeply missed, but never forgotten.

With heartfelt gratitude and respect,

Justin Joseph Arumanatharayil

Abstract

The oil and gas sector, which is essential to the world's energy production, must balance increasing productivity with reducing its negative environmental effects. This thesis investigates the transformative potential of biosurfactants environmentally friendly surfactants made by microorganisms in the framework of enhanced oil recovery (EOR) techniques to address these issues. The analysis emphasizes how important biosurfactants are to EOR, especially to Microbial Enhanced Oil Recovery (MEOR). Their distinct properties, which include modifying the wettability of reservoir rock, decreasing interfacial tension, and augmenting microbial motility, establish them as essential instruments for optimizing oil recovery from subterranean reservoirs. Moreover, biosurfactants' low toxicity, biodegradability, and renewable source make them environmentally friendly and consistent with the global trend toward sustainable practices. Despite the difficulties such as yield issues and safety concerns related to biosurfactants, such as rhamnolipids increasing corporate interest and continued research highlight their potential as reasonably priced and ecologically benign substitutes. Because biosurfactants can be made from a variety of microorganisms and have a broad range of structures, they present new avenues for research and application. Beyond EOR, the analysis highlights the versatility of biosurfactants in a range of industries, such as bioremediation, pharmaceuticals, cosmetics, and food production. Because of their versatility, biosurfactants including those made from plants offer more opportunities for creativity and novel applications. Scalability and cost-effectiveness of production must still be addressed, though, to compete with surfactants made chemically. The significance of thorough evaluations in the production of biosurfactants is highlighted by a life cycle analysis that takes social and economic factors into account. Social and environmental aspects could be improved by using sustainable methods like solid-state fermentation and using waste feedstocks. To fully realize biosurfactants' potential for building a sustainable and environmentally friendly future, the thesis calls for continued research and innovation. Within EOR, biosurfactants present themselves as environmentally friendly and economically viable alternatives that have the potential to completely transform upstream processes. Because of their biodegradability, reduced toxicity, and capacity to adapt to various reservoir types, they are important candidates for use in sustainable energy practices. Their capacity to reduce surface tension and promote microbial degradation has shown them to be effective in large-scale oil spills, and they hold great promise for environmental remediation. Biosurfactants provide surfactant, antioxidant, and antimicrobial properties to the pharmaceutical and cosmetic industries, paving the way for drug delivery, wound healing, and skincare. Biosurfactants demonstrate their versatility in promoting efficiency and sustainability in agriculture by helping to protect seeds, support growth, and nourish animals. But issues with scalability and production costs demand more investigation into more accessible raw materials, enhanced fermentation processes, and different production strategies. Despite the challenges, biosurfactants seem to have a bright future in a variety of industries. To reach their full potential and become the go-to solutions for a variety of applications, more research, creativity, and a dedication to environmentally friendly practices are essential.

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1 Introduction

1.1 Overview of Oil and Gas Industry

The last decade has witnessed remarkable growth in the use of renewable energy such as wind, solar, biofuel and geothermal for power generation. However, despite this progress many countries still rely heavily on fossil fuels such as crude oil and gas. According to the World Energy Council report, oil is the world´s primary fuel accounting for the one third of world´s energy consumption followed by natural gas. Generally, the oil and gas industry are divided into three major segments: upstream, midstream, and downstream (Shafiee *et al*., 2019). The upstream sector is primarily deals with extraction of crude oil and natural gas, meanwhile the midstream sector focuses on logistical network connecting upstream and downstream, which includes pipelines, ships, and other various storage facilities. The downstream sector includes the activities such as refining crude oil, processing natural gas, petrochemical industry that handle byproduct from refineries and the distribution of the final products to consumers (Wari *et al*., 2023).

1.2 Traditional Enhanced Oil Recovery Methods

Methods of recovering oil from reservoirs includes primary, secondary, and tertiary recovery. The primary oil recovery is known has the first initial phase of oil and gas extraction, which relies on the natural characteristic driven by reservoirs initial pressure. This phase recovers a relatively a small percentage of the oil. The secondary oil recovery also known as waterflooding is the next phase after primary recovery. In this method water is injected into the reservoir to maintain pressure and displace additional oil towards production well. The process helps to sweep more of the oil to the production wells by pushing it through the reservoir. Following primary and secondary recovery methods, typically only 15% to 40% of the oil in a reservoir is extracted. This incomplete recovery arises from challenges such as high interfacial tension between hydrocarbons and water zones, as well as the limiting viscosity of the oil, hindering its movement within the reservoir. Recognizing the significant untapped oil reserves left behind industries and experts are increasingly turning their attention to innovative strategies for oil recovery. This approach is commonly referred to as tertiary recovery or Enhanced Oil Recovery

(EOR). EOR methods aim to overcome the limitations of conventional recovery techniques, focusing on maximizing the extraction of residual oil from reservoirs (Wei *et al.*,2021).

EOR techniques aim to improve oil migration in a reservoir by modifying the physical properties of the reservoir fluid or reservoir rock, these techniques allow the oil to move freely, making it easier to it and allow it to flow into the production well.

There are various EOR techniques, each suitable for different resevoir and water condition:

Thermal EOR: Steam is injected into the reservoir to heat the oil, reducing its viscosity and improving its flow, this is effective especially in heavy oil or tar sands reservoirs.

Miscible Gas EOR: Gas injection such as carbon dioxide (CO_2) or natural gas into the reservoir. This allows for increased reservoir pressure, oil displacement and sweep efficiency.

Chemical EOR: Chemical such as polymers, surfactants, alkaline substance are added to modify the properties of reservoir water and improve oil recovery.

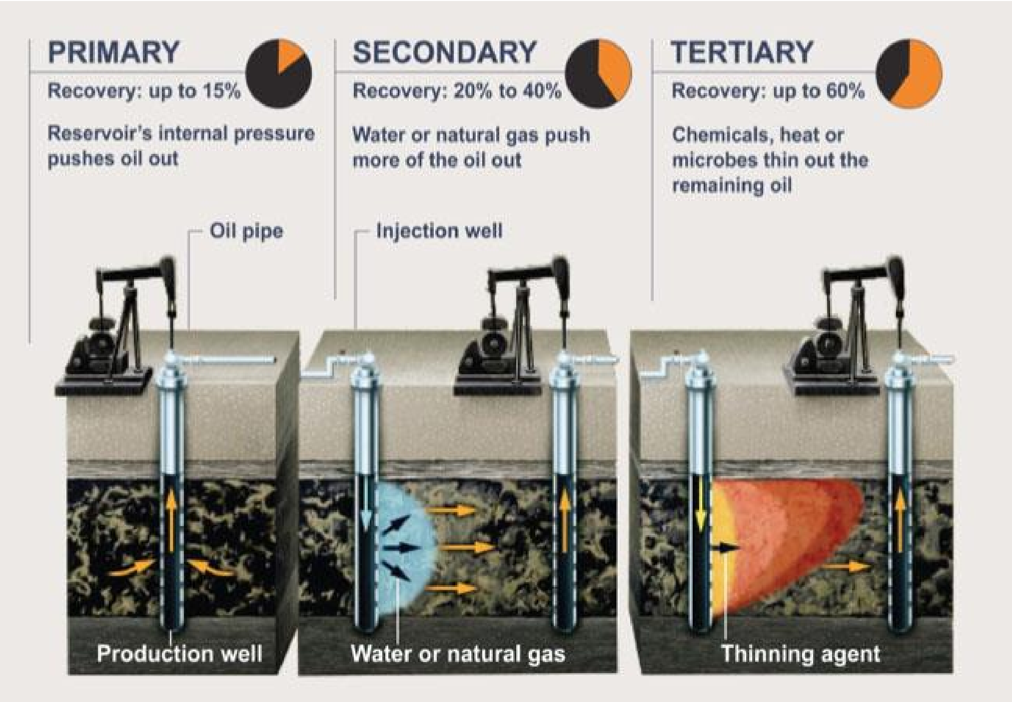

Fig. 1: Recovery Techniques for each process (Petroleum Geology, 2014)

The EOR processes are selected based on the specific characteristics of the reservoir, such as depth, temperature, pressure, water content, according to the captured oil and the objective is to produce the final oil from the reservoir size when considering economic benefits. The use of EOR technology is essential to extend the productive life of mature oil and to optimize the use of existing oil. As global energy demand increases, the importance of EOR in maximizing oil recovery and improving energy security is increasingly important (Al-Kaabi and Kokal, 2010).

1.3 Overview of Enhanced Oil Recovery Methods

The goal of enhanced oil recovery, or EOR, techniques is to extract more oil from reservoirs than can be accomplished with conventional techniques. The four primary types of these techniques are Gas Injection EOR Method, Chemical EOR Method, Thermal EOR Method, and Microbial EOR Method. Fig.1 below illustrate the four main types of EOR methods.

Gas Injection EOR Method: In unconventional reservoirs, where economic viability is dependent on oil prices, gas injection is thought to be an essential technique for improving oil recovery. Gas injection especially with carbon dioxide (CO2) becomes the go-to enhanced oil recovery (EOR) method when oil prices are low.

CO2 flooding of reservoirs has been thoroughly tested in real-world applications, primarily aimed at enhancing oil recovery in unconventional reservoirs. The principal means of achieving enhanced recovery during immiscible CO2 injection are oil swelling and a decrease in interfacial tension. Miscible injection techniques, on the other hand, produce the lightest oil. Through CO2 injection, recovery from unconventional oil reservoirs has improved. It's crucial to remember that it takes a lot of time to analyze how the reservoir's characteristics have changed after CO2 injection and how this could lead to leaks.

Nitrogen gas is an alternative to CO2 and is utilized in EOR techniques. Benefits of nitrogen include its affordability, plentiful supply, and non-corrosive nature. Numerical simulations conducted on established onshore fields have demonstrated encouraging outcomes regarding nitrogen's viability as a CO2 injection substitute for improving oil recovery.

Chemical EOR Methods: It is insufficient to mobilize oil trapped in porous rock structures because of capillary forces by flooding techniques alone. To tackle this, research into chemically enhanced oil recovery (EOR) techniques has yielded encouraging outcomes when juxtaposed with conventional thermal techniques. Alkaline substances, surfactants, and polymers are among the chemicals that have been thoroughly researched for EOR in a variety of combinations.

When alkaline solutions seep into viscous oils, they create water droplets inside the oil phase, a process known as alkaline flooding. By changing the interfacial properties, sweep efficiency is increased. Tests were conducted on sodium hydroxide and carbonate, which decreased interfacial tension and increased recovery rates. A theory indicating surfactant generation in the presence of alkali led researchers to investigate additional variables such as surfactant concentration, injection rate, and oil viscosity. Using surfactants and co-surfactants, surfactant flooding regulates the phase behavior. When crude oil and well-designed surfactant frameworks are mixed, they form micro-emulsions at the oil-water interface that greatly lower interfacial tension and improve oil recovery. Aiming to lower the interfacial tension between water and oil for better recovery, challenges include making sure surfactants perform well and resist reservoir conditions.

To improve incremental oil recovery, polymer flooding entails raising surfactant and polymer concentrations to an ideal level. Increases beyond a certain threshold are futile. In the presence of salts, experiments have been carried out to optimize the compositions of surfactants and polymers while monitoring incremental recoveries.

Thermal EOR Methods: The process of thermally enhanced oil recovery, involves heating the oil within the shale to lower its viscosity and allow for easier reservoir movement. Reducing the mobility ratio that is, the ratio of dispensing fluid to displaced fluid is considered a crucial component of thermal enhanced oil recovery (EOR). In addition to production rates, thermal propagation, and peak temperature, an understanding of fuel formation and the effects of mineral substrates is critical for in-situ combustion in shale. By injecting steam into the reservoir, the method has the dual benefits of enhancing oil mobility through network fractures and reducing viscosity. Oil recovery rates can be increased by 25-50% through steam injection when the oil-to-steam ratio is between 0.2 and 0.4 cubic meters per tonne of steam. Another thermal EOR technique is hot water injection, which lowers oil viscosity by causing thermal effects at 250–270 °C. It has been demonstrated that adding nanoparticles to low salinity water during hot water flooding changes surface energy, interfacial tension, and thermal energy, leading to higher recovery factors.

The use of electromagnetic heating to create nanoparticles and alter variables like viscosity, mobility ratio, and interfacial tension to improve oil recovery is one of the emerging techniques for enhanced oil recovery. Important factors like the rock's wettability, enthalpy, specific volume, and the latent heat of vaporization of the steam used in steam flooding determine whether enhanced oil recovery is economically feasible.

Microbial EOR Method: Microbial Enhanced Oil Recovery (MEOR) is a technique that has been used to recover a substantial amount of unreserved oil from reservoirs. This strategy makes use of microorganisms to speed up the healing process. MEOR uses several techniques, such as selective plugging, biopolymer synthesis, wettability modification, and the use of bio-solvents and bio-surfactants. Choosing the right microorganisms is important because they can both carry out vital biological functions and flourish in reservoir conditions. When compared to alternative Enhanced Oil Recovery (EOR) techniques, MEOR stands out as a selective and efficient oil recovery method. By accelerating the recovery process and producing metabolites like bio-surfactants, biopolymers, acids, gases, and biomass, microorganisms are essential to MEOR. By converting more oil into a gaseous form (methane) and producing biosurfactants in situ, the process enhances conventional methods of oil recovery. Knowing the microbiology of oilfields enables the extraction of otherwise unrecoverable oil thanks to the presence of established communities and in situ microorganisms. The choice to put MEOR into practice, even after a thorough review process, is contingent upon whether the increased oil output warrants the expenditure. Oil recovery managers should carefully consider the operation's economic viability even though MEOR typically increases oil production (Khan *et al.*, 2021).

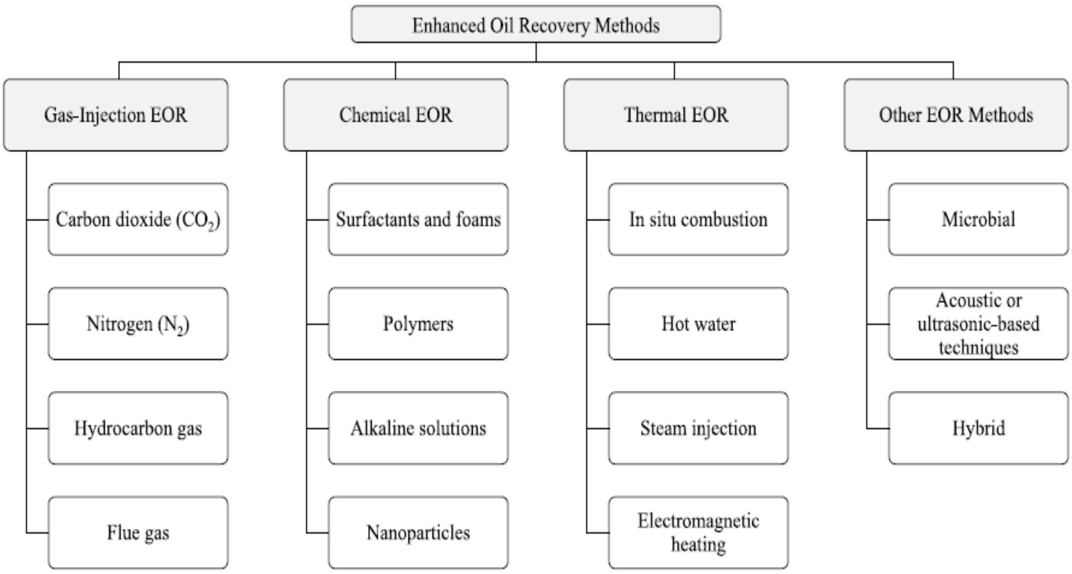

Fig.2: Main methods of Enhanced Oil Recovery (Massarweh & Abushaikha, 2020)

1.4 Importance of Surfactant in EOR

Surfactants are versatile substance that reduce the energy of the system by substituting high-energy molecules at the interface. Technically, they find applications as adhesives, flocculants, wetting agents, foaming agents, de-emulsifiers, and penetrants. In particular, the petroleum industry has been an important player in the upstream oil extraction sector, where the solubility of the oil is high (Abdeli *et al*., 2019).

One approach that can be used in enhanced oil recovery (EOR) to solve common problems in the oil and gas industry is the use of surfactant. These improve the large and small-scale displacement efficiency of crude oil trapped in reservoir. Improving crude oil viscosity, lowering the interfacial tension (IFT) between crude oil and reservoir brine, changing the wettability of the reservoir rocks (Blesic *et al*., 2017). Surfactant flooding is one of these approaches that shows the most promise for chemical EOR. This method involves injecting a surfactant solution into the reservoir. Several studies have examined the application of various surfactant types to enhance the recovery of crude oil from petroleum reservoirs. It has been observed by researchers that several variables, including the composition of the crude oil, brine salinity, temperature, rock type, and reservoir pressure, affect how effective this recovery enhancement is. Even with these developments, it is still difficult to find and use surfactants that are both appropriate and efficient for maximizing the recovery of crude oil from subsurface reservoirs (Anton and Uttam, 2021).

1.5 Scope of Research

The study of biosurfactant in the oil and gas industry has great potential as it seeks to solve important problems and improve process efficiencies. Bio surfactant produced by microorganisms have unique surfactants that have the potential to change completely different technological approaches. This research aims to investigate different applications of biosurfactants, such as enhancing oil recovery, reducing interfacial tension, and mitigating environmental impact associated with oil and gas exploration. The scope extends to research on biosurfactants as environmentally friendly alternatives to chemical surfactants, with a focus on their biodegradability and their ability to reduce environmental footprint. This comprehensive review aligns with the increasing efforts of industry to adopt green technologies and highlights the potential of biosurfactants to shape their future landscape of oil and gas operations.

1.6 Significance of Research

The study of biosurfactants in the oil and gas sector is extremely important since it is critical step toward the adoption of environmentally friendly and sustainable business practices. In place of chemical surfactants which are typically employed in the extraction and processing of oil and gas, biosurfactant which are naturally occurring surface active compounds produced by microorganisms offer a possible substitute. Their biodegradability and less environmental effect as compared to their chemical equivalents are two of their main advantages. The industry may be able to lessen the negative effects that chemical surfactants have on ecosystems and water supplies by utilizing biosurfactants. In addition, biosurfactant demonstrate a range of functions, including emulsification, foaming, and wetting, which contribute to their effectiveness in several oilfield applications, such as increased oil recovery and oil spill remediation. The use of biosurfactants in oil and gas operations not only demonstrates modern approach to fulfilling future energy demands, but also complies with environmental stewardship as the globe moves toward more sustainable energy methods. As a result, continuing research in this area not only helps to optimize the efficiency of present procedures but also clears the path for the oil and gas sector to follow a more ethical and environmentally friendly course.

1.7 Research Methodology

A comprehensive strategy was used to investigate the potential benefits of biosurfactants for enhancing oil recovery and mitigating environmental impact in the oil and gas sector. The first step was a thorough assessment of the literature review, with a focus on reliable sources such as Science Direct, Research Gate, Scopus. To locate pertinent and academic papers, a broad variety of keywords pertaining to biosurfactants, oil recovery, and environmental impact were utilized. Furthermore, a Google Scholar search was performed to incorporate the most recent research. To compile a list of publications that were directly relevant to the subject, a rigorous selection and refining process of probable sources was employed throughout the research process. The literature study encompassed a range of topics related to biosurfactants, such as their molecular weight and chemical composition classifications, characteristics, and influencing factors like carbon and nitrogen sources and environmental circumstances. The investigation extended beyond categorization and definitions. It also examined the manufacturing procedure, real-world uses for biosurfactants, and a thorough analysis of their benefits and limitations. The goal of this through approach was to give a comprehensive understanding of the function of biosurfactants in the oil and gas sector.

1.8 Limitation

While it holds great promise, there are several issues to be considered in the application of biosurfactants in the oil and gas industry. The availability of reliable and cost-effective large-scale production of good biosurfactant is a major obstacle. Scalability issues arise due to the complexity of microbial fermentation processes and the need for specific growth environments. Furthermore, the unique environmental conditions found in oil reservoirs such as high salinity and temperature can affect the stability and performance of biosurfactants. Moreover, the use of biosurfactants for oil recovery may be limited boundaries due to the complexity of the underlying geology due to interactions and the long-term effects of these interactions on the environment also need comprehensive research.

1.9 Summary

Despite notable advancements in renewable energy, the global oil and gas sector remains crucial in fulfilling energy requirements. It is divided into three segments: upstream, midstream, and downstream. It deals with the extraction, distribution, and refining of crude oil and gas. In order to maximize oil recovery from reservoirs, enhanced oil recovery (EOR) techniques, such as thermal, miscible gas, and chemical methods, have been developed to address issues with traditional extraction. The application of surfactants, adaptable compounds that improve displacement efficiency, lower interfacial tension, and change reservoir wettability, is especially crucial in EOR. One particularly interesting chemical EOR strategy is surfactant flooding, which involves injecting surfactant solutions into reservoirs.

The use of biosurfactants in the oil and gas sector is examined in this study, along with how they might improve oil recovery, lessen interfacial tension, and lessen environmental effects. Because they are biodegradable and have a smaller environmental impact than chemical surfactants, biosurfactants which are made by microorganisms present themselves as environmentally beneficial substitutes. Their versatility, which includes foaming, wetting, and emulsification, helps with oil spill cleanup and enhanced oil recovery. This study sheds light on the potential of biosurfactants to influence the future of oil and gas operations, which is in line with the industry's efforts to adopt green technologies. This research is important because it helps the oil and gas industry adopt sustainable practices. Biosurfactants present a feasible alternative to chemical surfactants, which may mitigate adverse impacts on aquatic resources and ecosystems. Furthermore, biosurfactants show promise in a range of oilfield applications, highlighting a cutting-edge strategy to satisfy future energy needs while upholding environmental stewardship objectives. A comprehensive strategy was used in the research methodology, which included a thorough review of the literature from reliable sources like Science Direct, Research Gate, and Scopus. By employing keywords associated with biosurfactants, oil recovery, and environmental impact, the research found and examined relevant papers. The study looked at the characteristics of biosurfactants, how they are made, practical uses, and advantages and disadvantages in the oil and gas industry. Nevertheless, there are obstacles to biosurfactant application, such as the requirement for dependable and reasonably priced large-scale production. The intricate nature of microbial fermentation processes gives rise to scalability challenges. Furthermore, the distinct environmental factors found in oil reservoirs, such as elevated salinity and temperature, raise questions about biosurfactant performance and stability. Comprehensive research is required for the effective

use of biosurfactants in oil recovery due to the long-term environmental effects and the complexity of the underlying geology. Despite these obstacles, this study is an important step in encouraging sustainable and eco-friendly business practices in the oil and gas sector.

2 Research Background

2.1 Introduction to Biosurfactant

Natural surface-active substances known as biosurfactants are created by a variety of microorganisms, such as bacteria, fungus, and yeasts. These substances function well in harsh temperature, pH, and salinity conditions, giving them distinct advantages over synthetic surfactants. They can be made from renewable resources, are biodegradable, and non-toxic. Furthermore, because of their biological origin, they can be modified using biochemical and genetic engineering techniques, opening up a wide range of applications. Biosurfactants are advantageous in a variety of fields and spheres of life. They have qualities that stabilize, emulsify, wet, spread, foam, and clean at various interfaces, such as liquid/solid, liquid/gas, and liquid/liquid. They are useful in industries like food production, detergent manufacturing, petroleum processing, cosmetics, and pharmaceuticals because of their adaptability. Because of their antimicrobial, antifungal, and antiviral properties, biosurfactants are also used in bioremediation, medicine, and agriculture. All things considered, the application of biosurfactants provides creative and sustainable solutions for a range of markets (Gürkok and Özdal, 2021).

2.2 Role of Biosurfactant in Oil Recovery

In tertiary oil recovery, a technique called Microbial Enhanced Oil Recovery (MEOR) is gaining popularity due to its economical and environmentally friendly characteristics. It modifies the flow characteristics of residual oil in oil fields by using microorganisms and their byproducts, including biopolymers, biosurfactants, bio-enzymes, biogases, solvents, and biogenic acids, either inside or outside the reservoir. MEOR's complicated mechanisms and the unpredictability of reservoir conditions hinder its widespread adoption in the petroleum industry, despite its potential. Even in Enhanced Oil Recovery (EOR) field trials, its performance has been patchy. Examining current MEOR technology research is essential to reducing risks and expenses related to uncontrollable factors.

MEOR mainly increases oil recovery by increasing swept volume and improving oil displacement efficiency by utilizing microbial metabolites. Among the mechanisms are:

- Biosurfactants: These compounds are used to improve bacterial mobility, change the wettability of porous media, emulsify residual oil, and reduce the tension between oil and water.
- Microorganisms and biopolymers: They specifically obstruct porous media with high permeability. Additionally, biopolymers function as adhesives to raise the water phase's viscosity.
- In oil reservoirs, carbonate rocks are dissolved by biogases, solvents, and biogenic acids, which allows water to enter the pores in the rock and come into contact with the residual oil. The gas generated can also increase reservoir pressure.
- Microorganisms: By breaking down long-chain saturated hydrocarbons and using crude oil as a carbon source, they improve the flow of oil and lower its viscosity. The first two mechanisms are thought to have the biggest effects on improving oil recovery.

To put it simply, MEOR is the deliberate application of microbial products to alter reservoir conditions in a way that maximizes oil recovery. However, widespread adoption in the petroleum industry has been hampered by difficulties in comprehending and managing these processes. The goal of ongoing research is to overcome these obstacles and maximize the use of MEOR for enhanced oil recovery (Wu *et.al*., 2022).

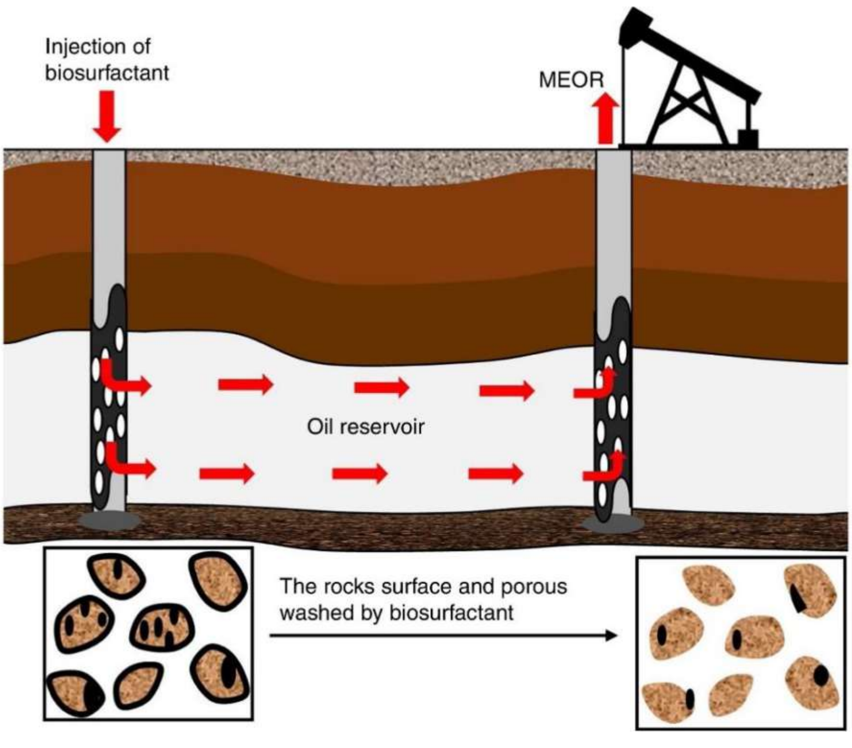

Fig.3: Microbial Enhanced Oil Recovery of crude oil (Akbari *et al*., 2018)

2.3 Environmental Impact of Synthetic Surfactant

Because they are discharged into various environmental compartments, surfactants which are widely used in oil and gas, agrochemicals, industrial products, and household activities can cause environmental pollution. The industrial goods like fabric treatments, detergents, and personal care products, as well as agrochemicals like biocides, herbicides, and pesticides, are responsible for this pollution. Laundry, cleaning, and fumigation are examples of household tasks that release surfactants into the environment. Temperature, salinity, and pH are examples of environmental variables that affect these processes. Surfactants are widely used in many different applications, which raises questions about their potential effects on the environment and the necessity of careful management to reduce pollution (Badmus *et al.*,2021).

2.4 Advantages of Biosurfactants

Compared to conventional chemical surfactants, biosurfactants offer a number of advantages. Due to their simple chemical composition, they are highly biodegradable, eco-friendly, and low in toxicity, which makes them appropriate for use in a variety of industries, including food, medicine, and cosmetics. Their high selectivity stems from the presence of particular functional groups, which enable targeted detoxification of particular pollutants. Furthermore, biosurfactants function well in harsh pH, salinity, and temperature environments. The various structures and characteristics of biosurfactants support the continuous scientific interest in their possible uses in various industries (Da Silva *et al.*, 2014).

2.5 Reducing Enivormental Impact

Stricter environmental regulations and greater public awareness are the results of an ongoing and growing concern about environmental pollution. The realization of the negative effects pollution has on human health, the environment, and the climate has spurred researchers to look for novel ways to combat pollution, especially hydrocarbon pollutants. After more than 20 years of research, biosurfactants are essential for reducing pollution and promoting sustainability. Waste management requires a focus on sustainability, which includes the "reduce, reuse, and recycle" principle. This is because the amount of hazardous and non-hazardous waste generated is increasing. International agreements to restrict increases in global temperature are part of global efforts to combat climate change. By lowering carbon dioxide emissions, a significant greenhouse gas, and supporting the more comprehensive idea of sustainability which long-term balances environmental, economic, and social factors biosurfactants help achieve this goal.

Compared to their petrochemical-based counterparts, biosurfactants are derived from renewable resources, which gives them an advantage over traditional surfactants. Biosurfactants are more efficient and effective at lower concentrations than synthetic surfactants, which are harmful to the environment and deplete resources. Biosurfactants are among the sustainable products that exhibit enhanced performance, reduced toxicity, durability, recyclability, and biodegradability post-use.

Growing environmental consciousness and changing regulations are fueling the momentum for biosurfactant research, emphasizing the material's ability to combat pollution and help create a more sustainable future (Olasanmi *et al*., 2018).

2.6 Challenge and Future Directions

Corporate attention to biosurfactants has increased recently due to their alignment with eco-friendly agendas and sustainability initiatives. The versatility of biosurfactants which can be customized for particular uses and still be more affordable than chemical surfactants makes them appealing. Before there is widespread adoption, there are a few significant issues that must be resolved. When it comes to rhamnolipids a particular class of biosurfactant the main issues are yield and safety. Although rhamnolipids have some effects on the immune system and are virulence factors, they are generally regarded as safe to use in a variety of products, especially laundry and cleaning supplies. A bigger problem is the pathogenic nature of the microorganism Pseudomonas aeruginosa, which makes rhamnolipids. Even though some businesses have been able to resolve this problem, nonpathogenic organisms are still being investigated as viable substitute producers, given that they satisfy yield and product requirements.

A quorum sensing system in Pseudomonas aeruginosa controls the synthesis of rhamnolipids, preventing the overproduction of these molecules by mutagenesis, selection, or genetic manipulation. The inability to obtain high yields may prevent rhamnolipids from being widely used in a variety of products. In spite of these difficulties, there doesn't appear to be a significant barrier preventing biosurfactants from being widely used in the upcoming years. It is anticipated that store shelves will carry an ever-growing range of household products that contain biosurfactants (Ekambaram *et al*., 2022).

2.7 Summary

Biosurfactants, which are naturally occurring surface-active substances produced by microorganisms like fungi, bacteria, and yeasts, have many advantages over synthetic surfactants. These non-toxic, biodegradable substances are adaptable, work well in challenging environments, and can be altered using genetic engineering and biochemical processes. Food production, detergent manufacturing, petroleum processing, cosmetics, pharmaceuticals, bioremediation, medicine, and agriculture are just a few of the industries that use biosurfactants.

Microbial Enhanced Oil Recovery (MEOR) is becoming more popular in tertiary oil recovery due to its cost-effectiveness and eco-friendliness. MEOR entails the purposeful application of microbial products, such as biosurfactants, to optimize oil recovery by changing reservoir conditions. MEOR has great potential, but its complicated mechanisms and unstable reservoir conditions present difficulties in comprehending and managing it. Sustained investigation endeavors to surmount these obstacles and augment the implementation of MEOR within the petroleum sector.

Environmental pollution is caused by surfactants, which are extensively utilized in agrochemicals, household activities, oil and gas, and industrial products. Compared to traditional chemical surfactants, biosurfactants have advantages due to their low toxicity and environmentally friendly characteristics. Because of their high selectivity and straightforward chemical makeup, biosurfactants are useful in a variety of industries. Stricter laws, growing public awareness, and growing environmental concerns are driving the need for long-term solutions like biosurfactants to fight pollution.

Biosurfactants are more efficient, effective, and sustainable than their petrochemical-based counterparts because they are derived from renewable resources. They perform better and are less toxic, durable, recyclable, and biodegradable after use. Research on biosurfactants is gaining traction due to shifting laws and corporate focus on sustainability and eco-friendly agendas.

Biosurfactants, especially rhamnolipids, have difficulties with yield and safety despite their potential. Rhamnolipids are used in a variety of products, but worries about the pathogenic potential of the microbe Pseudomonas aeruginosa that makes them linger. There is continuous work being done to find solutions to these problems, such as looking into nonpathogenic organisms as replacement producers.

In summary, biosurfactants address environmental issues and support sustainability initiatives by providing innovative and long-lasting solutions for a range of industries. In order to overcome obstacles and increase the broader adoption of biosurfactants in the upcoming years, research is still underway. Biosurfactants are becoming more and more popular among corporations due to their eco-friendly qualities, versatility, and growing attention from the industry. This makes them a promising alternative in the fight for a more sustainable future.

3 Current State of Biosurfactant

3.1 Overview of Biosurfactants

Biosurfactant are basically chemical compounds with water-absorbing (hydrophilic) and water-repellent (hydrophobic) parts. This unique feature allows them to lower the surface tension and facilitate the mixing of immiscible liquids. Biosurfactants are more enivornmentally friendly than conventional chemical surfactant derived from petroleum. These surface-active agents are produced by a variety of microorganisms, including bacteria and fungi, and they come in variety structure. These are classified on the basis of chemical composition and microbial production. Comparing biosurfactants to chemical surfactants reveals a number of benefits. Less toxicity, more biodegradability, environmental friendliness, selectivity, and the unique capacity to function in harsh environments at high pH and temperature levels are some of these benefits. In addition to being effective in environmental applications, biosurfactants also have the benefit of being derived from renewable resources (Costa *et al*., 2018).

Biosurfactants are undoubtedly being used in a variety of industrial processes, and it is projected that they will become very versatile materials in the twenty-first century. Currently, the petroleum industry is the main market for biosurfactants. In this sector, these compounds are essential for tasks like removing oil residue from storage tanks, cleaning up oil spills, enabling microbially enhanced oil recovery, and supporting soil and water bioremediation (Da Silva *et al*.,2014).

3.2 Compare Biosurfactant to Synthetic Surfactant

The effectiveness of various surfactants and their combinations in enhanced oil recovery (EOR) has been investigated. Generally, by lowering the interfacial tension (IFT) between water, rock, and oil, surfactants improve oil recovery. Additionally, they can enhance spontaneous imbibition. Surfactant use, however, might change how wettable the rock is.

The benefits of biosurfactants such as their increased foaming, specific activity under extreme conditions, improved environmental compatibility, higher biodegradability, and lower toxicity have led to a rise in interest in them in recent years. Renewable resources can be used to synthesize biosurfactants. Biosurfactants are relatively expensive due to their limited industrial-scale production and the fact that many are still in the laboratory, despite their benefits. It will take work to find new biosurfactants, create effective fermentation and recovery procedures, and use low-cost raw materials like agro-industry wastes in order to make biosurfactants more economically viable for EOR.

Plant-derived biosurfactants have not been as thoroughly studied as microbial biosurfactants such as rhamnolipids from Pseudomonas sp. and surfactin from Bacillus subtilis. Guar and locust bean gums, as well as aescin, lecithin, saponin, and tannin, are a few examples. While some microbial biosurfactants have been evaluated for enhanced oil recovery (EOR) in lab settings, little is known about the assessment of surfactants derived from plants as rock wettability modifiers.

Simple and affordable evaluations can be carried out to test the available surfactants prior to carrying out intricate oil displacement tests to determine the suitability of surfactants for EOR. The potential of surfactants for improved oil recovery processes is better understood thanks to these early assessments (Torres *et al*., 2011).

3.3 Properties of Biosurfactants

Natural substances called biosurfactants have special properties and are used in a variety of industries. Like traditional synthetic surfactants, they are able to self-assemble into micelles, exhibiting a variety of structures and improved specificity. They are useful in commercial applications due to their ability to effectively reduce interfacial and surface tension. Biosurfactants are more effective than chemical surfactants because they can reduce surface tension more effectively and at much lower concentrations.

For many applications, temperature and pH stability are critical, and biosurfactants are a more environmentally friendly option than their chemical counterparts because of their biodegradability. Understanding the microstructure of biosurfactants and how it relates to performance criteria has advanced recently. Surface activity, bulk rheology, and micro rheology are important characteristics that greatly affect their overall performance. The three most important performance factors in formulations are emulsification, foaming, and cleansing (Drakontis and Amin, 2020).

3.3.1 Surface and Interface Activity

Biosurfactants and other amphiphilic molecules are important in reducing interfacial and surface tension. This is necessary to produce stable emulsions. These molecules can adsorb at interfaces such as air/liquid, liquid/liquid, or solid/liquid because they contain both hydrophobic and hydrophilic sections. Surface or interfacial tension decreases because of these surfactant molecules replacing water or oil molecules at the interface and weakening the forces that hold solvent molecules together. In other words, these molecules reduce the energy needed to create new surfaces, making the process easier (Jahan *et al*., 2020).

3.3.2 Critical Micelle Concentration

The lowest concentration of a surfactant needed to obtain the greatest decrease in surface and interfacial tension is known as the Critical Micelle Concentration, or CMC. The effectiveness and surface characteristics of surfactants are strongly impacted by this concentration. Notable changes in density, viscosity, turbidity, osmotic pressure, conductivity, and chemical shifts can result from small concentration changes near the CMC. Despite both being soluble in water, biosurfactants typically have a lower CMC than many synthetic surfactants. Individual biosurfactant molecules arrange themselves into distinct molecular structures known as micelles above the CMC. A micelle is a unique assembly that is dispersed in a colloidal solution. Its hydrophilic (which attracts water) head is facing the solvent in the environment, while its hydrophobic (which repels water) tail is hidden inside the micelle's core (Kashif *et al*., 2022).

3.3.3 Emulsification and de-emulsification

Biosurfactants function as both deemulsifiers and emulsifiers. Emulsions are a type of mixture in which droplets of one liquid are dispersed throughout the second liquid, the one that doesn't mix well with the other. The majority of these droplets have a diameter of more than 0.1 mm. There are two primary varieties of emulsions: water-in-oil (where water droplets are dispersed in oil) and oil-in-water (where oil droplets are dispersed in water). Although emulsions have a limited amount of stability by nature, adding additives like biosurfactants can lengthen and improve this stability. One such is the water-soluble emulsifier called liposan, which is made by Candida lipolytica. It's used to coat oil droplets so they stay dispersed in water, resulting in stable emulsions. The food and cosmetics industries frequently use this technology to create stable oil-in-water emulsions (Vijayakumar and Saravanan, 2015).

3.3.4 Biodegradability and Low Toxicity

Compounds derived from microorganisms, like biosurfactants, are readily broken down and fit for use in natural processes like bioremediation. Alternatives to synthetic surfactants must be discovered in light of the expanding environmental concerns. The potential of marine microorganism-derived biosurfactants to eliminate phenanthrene and other poorly soluble pollutants from water surfaces has been investigated. In a study, 90% of the phenanthrene was removed using the biodegradable biosurfactant sophorolipid from marine algae, Cochlodinium.

The low toxicity of biosurfactants is one of their main advantages. Although little is known about their toxicity, biosurfactants are usually thought to be low or non-toxic. Because of this, they can be used in a variety of industries, such as the food, cosmetic, and pharmaceutical ones. According to a study, surfactants derived from chemicals are found to be more toxic than biosurfactants like rhamnolipids. The toxicity of chemical-derived surfactants was found to be ten times higher. Biosurfactants, like sophorolipids from Candida bombicola, are useful in the food industry because of their low toxicity (Roy, 2017).

3.3.5 Temperature, pH, Ionic Strength Tolerance

Different biosurfactants demonstrate exceptional stability and surface activity in a range of environmental circumstances. For instance, lichenysin, a biosurfactant from B. licheniformis JF-2, maintains its effectiveness up to 50 °C and within a pH range of 4.5 to 9.0. Another illustration is a lipopeptide made by B. subtilis LB5a, which can withstand elevated salt conditions and temperatures as high as 121 °C for up to six months without losing its surface activities. Similar to this, even after being exposed to high temperatures, surfactin and rhamnolipids show anti-adhesive qualities against microorganisms such as Staphylococcus aureus. When exposed to extreme pH levels, the biosurfactant produced by B. licheniformis, and P. aeruginosa remains resilient, and it can emulsify at temperatures as high as 50 °C. Even at pH levels of 7–8, the Bacillus subtilis strain JA-1 generates a biosurfactant with stable surface activity and emulsification capacity.

The biosurfactant produced by pseudomonas aeruginosa exhibits strong foaming and emulsifying properties as well as stability at high temperatures, pH levels, and salinities. Similar stability in its surfactant is produced by Virgibacillus salaries, which qualifies it for use in marine bioremediation. Similar to surfactants from B. subtilis and B. tequilens, Streptomyces sp. produces a biosurfactant that is stable with only minor fluctuations when subjected to varying temperatures and pH levels (Ekambaram *et al*., 2022).

3.3.6 Anti-adhesive agents

The important function that biosurfactants play in inhibiting microbial adhesion and encouraging microorganism detachment is well recognized. This applies not only to the biomedical industry but also to sectors such as food production. It is crucial to stop bacteria from attaching themselves to surfaces because this prevents the development of biofilms and swarming motion, two processes that are essential for bacterial colonization of surfaces and raise the risk of hospital-acquired infections. It is possible to effectively prevent harmful microorganisms from adhering to surfaces or infection sites by using biosurfactants. They accomplish this by altering the charges in bacterial cell walls or changing the characteristics of the substrate, which alters the interaction between microbial surfaces and influences the adherence and detachment of microbes. Even though the benefits of biosurfactants are widely acknowledged, their exact mode of action is still unclear and most likely entails a difficult procedure (Nalini *et al*., 2022).

3.4 Classification of Biosurfactant and their Production

Microorganisms produce biosurfactants, which can be classified according to their chemical composition and source. High molecular weight and low molecular weight molecules are the two main categories. Glycolipids, lipopeptides, and phospholipids are examples of low-mass surfactants; polymeric and particulate surfactants are examples of high-mass surfactants (Rosenberg and Ron, 1999).

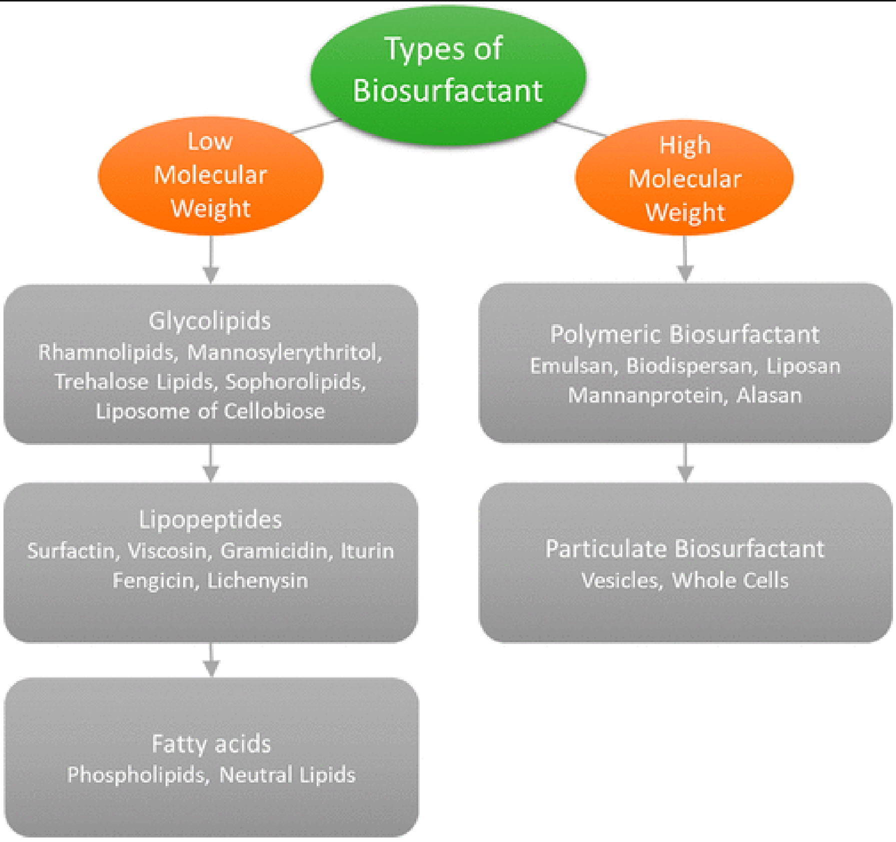

Fig.4: Classification of biosurfactant based on moleculare weight

3.4.1 Biosurfactant with Low Molecular Weight

3.4.1.1 Glycolipids

Low-molecular-weight biosurfactants called glycolipids are extensively studied and come from waste materials such as industrial and olive oil residues, as well as hydrocarbons. They are made up of a hydrophobic portion with long fatty acid chains and a hydrophilic part containing carbohydrates like glucose, mannose, and galactose. By causing ion channels and pores to form in biological membranes, these molecules effectively combat bacteria, viruses, and fungi. Glycolipids also influence how different biotechnological processes use enzymes by varying their activities. They are used to moisturize and stop bacterial adhesion in cosmetics.

Rhamnolipids, trehalose lipids, sophorolipids, mannosylerythritol lipids, cellobiose lipids, monoacylglycerol, diglycosyl diglycerides, lipomannosyl-mannitols, galactosyl-diglyceride, lipoarabinomannanes, and lipomannans are among the particular kinds of glycolipid biosurfactants. Particularly rhamnolipids have attracted interest because of their quick production, high emulsifying indexes, low surface tension, and low critical micellar concentration (Thakur *et al*., 2021).

3.4.1.1.1 Rhamnolipids

Rhamnolipids are type of biosurfactants, which are naturally occurring compounds made of β-hydroxyalkanoic acid and rhamnose that have a well-defined structure. There are two primary forms of these biosurfactants: dirhamnolipids, which have two rhamnose units, and monorhamnolipids, which have one rhamnose unit. The hydrophilic characteristics are displayed in the rhamnose "head" that is linked to a hydrophobic "tail" that is made up of the acid residue. Rhamnolipids are mostly produced by Pseudomonas aeruginosa, although they can also be produced by other Pseudomonas species and other organisms. Effective natural anionic surfactants, rhamnolipids lower water's surface tension and aid in the solubilization of organic compounds. They interact with microbial cells by forming emulsions and changing the hydrophobicity of cell surfaces. Rhamnolipids are versatile for a variety of applications, including enhanced oil recovery, anti-corrosive actions, plant protection, stabilization of food products, medical applications, cosmetics, and pharmaceuticals. This is because they have antimicrobial qualities in addition to their surfactant properties. Interestingly, they are heavily involved in efforts to clean up the environment, especially in bioremediation.

Rhamnolipids have the potential to effectively address heavy metals as well as organic pollutants, including petroleum hydrocarbons, in the context of soil remediation.

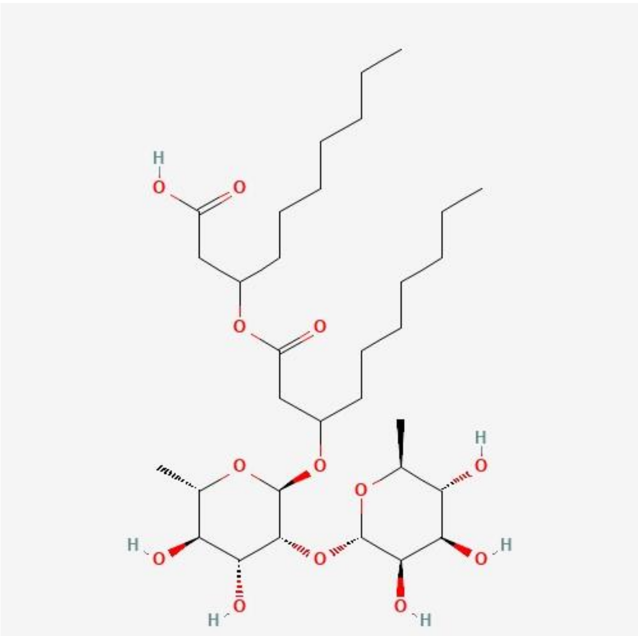

Fig.5: Chemical Structure of Rhamnolipids (PubChem, 2021)

Rhamnolipids improve the biodegradation of organic pollutants by making the pollutants more bioavailable to microorganisms. This is accomplished by the biosurfactant's solubilizing action, which mobilizes difficult-to-reach pollutants and encourages microorganisms to adhere directly to contaminants. Rhamnolipids help stabilize heavy metals by chelating the metals and reducing their mobility by preventing complex formation. On the other hand, soil flushing aims to remove particular metal ions under control by coordinating them with rhamnolipids. It's crucial to remember that research on rhamnolipids has been done in environments where contaminated soils contain both organic and inorganic pollutants (Parus *et al*., 2022).

3.4.1.1.2 Sophorolipids

When certain yeast strains are cultured on carbohydrates and lipophilic materials, they mainly produce sophorolipids. Disaccharide sophoroses, which are composed of two glucose molecules linked β glycosidically to the hydroxyl group at the penultimate carbon of fatty acids, are the most common form of these compounds. An anionic surfactant can be produced by hydrolyzing the terminal carboxyl group or by leaving it in the lactonic form. It has been demonstrated that both anionic and lactonic sophorolipids can lower surface and interfacial tension; however, lactone sophorolipids are superior to acid sophorolipids in their ability to lower water's surface tension.

Because of their wide range of biological activities, sophorolipids are used in cosmetics, pharmaceuticals, and the medical industry in addition to being effective at lowering surface tension. Although fermentation-derived sophorolipids are not commonly employed as emulsifiers due to their inability to stabilize water-in-oil emulsions, they can be transformed into a variety of derivatives with distinct hydrophilic-hydrophobic balances. These derivatives have a variety of functional qualities and surface activities, such as the ability to emulsify, wet, clean, and solubilize (Mnif *et al*.,2017).

3.4.1.1.3 Trehalolipids

Trehalolipids are a class of glycolipid biosurfactants with a variety of industrial uses, including food and cosmetic applications, microbial enhanced oil recovery (MEOR), and support for bioremediation. Additionally, their immunomodulatory and antitumor properties hold promise in the field of biomedicine. However, the low production yields, high recovery costs, and difficulty in isolating the product from the cells present obstacles to the commercialization of trehalolipids.

These biosurfactants are involved in adhesion to surfaces and the uptake of hydrophobic substances by Rhodococcus bacteria, which produce trehalolipids. This facilitates the cells access to water-insoluble substrates through adhering to emulsified oil (extracellular biosurfactant) or direct contact of hydrophobic cells with oil droplets (cell-bound biosurfactant). The type of substrate and the stage at which the cells are growing appear to have an impact on the mechanism at play. To increase production yields, scientists are actively investigating the behavior of Rhodococcus bacteria, which is known for aggregating and adhering to surfaces (Estopa *et al*.,2018).

3.4.1.1.4 Mannosylerythritol Lipids

Kinds of glycolipid biosurfactants are called mannosylerythritol lipids (MELs). They are composed of a water-repelling (hydrophobic) portion consisting of two fatty acyl groups and a water-attracting (hydrophilic) part composed of 4-O-β-D-mannopyranosyl-erythritol. When the concentration of MELs is at least 15 mg/L, they can reduce the surface tension of water. They are also effective under a variety of circumstances. They have a variety of biological functions and are recognized for being biocompatible. MELs have not been extensively embraced commercially despite these benefits.

The fact that chemically synthesized surfactants are already widely used for tasks like emulsification, cleaning, and wetting and are well-established and cost-effective across a range of industries, is one reason for the limited use of MELs. However, because these chemical surfactants are difficult to degrade, there are environmental concerns. MELs are viewed as viable substitutes for chemical surfactants, especially in sectors where environmental concerns are critical, like food, cosmetics, and agriculture.

The problem with MELs is that their fermentation processes are currently inefficient, which drives up their production costs relative to chemically synthesized surfactants. Despite this challenge, MELs are an intriguing subject for research as sustainable surfactant substitutes due to their many uses and favorable effects on the environment (Yang *et al*.,2023).

3.4.1.2 Lipopetides

Lipopeptide biosurfactants are a very interesting class of biosurfactants because of their wide range of uses. The two primary components of these molecules are an amide bond-connected short linear oligopeptide sequence and an acyl tail. A hydrocarbon chain makes up the acyl tail, whereas a peptide sequence with cationic and anionic residues as well as occasionally nonproteinaceous amino acids is found in the hydrophilic head.

One subclass of these biosurfactants, cyclic lipopeptides, performs exceptionally well in a variety of settings, including industry, environmental protection, and medicine. Their potential as antimicrobial and antitumor agents has been demonstrated. Lipopeptides are adaptable for application in a variety of contexts due to their structural diversity and functional characteristics.

The synthesis of lipopeptide surfactants is aided by the enzyme Non-ribosomal peptide synthetase (NRPS), which is produced by a variety of microbes. The goal of finding novel lipopeptides is to increase their applications across a range of industries. Based on their structure, lipopeptide surfactants are divided into several groups, with distinct D and L amino acid compositions found in different isoforms (Carolin *et al*., 2021).

3.4.1.2.1 Surfactin

A unique class of biosurfactant generated by Bacillus subtilis is called surfactin. This bacterium can produce endospores and is Gram-positive. Because surfactin is composed of seven amino acids joined to long-chain fatty acids to form a cyclic lactone ring structure, it is unlike other proteins. Surfactin is unique in that it remains stable in a broad range of temperatures and pH values, which makes it appropriate for a variety of cosmetic formulations. This biosurfactant has a reputation for being adaptable. It is acidic and dissolves in alkaline water, a variety of organic solvents, including butanol, ethanol, methanol, dichloromethane, and chloroform, as well as in water and oil mixtures. The hydrophilic-lipophilic balance (HLB) of surfactin is 10–12. Surfactin is an efficient surface-active agent because, at the same concentration, it has a lower surface tension than sodium lauryl sulphate (SLS), a common synthetic surfactant.

Surfactin is a mixture of isoforms with a molecular weight that ranges from 1007 to 1035 Da. The amphiphilic nature of surfactin is attributed to its distinct structure, particularly the particular arrangement of amino acids such as leucine, which makes it an effective surfactant. Surfactin has a wide range of uses in the environmental, cosmetic, and medical domains. It demonstrates a range of biological activities, including blocking the conversion of fibrin monomer to fibrin polymer, which delays the formation of fibrin clots. Surfactin has shown antimycoplasmal, antibacterial, antiviral, antiadhesive, anti-inflammatory, and even anticancer qualities in therapeutic applications. The way surfactin interacts with target cell membranes is thought to be responsible for these effects (Ashtiani *et al*., 2020).

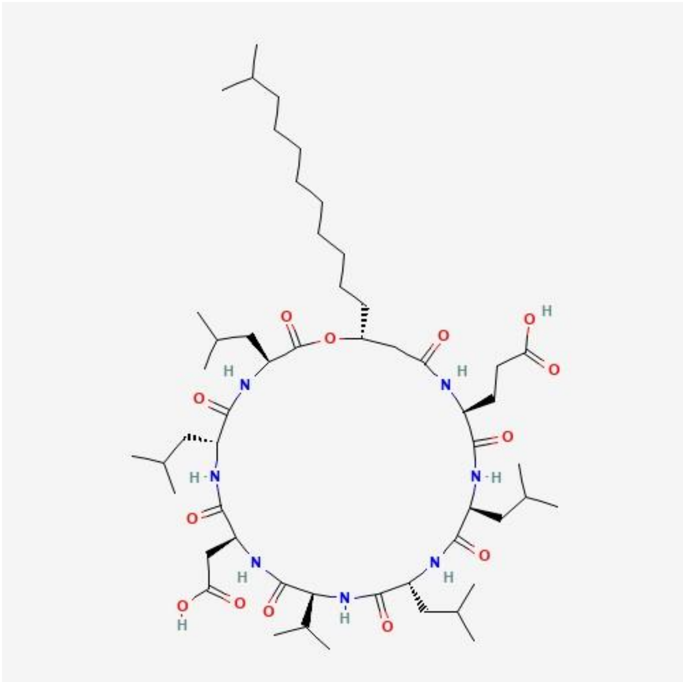

Fig.6: Chemical Structure of Surfactin (PubChem, 2005)

3.4.1.2.2 Lichenysin

One kind of cyclic lipoheptapeptide biosurfactant that Bacillus licheniformis produces is called lichenysin. Lichenysin A is the most common of the six varieties (lichenysin B, C, D, G, and surfactant BL86). These biosurfactants contain a β-hydroxy fatty acid with 12–17 carbon atoms and a peptide segment made up of seven amino acids. Because lichenysins contain residues of Glu and/or Asp, they function as anionic surfactants. A powerful surfactant, lichenysin, especially lichenysin A, can lower surface tension to 28.5 mM m−1 at a critical micelle concentration (CMC) of 15 mg L−1. With a molecular mass difference of just 1 Da, lichenysin A and surfactin are closely related. Its physicochemical characteristics are significantly impacted by this tiny variation, particularly in terms of surface tension reduction.

Under ideal circumstances, lichenysin B and BL86 have a very low CMC in comparison to other synthetic surfactants. These two lichenysins have the ability to lower water's surface tension. Lichenysins possess potent inhibitory effects on pathogenic strains' ability to form biofilms, as well as the ability to emulsify and permeabilize membranes via the colloid-osmotic process.

When synthesized by Bacillus licheniformis, lichenysin A exhibits slightly less antimicrobial activity than surfactin. When applied to different types of bacterial cells, native lichenysin A exhibits strong antibacterial activity. Furthermore, lichenysins' anti-inflammatory and antitumor properties have been emphasized by certain research. It is imperative to boost lichenysin production yield in order to facilitate large-scale application (Ashtiani *et al*., 2020).

3.4.1.2.3 Viscosin

One class of cyclic lipopeptide with surface-active characteristics is viscosin. It is made up of a nine-amino-acid peptide and hydroxydecanoic acid, which together form a lactone ring with seven amino acids. First identified in 1951 as an antimycobacterial agent in Pseudomonas viscosa, more recent studies have shown that Pseudomonas libanensis M9-3 produces it. Water surface tension is reduced by viscosin at a critical micelle concentration (CMC).

In the P. libanensis M9-3 investigation, a minimum surface tension can obtained at a CMC. Even at low concentrations, viscosin shows the ability to form stable emulsions in the finished product. Variations in purification techniques and measurement approaches may be the cause of discrepancies in reported CMC values amongst studies. To improve production yields and understand the mechanisms underlying Pseudomonas strains' production, more investigation is needed (Ashtiani *et al*., 2020).

3.4.1.2.4 Gramicidin

One kind of lipopeptide biosurfactant with antimicrobial qualities is gramicidin. Gramicidin A (80%), gramicidin B (6%), and gramicidin C (14%), which are all derived from the soil bacterium Bacillus brevis, make up this mixture.

Bacillus brevis is the source of the cyclo-symmetric decapeptide antibiotic known as Gramicidin S. Gramicidin S forms a rigid ring in a solution, with the hydrophobic side chains of other residues on one side and two positively charged ornithine side chains on the other. Gramicidin S is highly affinic for polyanions and negative surfaces, converting them into lipophilic structures. It's interesting to note that a molecule that can partition into organic solvents can form a stable coordination complex with two Gramicidin S molecules (Ashtiani *et al*.,2020).

3.4.1.2.5 Iturin Fengicin

Iturin's structure was first discovered in 1978, and it is a cyclic heptapeptide made up of seven amino acids. Bacillomycin L, along with its six other variants (iturin A and C, bacillomycin D, F, L, and mycosubtilin), is only produced by B. velezensis. The length of their hydrophobic tails (C14–C17) and the makeup of their amino acids are different in these variants. Tyrosine, Asparagine, Serine, Glutamine, Proline, Glutamate, and Threonine are the common structural elements of iturin. The amphiphilic nature of this lipopeptide implies that it has a preference for cellular membranes, which suggests a likely site of action. An amide bond forms between the first and last amino acids during cyclization. Iturins have limited antibacterial activity but strong antifungal activity against Penicillium expansum, Botrytis cinerea, and Alternaria alternate. While the lipopeptide exhibits strong surface activity and destabilizing effects, its hemolytic potential is lower than that of surfactins.

Decapeptide fengycin has a linear structure and a β-hydroxyl fatty acid chain (C14–C18). The phenol side chain of the third amino acid and the C-terminus of the tenth amino acid are where it goes through cyclization. Fengycin A and B have strong antifungal activity against filamentous fungi, and they were first found in B. subtilis. By preventing quorum sensing, they also lower the population of Staphylococcus aureus. Through direct interactions with lipid bilayers and sterol molecules, fungycin can change the structure and permeability of cell membranes. Plipastatin, a closely related lipopeptide that differs from fengycin in the positions of L- and D-tyros, was discovered (Carolin *et al*.,2021).

3.4.1.3 Fatty Acids

Biosurfactants like fatty acids and phospholipids can be produced by bacteria and fungi through microbial fermentations that use hydrophobic substances like n-alkanes. These substances are produced by microbial oxidation of alkanes. In the food industry, fatty acids long-chain aliphatic carboxylic acids are frequently utilized. On the other hand, bacteria like Thiobacillus thiooxidans and Acinetobacter spp. produce phospholipids, which are complex lipids that contain phosphoric acids, alcohol, fatty acids, and nitrogen bases.

Phospholipids are essential for maintaining the fluidity of cell membranes. The interior of the bilayer is made up of their hydrophilic head and hydrophobic tail. Phospholipids are produced in large quantities when bacteria or yeast are grown on alkane substrates. These phospholipids function as biosurfactants, as do fatty acids and neutral lipids. In this context, biosurfactants are substances that lower surface tension; in the process of breaking down hydrocarbons, microorganisms produce them. The food industry uses fatty acids, and because of their membrane-like characteristics, phospholipids are used in gene carrier systems. In these microbial processes, neutral lipids and particulate compounds can also be regarded as biosurfactants (Bose *et al*., 2023).

3.4.2 Biosurfactant with High Molecular Weight

EPS (exopolysaccharides), or high-molecular weight bio emulsifiers, are more complex than biosurfactants. They are made up of different combinations of proteins, lipoproteins, heteropolysaccharides, and lipopolysaccharides. In contrast to low-molecular weight biosurfactants, EPS molecules efficiently combine two liquids, like water and oil, that wouldn't normally mix. They do not, however, lessen surface tension as effectively EPS molecules firmly cling to dispersed hydrocarbons in oil-polluted environments, preventing oil droplets from aggregating and fragmenting. Emulsion stabilization is the term for this phenomenon, which is caused by the exposure of numerous reactive groups in EPS structures (Nikolova and Gutierrez, 2021).

3.4.2.1 Polymeric Biosurfactants

A wide range of industries rely heavily on polymeric biosurfactants because of their special qualities. These biosurfactants include, among others, polysaccharide-protein complexes, alasan, liposan, lipomannan, and emulsan.

Candida lipolytica produces the water-soluble molecule liposan, which is made up of 17% protein and 83% carbohydrates. This specific biosurfactant has adaptable characteristics and may find use in a variety of industries.

Emulsan is a complex compound mostly produced by Acinetobacter calcoaceticus. It is made up of three unbranched aminosugars in equal proportions: d-galactosamine, galactosaminouronic acid, and dideoxydiaminohexose, as well as a fatty acid chain with between 10 and 22 carbons. Emulsan, which has a molecular weight of approximately 1,000 kDa on average, is a useful emulsifier that can be used to create stable emulsions with different oils and hydrocarbons.

Produced by A. radioresistens, alasan is a strong emulsifier that is made up of proteins, polysaccharides, and alanine. The ability of this biosurfactant to form stable emulsions with various oil types and hydrocarbons has been demonstrated. Its emulsifying qualities are enhanced by its complex structure, which makes it useful in industrial processes.

Microorganisms such as Saccharomyces cerevisiae and Acinetobacter sp. produce glycoproteins known as mannoproteins, which belong to another class of polymeric biosurfactants. Mannoproteins, which are composed of proteins and carbohydrates, have strong emulsifying properties that enable them to form stable emulsions with a variety of oils and hydrocarbons. They are also antimicrobial, which makes them more applicable in a variety of environments.

In conclusion, a variety of functional qualities are provided by these polymeric biosurfactants, including liposan, emulsan, alasan, and mannoproteins, making them useful in industrial processes ranging from emulsion stabilization to antimicrobial applications. They are attractive options for many industries looking for efficient and sustainable surfactant solutions because of their distinct compositions and capabilities (Sharma *et al*.,2021).

3.4.2.2 Particulate Biosurfactant

Protein, lipopolysaccharide, and phospholipid make up purified vesicles. These constituents combine to create microemulsions. Biosurfactants are naturally occurring surface-active agents that can accumulate at various phase interfaces due to their hydrophilic (attracting water) and hydrophobic (repelling water) properties.

Generally, biosurfactants consist of a nonpolar tail made up of fatty acids and sometimes cyclic structures, with a simple polar head made up of substances like amino acids and peptides. Spherical biosurfactant vesicles are formed when these molecules are present in concentrations higher than their critical micelle concentration (CMC), demonstrating their distinct characteristics.

The ability of biosurfactants to effectively decrease the attachment of biofilm formers is one notable application. This characteristic is advantageous in a variety of situations where it is intended to prevent the formation of biofilms, such as in industrial and medical settings. Overall, biosurfactants' complex interplay between hydrophilic and hydrophobic constituents adds to their adaptable ability to modify interfacial characteristics and engage with biological systems (Ekambaram *et al*., 2022).

3.4.3 Biosurfactant Diversity and Surface Tension Reduction

Biosurfactant Type	Organism	Surface Tension Reduction (mN/m)	Reference
Rhamnolipids	Pseudomonas aeruginosa	27	(Amani *et al.*, 2013)
Sophorolipids	Torulopsis bombicola	32,4	(Imura, *et al.*, 2014)
Trehalolopids	Rhodococcus sp.	25	(Andreolli *et al.*, 2023)
Lipopetides	Bacillus licheniformis	28	(Yakimov *et al.*,1995)
Surfactin	Bacillus subtilis	27,7	(Liu *et al.*, 2015)
Viscosin	Pseudomonas fluorescens	25	(Laycock *et al.*, 1991)
Emulsan	Acinetobacter calcoaceticus	29,2 - 30	(Sadeghi *et al.*, 2023)
Liposan	Candida lipolytica	25	(Rufino *et al.*, 2014)

Tab.1 Value of Surface tension reduction from various Biosurfactants

Biosurfactants are important in industrial processes and environmental remediation because they lower surface tension. They are produced by a variety of microorganisms. The Tab.1 above demonstrate the differences in surface tension reduction capacities between low molecular weight and high molecular weight biosurfactants.

The ability of the low molecular weight biosurfactants to reduce surface tension varied. With a reduction of 32.4 mN/m, Sophorolipids showed the largest amount, closely followed by Lipopeptides (28 mN/m) and Surfactin (27.7 mN/m). Viscosin, Trehalolipids, and Rhamnolipids all showed significant surface tension reduction, with values between 25 and 27 mN/m.

High molecular weight biosurfactants, on the other hand, demonstrated competitive surface tension reduction abilities. Emulsan's effectiveness in lowering surface tension was demonstrated by its range of 29.2 - 30 mN/m surface reduction, which was produced by Acinetobacter calcoaceticus. Candida lipolytica's Liposan displayed a surface reduction of 25 mN/m, which was comparable.

The findings suggest that biosurfactants, irrespective of their molecular weight, demonstrate interesting capacities to mitigate surface tension. Depending on the needs of a particular application, low or high molecular weight biosurfactants may be chosen. Utilizing these biosurfactants to their full potential for a range of industrial and environmental applications can be facilitated by additional research and optimization.

3.5 Factor affecting Biosurfactant Production

Biosurfactants are essential for improving microbial access to insoluble substrates. They are generated either by excretion or by adhering to cells. By lowering surface tension between distinct phases, they facilitate the growth and metabolism of microorganisms by increasing the accessibility of hydrophobic substrates. It has been observed that there are a number of different uptake mechanisms, including direct uptake of dissolved hydrocarbons, contact with large hydrocarbon droplets, and interaction with emulsified droplets.

It is difficult to achieve the ideal yield of biosurfactants because of various factors that affect the growth and metabolism of microbes during production. Research has focused on determining the optimal substrate combination in a specified culture medium to promote intracellular diffusion and compound production. The choice of carbon and nitrogen sources, the concentration of lipophilic substrates, the availability of micronutrients, the size of the inoculum, temperature, pH, aeration, and agitation speed are important factors to take into account for the best biosurfactant production. Investigating the growth phase (stationary or exponential) that produces the maximum production rate is crucial.

Factors affecting microbial growth and metabolism during production make it difficult to achieve the ideal biosurfactant yield. A primary focus of research has been to determine the optimal substrate combination in a defined culture medium to promote intracellular diffusion and compound production. Choosing the right carbon and nitrogen sources, lipophilic substrate concentration, micronutrient availability, inoculum size, temperature, pH, aeration, and agitation speed are important factors to take into account for the best biosurfactant production. Investigating the growth phase either exponential or stationary that produces the greatest rate of production is crucial (Sarubbo *et al*., 2022).

3.5.1 Carbon Sources

The majority of microorganisms that make biosurfactants are heterotrophs, which means that their growth and metabolite production depend on consuming organic carbon sources. However, the preparation of the growth and production medium accounts for a sizable portion (30–40%) of the overall cost of producing biosurfactants. This expensive price highlights how crucial it is to identify more affordable feedstocks.

During cultivation, the rate at which microorganisms consume carbon regulates biomass and product formation. In the synthesis of biosurfactants, three primary carbon sources are frequently utilized: hydrocarbons, oils and fats, and carbohydrates. Simple sugars, starch, and plant-based sugars are the main carbon sources used in the production of biosurfactants within the carbohydrate category. For example, glucose is a common carbon source that microorganisms readily metabolize to produce energy via the glycolysis pathway, and it is frequently linked to increased yields of biosurfactants (Nurfarahin *et al*., 2018).

3.5.2 Nitrogen Source

Because it is essential for the growth of microorganisms and is required for the synthesis of both proteins and enzymes, nitrogen is a key component in the synthesis of biosurfactants. For the synthesis of biosurfactants, a variety of nitrogen compounds have been used, such as urea peptone, yeast extract, ammonium sulfate, ammonium nitrate, sodium nitrate, meat extract, and malt extracts. Although yeast extract is often utilized, the best concentration varies depending on the particular microorganism and culture medium. Arthrobacter paraffineus favors urea and ammonium salts as nitrogen sources for biosurfactant synthesis, whereas Pseudomonas aeruginosa uses nitrate to produce the greatest amount of surfactant (Fakruddin, 2012).

3.5.3 Salinity Factor

Ensuring the stability of biosurfactants produced by particular microorganisms requires optimizing the salinity of the culture medium. Sodium chloride, or NaCl, is commonly used to control the osmolarity of the growth medium in microbiological culture. Studies show that when the concentration of NaCl was set at 3%, the marine endosymbiotic fungus Aspergillus ustus (MSF3), which was isolated from the marine sponge Fasciospongia cavernosa, demonstrated the highest E24 index, outperforming other concentrations of NaCl utilized in the production medium.

Different NaCl concentrations had an impact on the growth of bacteria, including B. licheniformis. At 2% NaCl, the maximum reduction in surface tension and optimal growth were observed. When 8–10% NaCl was added to the production medium, Trichosporon asahii showed the highest E24 index among the yeast species.

Numerous studies have shown that bacteria can generally adapt to a narrow range of salt concentrations, usually not going above 5% (Nurfarahin *et al*.,2018).

3.5.4 Aeration and Agitation

By encouraging the transfer of oxygen from the air to the liquid phase, agitation and aeration are essential for increasing the production of biosurfactants. The physiological function of the microbial emulsifier is intimately associated with this process, indicating that the production of bioemulsifiers can enhance the solubilization of substances that are water-insoluble. Consequently, this makes it easier for microorganisms to receive nutrients. According to research, when the dissolved oxygen concentration was kept at 50% saturation and the air flow rate was 1 vvm, the best surfactant production (45.5 g/l) took place (Fakruddin, 2012).

3.6 How Biosurfactant work in EOR.

In contrast to chemically synthesized surfactants, biosurfactants have several advantages in a variety of industries, including metal processing, food, agriculture, medicine, and cosmetics. The petroleum industry finds them appealing, especially in Enhanced Oil Recovery (EOR) for upstream operations. Microorganisms generate biosurfactants, which are essential for Microbial EOR because they lower surface tensions and liberate trapped oil in reservoirs.

Biosurfactants are a cost-effective solution for enhanced oil recovery (EOR) because of their low toxicity, biodegradability, and compatibility. Biosurfactants offer a safe and affordable substitute for traditional surfactants, which are expensive and dangerous. Biosurfactants are a better option because of how easy it is to use microorganisms for oil recovery and because of their capacity to change the properties of the rock surface and lower the mobility ratio.

Biosurfactants have lower surface tension and good emulsification qualities. They are derived from renewable sources, such as bacterial metabolites. By adjusting the type of bacteria, growing medium, and incubation conditions, they can improve oil recovery in a variety of reservoir types, such as carbonate and sandstone, and they can adapt to different conditions. In situations involving heavy crude oil, microorganisms injected into reservoirs can enhance oil quality, break down heavy constituents, and speed up the production of biosurfactants in situ.Microorganisms also help the environment by removing heavy metals and sulfur from heavy oils. Because of their adaptability, biosurfactants can be used with bitumen and all classes of crude oil, including light, medium, and heavy crude oil. Interestingly, they help upgrade bitumen and heavy crude, something that other EOR techniques do not share.

Unlike traditional chemical surfactants, some classes of biosurfactants show good solubility in harsh environments, including strongly alkaline environments, high concentrations of minerals, and elevated temperatures. Economically speaking, biosurfactant-assisted EOR methods have low injection costs, easy facility setups, and minimal energy needs for microbial metabolism.

Over time, the continuous metabolic activities of microorganisms improve the efficiency of biosurfactants, generating a range of products and byproducts that simultaneously support multiple mechanisms of oil recovery. All things considered, using biosurfactants in EOR is an environmentally sound, economical, and sustainable approach (Bera *et al*.,2021).

3.7 Eco-Friendly approach to Biosurfactant production

The adoption of sustainable production practices has gained prominence in recent decades, with the goal of striking a balance between resource conservation and economic benefits while minimizing environmental impact. Many studies concentrate on the cost-effectiveness of raw materials when assessing the production of biosurfactants through a life cycle assessment (LCA), which takes into account the entire process from resource extraction to product delivery. A thorough LCA should, however, also take into account variables that differ between locations and make standardization more difficult, such as feedstock production, distribution, processing, and transportation.

Harmonizing life cycle assessment (LCA) methods for the production of biosurfactants presents challenges because different factors have different origins and non-renewable resources are involved. Utilizing waste feedstock has been shown in some studies to have a lower environmental impact; however, materials, enzymes, and electricity are still frequently derived from non-renewable sources. It is difficult to define precise limits for LCA factors, so guidelines are required to direct how inputs and outputs are taken into account. Utilizing waste products can reduce the cost of raw materials, but there are important considerations, including waste type, availability, stability, and purity. The total sustainability of biosurfactant production may be impacted by waste utilization, which may call for extra purification procedures. Emissions of greenhouse gases, energy use, input costs, and overall process costs are important metrics to track.

The goal of sustainable production methods is process optimization through lower costs, less undesirable outputs, or higher product yields. Notably, discussions about the production of biosurfactants frequently overlook social life cycle assessment in favor of concentrating on the economic and environmental effects. Therefore, in order to provide a more thorough understanding of its sustainability, more research on the social aspects of biosurfactant production is required (Manga *et al*., 2021).

3.8 The Role of Biosurfactants in Social, Environmental and Industrial Sustainability

Comparing Social Life Cycle Assessment (sLCA) to other components of the Life Cycle Sustainability Assessment (LCSA), it is a more recent and underdeveloped aspect. In order to guarantee compatibility with conventional LCA, the United Nations Environmental Program introduced sLCA guidelines that complied with ISO 14040/14044 standards. sLCA is a technique for assessing a product's social and socioeconomic aspects over the course of its life cycle, taking into account both positive and negative effects. Stakeholder engagement is integrated throughout, and it exhibits heightened awareness of shifting regional contexts. Nevertheless, the absence of defined protocols and standardized indicators in sLCA limits its ability to effectively address the social aspects of sustainability.

Population growth has caused socioeconomic changes that have accelerated industrialization and raised the use of different chemicals in common products. Synthetic chemical additives are frequently used to address health needs and food security for a growing population, but there may be toxicity risks associated with them. Biosurfactants present themselves as alternatives due to their reduced toxicity and potential for sustainable applications. For widespread use, however, issues like obtaining high-purity products and the requirement for additional in vitro research on their effectiveness and safe concentrations need to be resolved. Environmental pollution is a result of an increase in the amount of organic and inorganic waste that is released into the environment as a result of industrial activity. Because of their structural adaptability, biosurfactants can bind to pollutants and increase their availability for biological activity or make their removal easier. To guarantee a beneficial overall impact, a comprehensive assessment of the biosurfactant value chains' overall environmental impact is necessary.

When evaluating the environmental sustainability of biosurfactant production, life cycle assessment, or LCA, is essential. Throughout the course of the product life cycle, the environmental effects including air pollutants and energy requirements are examined. For instance, a more sustainable method for producing biosurfactants from oil wastes is to use a consortium. However, there is a dearth of knowledge and a need for more research regarding the environmental effects of the various steps in the biosurfactant value chain, such as feedstock production and transportation. A key component of sustainability is total life cycle cost (LCC), which focuses on all costs directly incurred by participants in the product system. It consists of capital costs, transportation costs, waste management costs, fixed operating costs, and end-of-life disposal costs. A comprehensive study promoting a circular bioeconomy should incorporate the cradle-to-cradle approach, which emphasizes a closed-loop system from raw material to end product.

Solid-State Fermentation (SSF) is one sustainable technology that can be used to produce high-value biosurfactants from a variety of industrial wastes, including food and agriculture. This waste utilization addresses social and environmental issues in line with the objectives of a sustainable bioeconomy.

In order to create sustainable bioeconomies, biosurfactants are essential to the mining, petroleum, textile, paper, and agricultural sectors as well as industrial waste management. Comparable to the circular economy framework, industrial symbiosis integrates wastes or byproducts from one industry into another's operations to minimize resource waste and ecological footprints.

To sum up, the implementation of sustainable practices and biosurfactants in diverse industries has the potential to tackle environmental and social issues, support the global development agenda, and facilitate the shift towards circular and bio-based economies (Manga *et al*., 2021).

3.9 Methods and mechanisms of oil recovery by Biosurfactants

The in situ method involves the direct injection of microbes into the oil reservoir or the stimulation of naturally occurring bacteria under reservoir conditions. These microorganisms produce biosurfactants, organic solvents, acids, biomass, or gases following a shut-in phase and water flooding. By lowering tension, changing wettability, breaking down oil, creating emulsions, and regulating mobility, these chemicals aid in oil recovery. A sustained process is ensured by the microbes' continuous growth, and the chemicals they produce have the ability to restore near-wellbore permeability.

The ex situ approach, on the other hand, entails creating microbial products outside of the reservoir. Biological processes are used to create various substances, including biosurfactants. Subsequently, a mixture of chosen products and injecting fluid is added to the reservoir. Although this approach offers improved control and optimization in the laboratory, it may encounter difficulties with adsorption, salt tolerance, and reservoir stability.

In situ technology is thought to be economical and effective, with successful field, pilot, and lab applications. Although surface bioreactors are not necessary, it is important to have ideal reservoir conditions. It may result in the unintentional growth of some bacteria, which presents difficulties. Ex situ has proven successful in the lab, providing chances for control and optimization. Large bioreactor installations, however, raise capital costs and compromise their economic viability. Each approach has advantages and disadvantages, and the decision is based on the particular reservoir as well as financial factors (Bera *et al*., 2021).

3.10 Summary

Microorganisms such as bacteria and fungi produce chemical compounds called biosurfactants, which have parts that are both hydrophobic (repelling water) and hydrophilic (attracting water). Their special power lies in their capacity to reduce surface tension and make immiscible liquids easier to mix. Biosurfactants, with advantages like reduced toxicity, increased biodegradability, and selectivity, are more environmentally friendly than traditional petroleum-derived surfactants. They have a wide range of uses and are made from renewable resources, especially in the petroleum industry for jobs like enhanced oil recovery (EOR) and oil spill cleanup.

Biosurfactants are categorized according to the microbial production and their chemical makeup. Glycolipids, which include rhamnolipids, are one well-known kind that have proven useful in a number of applications. Produced by microorganisms such as Pseudomonas aeruginosa, rhamnolipids have been studied for their potential role in bioremediation, particularly in the removal of organic pollutants and heavy metals from soil. They also exhibit antimicrobial properties.

Lipopeptides, which include surfactin and lichenysin as examples, are another class of biosurfactants. These surfactants are appropriate for use in a variety of industries, such as cosmetics, pharmaceuticals, and environmental cleanup, because they exhibit stability and surface activity in a wide range of environmental conditions.

Produced by Bacillus velezensis, iturin is a biosurfactant with antifungal properties that can be used in agriculture to stop the growth of harmful fungus. Furthermore, mannoproteins, trehalolipids, and other glycolipids add to the variety of biosurfactants and may find application in the pharmaceutical, cosmetic, and food sectors.

Exopolysaccharides (EPS), a type of polymeric biosurfactant, have special properties that allow them to stabilize emulsions in environments contaminated with oil. These high-molecular-weight compounds' emulsifying qualities make them essential to many different industries. Polymeric biosurfactants, such as alasan, emulsan, and liposan, have a wide range of applications. Biosurfactants are a desirable substitute for synthetic surfactants due to their low toxicity and biodegradability, among other environmental advantages. To improve their economic viability, though, issues like restricted industrial-scale production and the requirement for more affordable synthesis methods must be resolved. Research is still being done to find new biosurfactants, improve fermentation and recovery processes, and use inexpensive raw materials.

Because they reduce surface tension, biosurfactants are essential for improving microbial access to insoluble substrates and fostering microbial growth and metabolism. It is difficult to achieve the ideal biosurfactant yield because of various factors that impact microbial growth and metabolism in the production process. Finding the ideal substrate combination is emphasized by research, which takes into account factors like agitation speed, temperature, pH, aeration, inoculum size, micronutrients, substrate concentration, and carbon and nitrogen sources.

The selection of nitrogen compounds (urea, peptone, yeast extract) and carbon sources (hydrocarbons, oils, fats, and carbohydrates) has a major impact on the synthesis of biosurfactants. Sodium chloride affects microbial growth at different concentrations and controls the stability of biosurfactants. By promoting oxygen transfer, agitation and aeration are crucial for raising the production of biosurfactants.

Biosurfactants provide an economical, environmentally benign substitute for conventional surfactants in enhanced oil recovery (EOR) due to their low toxicity, biodegradability, and compatibility. They can upgrade bitumen and heavy crude and enhance oil recovery in a variety of reservoir types and conditions. Biosurfactant-assisted EOR techniques offer a sustainable and environmentally friendly solution due to their low energy requirements and cheap injection costs.

In order to produce biosurfactants in a sustainable manner, life cycle assessment (LCA), feedstock selection, waste utilization, and environmental impact must all be taken into account. Reducing environmental impact by using waste feedstock is possible, but there are obstacles to overcome, such as waste type, availability, stability, and purity. To fully evaluate sustainability, social life cycle assessment (sLCA) is still an underdeveloped field that needs more study.

With regard to toxicity, biosurfactants offer an alternative to artificial chemical additives. By attaching to contaminants and making it easier to remove them, they also support the sustainability of the environment. For the purpose of assessing sustainability, life cycle cost (LCC) analysis which takes into account capital expenses, transportation, waste management, and end-of-life disposal costs is essential.

In line with the objectives of a sustainable bioeconomy, solid-state fermentation (SSF) is a sustainable technology for producing biosurfactants from industrial wastes. The adoption of sustainable practices and biosurfactants in diverse industries can effectively tackle environmental and social concerns, thereby facilitating the transition towards circular and bio-based economies. While the ex situ strategy produces microbial products outside the reservoir, the in situ method for microbial EOR involves directly injecting microbes into oil reservoirs. Every approach has benefits and drawbacks, and the decision is based on the particular reservoir as well as budgetary constraints.

To sum up, biosurfactants are unique and adaptable substances that have a lot going for them in comparison to conventional surfactants. Their special qualities make them ideal for a variety of uses, from different industrial processes to environmental cleanup. Attempts to fully realize the potential of biosurfactants are being made in order to overcome obstacles that stand in the way of their widespread application in the twenty-first century. Let's sum up by saying that these substances are essential to microbial Enhanced Oil Recovery (EOR) and provide environmentally and socially viable solutions for a variety of industries through practices like waste utilization, sustainable production, and life cycle assessments. The decision between in situ and ex situ techniques in microbial EOR is based on reservoir characteristics and economic factors, which is in line with the global shift towards circular and bio-based economies.

4 Market Overview

4.1 Applications of Biosurfactants

Biosurfactants are used in many different industries. For example, they can be used to clean crude oil storage tanks and improve oil recovery by decreasing oil viscosity. Although their potential in Enhanced Oil Recovery (EOR) is still being investigated, their higher cost in comparison to chemical surfactants makes commercial adoption more difficult. But biosurfactants perform better than their chemical counterparts in a variety of applications because of their noteworthy environmental advantages, such as their lower toxicity and renewable source derivation (Wei *et al*., 2021). The hydrophobic character of biosurfactants' cell surfaces accounts for their unique characteristics. Because of their dual nature, these molecules are both hydrophilic and hydrophobic, which effectively lowers the surface tension that separates immiscible and miscible liquids. Because of their rapid and controlled inactivation and degradation capabilities, as well as their substrate selectivity, biosurfactants are useful in a variety of remediation technologies.

Biosurfactants are widely used in a wide range of industries, including food production, paint manufacturing, petrochemicals, medicine, textiles, pollution control, and the mediated biosynthesis of metallic nanoparticles (Ambaye, 2021). The vast range of uses for biosurfactants in the industrial product manufacturing sector are illustrated graphically in Fig.7 below.

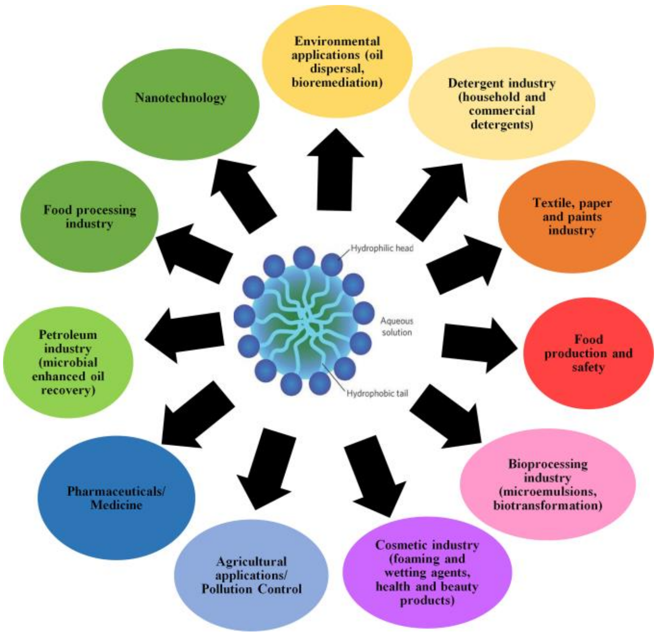

Fig.7: The summary of diverse applications of biosurfactants (Jimoh *et al*., 2019)

4.1.1 Application of Biosurfactan in Oil and Gas Industry

The oil and gas industry is the main user of biosurfactants, especially in the production of petroleum and the formulation of products derived from it. This covers their application in tasks like cleaning up oil spills both on land and at sea, emptying storage tanks of oil sludge, and enhancing oil recovery procedures. Emulsion polymerization, which uses biosurfactants to make paints, paper, and industrial coatings, is the second major market for these chemicals. Biosurfactants are also used in a number of other industries. They work in industrial cleaning procedures, the food industry, and the cosmetics industry. Biosurfactants are used in pesticides and to improve fertilizer and active compound penetration and dispersal into plants (Banat, 2000).

4.1.1.1 Microbial Enhanced Oil Recovery (MEOR)

By introducing microorganisms and their byproducts into mature oil reservoirs, a technique known as Microbial Enhanced Oil Recovery (MEOR) can recover more crude oil that was left over from the initial extraction processes. The idea depends on the reservoir's environment being conducive to the growth of introduced microbes and the mobilization of leftover oil by their byproducts. MEOR comes with different application processes, benefits, and drawbacks.

MEOR is based on two fundamental ideas. First, by changing interfacial properties decreasing interfacial tension (IFT) to improve displacement efficiency, reservoir pressure as a driving force, fluidity via techniques like miscible flooding, and sweep efficiency through selective plugging it makes oil movement through rock formations easier. The second principle deals with sulfur and heavy metal removal from heavy oils through microbial degradation. In the majority of MEOR field trials, injecting native or other appropriate pre-cultured bacteria with nutrients is the recommended approach. This is due to the reservoir's ability to produce biosurfactants by bacteria, which drastically lowers operating expenses. On the other hand, externally generated biosurfactants may also promote microbial development in oil reservoirs. Because biosurfactants low capillary forces that impede oil movement through rock pores, they improve recovery by lowering the interfacial tension between water and oil.

In order to be useful in MEOR, biosurfactants must lower IFT to at least 10 mN/m; for recognized biosurfactants, this value has not yet been published. Their usefulness might be impacted by this restriction. Additionally, the amount of biosurfactant needed for a significant recovery could be large and might not be practical or cost-effective given the type of oil reservoir, residual oil saturation, and targeted oil recovery rates. In addition to lowering IFT, biosurfactants also change the wettability of rocks, emulsify crude oil, and aid in the microbial metabolism of viscous oil (Nikolova and Gutierrez, 2021).

4.1.1.2 Crude Oil Transportation by Pipeline

Long-distance transportation of crude oil from extraction sites to refineries presents difficulties, particularly when handling heavy and extra-heavy crude oil. These difficulties arise from heavy crude oil's high viscosity and asphaltene content, which can cause paraffin, and asphaltene deposition as well as a drop in pressure that can clog pipelines. When heavy crude oil is exposed to ferric ions and acidic environments, it can solidify into deposits known as "asphaltene mud" in metal pipelines, which can impede the oil's ability to flow freely. To solve this, asphaltene mud is dissolved using solvents like toluene and xylene; however, this method raises production costs and produces toxic waste. A new technology that creates a stable oil-in-water emulsion to improve oil mobility is a promising remedy. This technology makes use of emulsifiers that are based on biosurfactants, more precisely bio emulsifiers. Emulsan and other bio emulsifiers are distinct from conventional surfactants and possess special qualities. They are excellent at stabilizing oil-in-water emulsions, but they might not be as good at lowering interfacial tensions. Because bio emulsifiers have a lot of reactive groups, they attach themselves tightly to oil droplets and form a barrier that keeps the droplets from coalescing. Among the powerful bio emulsifiers with potential uses in the petroleum industry is emulsan, which can be used to form heavy oil-water emulsions and lower viscosity during pipeline transport. Compared to conventional techniques, this alternate strategy might be more advantageous in terms of efficiency and environmental impact (Da Silva *et al*.,2014).

4.1.1.3 Cleaning Procedure for Oil Storage Tanks

Large amounts of crude oil are shipped to refineries every day and kept in tanks. Cleaning these tanks on a regular basis is required for maintenance. One problem, though, is the buildup of waste and heavy oil residues on the bottom and walls of the tank. Because of their high viscosity and tendency to solidify, these residues are difficult to remove using conventional pumping techniques. Conventional cleaning is a risky, costly, and time-consuming procedure that requires the use of solvents and manual labor. Hot water spraying, solvent liquefaction, and waste disposal on land afterward are some of the techniques. A different cleaning strategy is to apply microbial biosurfactants. Through the creation of an oil-in-water emulsion, this technique seeks to lower the viscosity of sludge and oil deposits, facilitating the pumping out of the waste. Furthermore, when the emulsion breaks, this procedure makes crude oil recoverable. This substitute not only tackles the difficulties associated with traditional cleaning techniques but also presents an opportunity for financial savings and an environmentally sustainable method (Da Silva *et al*.,2014).

4.1.1.4 Biosurfactant solution for Marine Oil spill cleanup

Unfortunately, because of the way that oil is transported and used, even the largest oil reservoirs the oceans are vulnerable to large-scale oil spills. Three types of traditional techniques are used to deal with these spills: chemical, biological, and physical/mechanical. While biological methods rely on natural processes for remediation, physical methods contain and collect oil using booms and skimmers. Chemical techniques use agents such as dispersants to fragment oil into tiny particles and hasten the process of natural deterioration.
Despite their effectiveness, chemical dispersants have disadvantages. The need for environmentally friendly alternatives is highlighted by the fact that they can be toxic to marine life and are not readily biodegradable. Natural substances made by microorganisms called biosurfactants present a promising remedy. Extreme temperatures and high salinity don't affect these substances' stability. Biosurfactants promote the biodegradation of hydrocarbons in oil-contaminated environments by two different mechanisms. Firstly, they lower surface tension, which allows microorganisms to more easily access hydrophobic materials. Secondly, they engage in surface-level interactions with cells, altering membranes to improve hydrocarbon adherence while sparing the cells. Biosurfactants are a sustainable and efficient method of cleaning up oil spills because they encourage molecular rearrangements, lower surface tension, increase surface area, and improve the availability and degradability of oil (Filho *et al*., 2023).

4.1.1.5 Biosurfact in Oil Waste Treatment

Oily sludge is produced in large quantities during the extraction and refining processes in the oil and gas industry, which presents a significant disposal challenge. This sludge is a complex mixture of water, heavy metals, solid particles, and petroleum hydrocarbons. Various physical and chemical processes, such as solvent extraction, dewatering, incineration, and more, have been used worldwide to address this waste, which is a critical issue. But these techniques are often expensive and require sophisticated equipment.

There is increasing interest in biological approaches, especially those that use biosurfactants, to address these issues. Bacteria produce compounds called biosurfactants, which have a beneficial interaction with oil. In an effort to increase oil recovery, researchers have looked into the application of biosurfactants in the treatment of oily sludge. The management of large amounts of oily wastewater is another challenge facing the oil and gas industry.

Centrifugation, ultrafiltration, and flocculation are examples of physical and chemical procedures used in traditional separation technologies. Often, chemical coagulants are employed to improve the effectiveness of the oil-water separation process. Nonetheless, biosurfactants exhibit potential as dispersants or coagulants that can raise the efficiency of these separation methods. In a pilot study, for instance, the addition of biosurfactants improved the dissolved air flotation method's ability to extract emulsified oil products from water, increasing the separation efficiency from 80.0% to 98.0% (Almeida *et al*.,2016).

4.1.2 Application of Biosurfactant in other Industries

In addition to being used in agriculture, environmental cleanup, and petroleum, biosurfactants are applied in a wide range of industries. They have antimicrobial, anticancer, anti-adhesive, immunological adjuvant, antiviral, and gene delivery qualities in the medical field. In the food business, biosurfactants are essential because they function as foaming agents, adhesives, emulsifiers, stabilizers, and antimicrobials. The need for sustainable solutions and environmental concerns is driving up the demand for biosurfactants in household and personal care products, such as laundry detergents and cosmetics. Products for the home and personal hygiene account for more than 60% of the use of biosurfactants, with industrial cleaners and petroleum biotechnology applications coming in second and third (Fenibo *et al*., 2019).

4.1.2.1 Application of Biosurfactant in Agriculture

In many agricultural applications, especially in the production of plants and farm animals, biosurfactants are essential. Natural substances with minimal environmental effect are called biosurfactants, and their high digestibility, low toxicity, and biodegradability make them superior to synthetic alternatives.

Biosurfactants such as plant-derived alkyl polyglucosides (APG) are used in farm animal production to improve nutritional aspects. APG has been demonstrated to have a positive effect on ruminant physiological and production parameters by boosting microbial protein synthesis in the rumen and improving the organic matter's digestibility. APG may also have a positive effect on the rumen microbiota, fostering a favorable environment.

Similar to APG, microbial biosurfactants exhibit higher rates of organic matter degradation and enzymatic activity, such as rhamnolipid. Through the use of particular additives or yeast cultures, biosurfactants can be added to animal diets to enhance the digestibility of fats and oils. This is an affordable way to raise the energy content of animal feed.

Biosurfactants may find use in growth promotion and seed protection in addition to animal nutrition. For example, lysophospholipids (LPs) and rhamnolipids are useful in agriculture because they have shown efficacy against plant pathogens. In particular, rhamnolipids have demonstrated potential as fungicides, biopesticides, and agents against pathogenic spores due to their ability to disrupt cell membranes (Naughton *et al*., 2019).

4.1.2.2 Application of Biosurfactant in Food Industry

Growing interest has been seen in the use of biosurfactants in food applications in recent years. The desire for sustainably produced and vegetarian/vegan food items among consumers is the driving force behind this. Derived from microorganisms classified as Generally Regarded as Safe (GRAS), biosurfactants provide a number of advantages without endangering health. They can improve food formulations through viscosity and texture modifications, stop the growth of dangerous microorganisms, and increase food safety, quality, and shelf life.

Some biosurfactants also function as antioxidants, preventing oxidative damage and maintaining their stability under a range of temperature, acidity, and alkalinity conditions. Due to their emulsification, surfactant, antimicrobial, and antioxidant qualities, a number of biosurfactants produced by microorganisms such as Saccharomyces cerevisiae, Meyerozyma guilliermondii, C. lipolytica, C. utilis, and Starmerella bombicola show promise.

Due to their low toxicity, these microbial surfactants complement consumer preferences for food that is higher in naturally occurring substances and lower in chemically synthesized ones. Biosurfactants have the potential to take the place of food additives, which when taken in excess can have long-term negative health effects. Notably, applications in ice cream, salad dressings, flavoring oils, and bakery goods (like bread, cakes, cookies, and muffins) have been investigated. To guarantee their efficient operation in intricate food matrices under various processing circumstances, more research is necessary. The goal of strategies should be to use these biomolecules at the lowest effective concentrations possible to make their application economically feasible (Sarubbo *et al.*, 2022).

4.1.2.3 Biosurfactant solution for Heavy Metal Remediation

Hazardous pollutants that are difficult to degrade are known as heavy metals. Nevertheless, biosurfactants a unique class of compounds have the potential to effectively remove these harmful heavy metals. They employ a number of techniques, including complexation, emulsification, mobilization, and solubilization, to achieve this.Through a variety of processes, including ion exchange, precipitation, counter-ion binding, and electrostatic interactions, these biosurfactants interact with metal ions to form complexes. A number of variables that impact the stability and availability of heavy metal ions, including pH, temperature, and redox potential, determine how effective these processes are.

Forming complexes with heavy metals, which lowers their activity in the solution and causes them to separate from contaminated soils, is one of the main ways biosurfactants function. The biosurfactant and the metal ions on the soil's surface interact directly in this process. While cationic biosurfactants work well against negatively charged heavy metal ions, anionic biosurfactants have a strong affinity for positively charged ions.

Biosurfactants' carboxyl, hydroxyl, and amino groups are among the chemical groups that contribute to their ability to bind with metal pollutants. By encouraging the formation of micelles, the lower surface tension of biosurfactants aids in the removal of heavy metals from soil. The heavy metals become more soluble and mobile when these micelles bind with oppositely charged metal ions, which facilitates the heavy metals' removal from the soil (Mishra *et al.*, 2021).

4.1.2.4 Application of Biosurfactant in Cosmetic Industry

The beauty industry has changed as a result, focusing on creating cosmetics with fewer hazardous ingredients, protecting the environment and public health, and encouraging ethically conducted procedures.

The use of surfactants in cosmetics and hygiene products is essential because they help create foams, emulsions, and cleaning qualities. But a lot of conventional surfactants come from petroleum, which is bad for the environment and for health. Biosurfactants are being investigated as a potential remedy, especially those originating from plants and microorganisms. Phospholipids, proteins, hydrolyzed proteins, and saponins are examples of plant-based surfactants that are gaining popularity. Saponins are widely distributed in the kingdom of plants and have shown promise in a variety of biotechnological applications due to their unique structure, which consists of a steroidal or triterpenoid aglycone linked to sugar molecules.Bio surfactants have garnered attention due to their historical use in prehistoric societies and the possibility of achieving higher extraction yields in comparison to microbial biosurfactants. Particularly saponins have shown a great deal of promise for use in skincare and cosmetic products like shampoos and conditioners. The wide range of activities, which include cleansing and anti-inflammatory qualities, are highlighted in several patents (Bezerra *et al*., 2021) .

4.1.2.5 Application of Biosurfactant in Pharmaceutical Industry

Biosurfactants have drawn a lot of interest from the pharmaceutical industry due to their wide range of uses, especially in drug delivery and research on antiviral and antibacterial properties. The study of biosurfactants as possible substitutes for controlling biofilms layers of microorganisms that can lead to a variety of problems has been the focus of recent research. It has been discovered that biosurfactants, particularly those generated by Gram-negative bacteria, alter the surface characteristics of bacterial cells, obstructing the formation of biofilms and preventing bacterial adhesion to surfaces. Another study used lipopeptide biosurfactants derived from Acinetobacter junii B6 to show improved wound healing in rats. The antioxidant qualities of the biosurfactants, which lessen oxidative stress by reducing the generation of reactive oxygen species and increasing free radical scavenging activities, may be responsible for the faster healing. Because lipopeptide biosurfactants contain fatty acid chains and peptide groups in their structure, they also show anticancer properties. Through processes including cellular differentiation, signal suppression, apoptosis induction, and cell cycle arrest, research has investigated their potential to impede tumor growth (Kashif *et al*., 2022).

4.1.2.6 Application of Biosurfactant in Detergent Industry

Products for personal hygiene, household cleaning, and heavy industrial cleaning are all included in the detergent market. Traditionally, the petrochemical sector particularly crude oil has provided the surfactant compounds used in these goods. The disinfectants that were widely used in personal and home care during the COVID-19 pandemic are difficult to biodegrade and may be hazardous to aquatic environments because they contain surfactants that are derived from crude oil. Biosurfactants, which provide a more environmentally friendly alternative to synthetic surfactants, are gaining popularity as a solution to these environmental issues. Since biosurfactants come from biological sources instead of petrochemicals, they are thought to be a promising commercial substitute. The demand for environmentally friendly products, particularly in the form of biodegradable detergents, is what is driving the shift towards biosurfactants. Because these detergents are made of organic compounds with a straight chain and no branches, microbiological degradation is facilitated effectively. One strategic way to improve detergent sustainability is to replace synthetic surfactants with "green" surfactants, like biosurfactants. These biosurfactants should ideally show efficacy in harsh environments, such as cold climates and hard water, in addition to cleaning. Highlighting the emulsifying ability of biosurfactants a critical characteristic for detergent activity makes them especially pertinent for use in laundry and detergent industries. To sum up, the industry is adopting biosurfactants as an efficient and eco-friendly substitute for conventional synthetic surfactants as a means of creating more sustainable detergents (Sarubbo *et al*., 2022).

4.2 Current Challenges and Opportunities

Because of their sustainable applications, biosurfactants are becoming more and more popular. There is room for cost-effective production while advancing environmental and social sustainability, according to research on sustainable production methods. In different stages of the product lifecycle, biosurfactants appear to be more sustainable than synthetic surfactants, according to recent studies employing Life Cycle Assessment (LCA) and sustainability assessment tools. Before being widely accepted, LCA evaluations for biosurfactant production must still be improved. In comparison to synthetic surfactants, the cost-effectiveness of biosurfactant production also needs to be improved. Further testing is necessary because the majority of biosurfactant research has been restricted to lab studies and field applications. Insufficient information results from a reluctance to use social, economic, and environmental life cycle assessment (LCA) tools to evaluate the sustainability of biosurfactants. This reluctance is a result of difficulties with LCA approaches, including feedstock type, regional variances, impact variables, and practitioner bias.

Biosurfactants have demonstrated safety in enhancing industrial processes, environmental sustainability, and human health in spite of these obstacles. Their characteristics, adaptability, and safety for the environment make them viable substitutes for synthetic surfactants. The need for biosurfactants is predicted to rise in the upcoming years due to pressure from all over the world to switch to sustainable processes, which makes them crucial for creating sustainable bioeconomies. Research should continue to address issues by concentrating on novel strains, overproduction tactics, enhanced production procedures, and the creation of uniform frameworks for sustainability assessments. To make biosurfactants more competitive in the market, researchers are urged to develop novel, affordable solutions, evaluate field performance, create standardized procedures, and enable large-scale application and testing (Manga *et al*., 2021).

4.3 Global Market of Biosurfactant

Because of their low toxicity, biodegradability, and other environmentally beneficial qualities, biosurfactants are becoming more and more well-liked on a global scale. With an anticipated 5.6% annual growth rate, the global biosurfactant market, which was valued at $4.20 billion in 2017, is projected to reach $5.52 billion by 2022. Numerous industries, including those in the personal care, home care, and environmentally conscious sectors, are exhibiting this growing demand.

Glycolipids are a class of biosurfactant whose high purity and functional qualities similar to rhamnolipids are expected to drive significant growth. Applications for biosurfactants can be found in personal hygiene, drugs, farming, food processing, and detergent production. Interestingly, because of their propensity to break down and eliminate hydrophobic materials in neutral environments, they are used extensively in the production of detergents.

Globally, there is a high demand for biosurfactants in the Middle East, Africa, North and South America, Asia Pacific, and Europe. Europe has emerged as a significant biosurfactant market due to growing consumer awareness of environmental issues. The production of biosurfactants faces difficulties despite the rising demand, such as high costs linked to low productivity, pricey raw materials, and less sophisticated purification technologies than chemical alternatives. Improvements to production procedures and a decrease in related expenses are required to guarantee the biosurfactant industry's continued expansion (Ambaye *et al*., 2021).

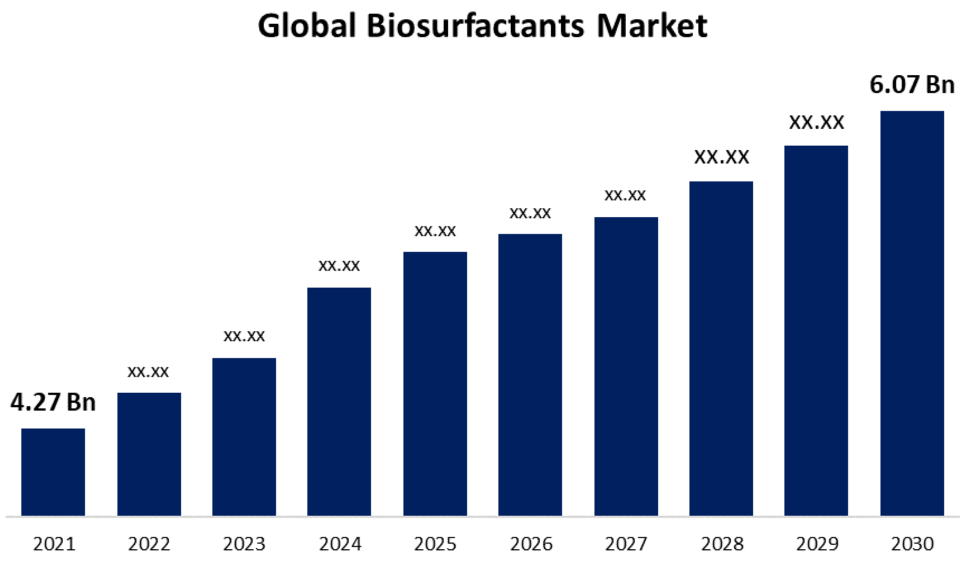

Fig. 8: Global Biosurfactants Market Insights Forecasts to 2030 (Spherical Insights, 2021)

According to Spherical Insights Fig.8 illustrated above, the global biosurfactants market is expected to grow at an average annual rate of 4.0% from 2021 to 2030, reaching $6.07 billion. Biosurfactants are in high demand due to their exceptional capacity to form stable liquid mixtures and their growing use in enhancing oil extraction, which is expected to increase crude oil production.

4.4 Summary

Biosurfactants, which are sourced from renewable resources, offer unique properties such as reduced toxicity and environmental benefits, which make them useful in a variety of industries. Biosurfactants are used in Microbial Enhanced Oil Recovery (MEOR) in the oil and gas industry to improve the extraction of crude oil, specifically by reducing interfacial tension and boosting microbial metabolism. They are also essential in the transportation of crude oil because they stop problems like pipeline asphaltene deposition. Additionally, biosurfactants provide an environmentally friendly way to clean oil storage tanks while facilitating effective waste disposal and crude oil recovery.Biosurfactants offer an environmentally friendly substitute for chemical dispersants in the cleanup of marine oil spills, thereby addressing environmental concerns. Furthermore, biosurfactants are essential to the treatment of oil waste because they make it easier to manage oily sludge by utilizing improved separation techniques.Biosurfactants are used in many different industries besides the oil and gas sector. They support animal nutrition, seed preservation, and growth promotion in agriculture. Biosurfactants provide better formulations, safety, and shelf life for the food industry. Moreover, biosurfactants provide solutions for heavy metal remediation; they are effective in the solubilization, emulsification, and complexation stages.

The cosmetics industry is investigating the potential of biosurfactants, especially those derived from plants, in skincare and cosmetic products. The increasing demand from consumers for sustainable and eco-friendly products is met by these natural substitutes. Within the pharmaceutical sector, biosurfactants demonstrate potential for use in wound healing and even have anticancer qualities. They also fight biofilm formation and aid in drug delivery.The detergent industry is moving away from synthetic surfactants made from crude oil and toward biosurfactants as a more environmentally friendly and sustainable alternative. Customer demand for biodegradable detergents with less of an adverse effect on the environment is what is driving this change. Despite the benefits biosurfactants have shown to have for the environment and human health, issues like cost-effectiveness and a lack of large-scale applications still exist. The demand for sustainable practices across a range of industries and rising environmental awareness are expected to fuel the global biosurfactant market's steady growth despite these obstacles. Ongoing research endeavors to augment their competitiveness by concentrating on innovative strains, economical production techniques, and uniform sustainability evaluations.

In summary, biosurfactants are becoming more and more popular around the world as environmentally friendly fixes for sustainable business practices.

5 The Future of Biosurfactants

5.1 Challenges for the Future

In many ways, biosurfactants are superior to chemical surfactants and have enormous potential for use in a variety of industrial and environmental applications. However, there are obstacles in the way of their widespread adoption, chief among them being high production costs, low yields, ineffective purification techniques, and high raw material costs. Biosurfactants have advantages over synthetic surfactants, but their production costs are approximately 10–12 times higher, which makes them less competitive in the market today.

The substrate is one of the main cost-factors, contributing half of the total production cost. The costs of raw materials, purification, and fermentation processes must be significantly reduced for biosurfactants to become commercially viable and displace their synthetic counterparts. Even though they are more expensive than conventional alternatives, biosurfactants may find use in the medical and cosmetics industries once these costs come down.

Researchers are looking into alternative production techniques, with an emphasis on using inexpensive raw materials, to improve cost-effectiveness. Furthermore, it is imperative to enhance the production process through the utilization of thermophilic and halophilic bacterial species that exhibit resilience against harsh environmental conditions. Techniques like recombination and mutation can be used to improve microbial species that can produce large amounts of food. Moreover, more economical, sustainable, and controllable biosurfactant production methods can be achieved by utilizing integrated systems for the concurrent production of biosurfactants and related products, utilizing statistical models for fermentation optimization, and integrating inexpensive and renewable substrates (Kanwal, 2022).

5.2 Towards greener technology and environmental sustainability

International agreements have been made to limit the rise in global temperatures, and efforts have been made to address greenhouse gas emissions on a global scale. Safer environmental regulations have been passed because of grassroots movements and raised public awareness that have sparked creative solutions to environmental problems. Growing awareness has accelerated the search for technologies to remove organic and inorganic pollutants from the environment.

Environmental pollution is associated with waste management, sustainability, and climate change. To counteract this, interest in using Biosurfactants has grown. In waste management, the "reuse, reduce, and recycle" approach has gained importance, highlighting the necessity of affordable Biosurfactants synthesis to address environmental concerns. Beyond the effects of climate change, other issues with environmental sustainability include pollution and the depletion of natural resources. The goal of the sustainability science focus is to use technology and science to advance sustainability across a range of industries. Biosurfactants have drawn attention due to their lower environmental impact and perceived friendliness when compared to chemical surfactants. They support the objective of striking a balance between environmental, economic, and social concerns for long-term sustainability and are essential in lowering carbon dioxide emissions.

Green technology has gained popularity as natural resources continue to be depleted. The phrase refers to eco-friendly technological solutions that protect the environment and its resources. Cleaner technologies are required because of air and water pollution, with an emphasis on smart energy to safeguard the future and avert environmental catastrophes.

Biosurfactants provide benefits over synthetic surfactants and lessen reliance on non-renewable petrochemicals, which promotes sustainability. They meet the requirements for a sustainable product because they are more effective, less toxic, durable, reusable, and biodegradable. Improved environmental laws, public awareness, and a dedication to eco-friendly solutions are what motivate more Biosurfactants research (Jimoh and Lin, 2019).

5.3 Nanotechnology Integration

One area of nanoscience and nanotechnology that is expanding quickly is the use of extremely small materials and structures, usually ranging in size from 1 to 100 nanometers. These minuscule substances exhibit considerable potential in tackling diverse issues related to solar energy harvesting, catalysis, medication, and water purification. The increasing need for these applications makes it imperative to implement "green" chemistry, or environmentally friendly synthesis techniques. This is in line with international efforts to reduce the production of hazardous waste by fusing environmentally friendly chemical processes with advances in science and business (Farias *et al*., 2014).

5.4 Microbial Nanoparticles Synthesis

There are several ways to create nanoparticles, including liquid-phase, gas-phase, and grinding methods. Commercially speaking, liquid-phase techniques especially chemical reduction are frequently employed. However, hazardous chemicals are frequently used in these procedures. On the other hand, more environmentally friendly methods use microorganisms for biosynthesis. One method makes use of fungi or bacteria that function as bio-reducing agents to produce an environment that is favorable for the synthesis of nanoparticles. Uncontrolled synthesis and the challenge of removing nanoparticles from microbial systems are among the difficulties this approach faces. Utilizing microorganism metabolites as stabilizers in the synthesis of nanoparticles, such as biosurfactants, is another environmentally friendly method. By adhering to the surface of the nanoparticles, biosurfactants inhibit their aggregation and modify their characteristics. Achieving the desired nanoparticle structures requires fine-tuning the synthesis procedure, taking into account variables like pH, temperature, and surfactant concentration. Glycolipids and lipopeptides are examples of biosurfactants that are important capping agents because they decrease nanoparticle agglomeration and improve dispersion in liquid media. All things considered, these green synthesis techniques provide advantageous and ecologically friendly substitutes with particular difficulties (Vecino *et al*., 2021).

Microorganisms such as algae, fungi, bacteria, and actinomycetes present exciting prospects in the field of nanotechnology, especially in the development of sustainable processes to produce metallic nanoparticles. The wide variety of microorganisms indicates that they have the innate ability to function as bio-factories for the synthesis of nanoparticles. To increase the synthesis rate and guarantee consistent product quality, however, a deeper comprehension of the biochemical and molecular mechanisms underlying the biosynthesis of metallic nanoparticles is essential.

Investigating how biosurfactants function in the biosynthesis process and how they affect the size, shape, dispersion, and characteristics of metallic nanoparticles is crucial to achieving this. Controlling the final nanoparticles' size, shape, and crystallinity requires an understanding of these mechanisms. Subsequent studies ought to concentrate on determining the ways in which biosurfactants affect the synthesis, resulting in the creation of nanoparticles with particular and advantageous characteristics (Plaza *et.al*., 2014).

5.5 Summary

Because biosurfactants are superior to chemical surfactants, they have substantial potential for a wide range of industrial and environmental applications. Nevertheless, obstacles like exorbitant manufacturing expenses, inadequate yields, and inadequate purification methods impede their extensive integration. With the substrate accounting for half of the total production cost, it is the primary cost factor. Efforts are being made to lower the costs of raw materials, purification, and fermentation processes.

Reserchers are investigating substitute methods of production, stressing the application of low-cost raw materials and hardy bacterial species. To improve cost-effectiveness, recombination, mutation, and integrated systems for concurrent production are being studied. Even though they are more expensive, biosurfactants might find use in the cosmetics and medical sectors once manufacturing costs go down.

Environmental regulations have become safer as a result of the global focus on reducing greenhouse gas emissions and raising the temperature limit. In waste management, biosurfactants have drawn attention because they support the "reuse, reduce, and recycle" strategy. By providing a reduced environmental impact and fostering a balance between social, economic, and environmental concerns, they aid in sustainability.

The depletion of natural resources has led to an increasing importance of green technology. Because they provide environmentally friendly alternatives, lessen dependency on non-renewable petrochemicals, and reduce carbon dioxide emissions, biosurfactants are essential for promoting sustainability. The expanding fields of nanotechnology and nanoscience are delving deeper into green synthesis methods, such as the synthesis of nanoparticles using microbes and biosurfactants.

Hazardous chemicals present a challenge in traditional methods of synthesizing nanoparticles, which are essential for applications in water purification, medication, solar energy, and catalysis. Microorganism-based environmentally friendly methods, especially those involving biosurfactants, appear promising. By acting as stabilizers, biosurfactants enhance dispersion and prevent nanoparticle aggregation. Optimizing synthesis parameters is crucial to attain the intended structures of nanoparticles.

Microorganisms such as actinomycetes, fungi, bacteria, and algae offer promising prospects for the synthesis of sustainable metallic nanoparticles in nanotechnology. In order to increase synthesis rates and guarantee consistent product quality, it is essential to comprehend the biochemical and molecular mechanisms underlying biosynthesis. Controlling these properties and advancing sustainable nanotechnology require further research into how biosurfactants affect the size, shape, dispersion, and characteristics of nanoparticles.

In conclusion, biosurfactants are positioned as promising agents for a more environmentally and financially viable future due to their potential benefits across a range of industries, ongoing research efforts to address production challenges, and their role in sustainable practices.

6 Conclusion

Research on biosurfactants and their various uses in various industries, especially for improving oil recovery (EOR), is a fascinating and fast-paced area. Several important themes have been highlighted by this thorough review.

First, it is highlighted how important biosurfactants are to EOR, particularly to microbial enhanced oil recovery (MEOR). Their distinct characteristics, like modifying the wettability of reservoir rock, diminishing interfacial tension, and augmenting microbial motility, render them indispensable instruments for optimizing oil recovery from subterranean reservoirs. The underlying mechanisms have been well studied, including their effects on metabolites and microbial adhesion.

Beyond this, biosurfactants are more environmentally friendly than their petrochemical counterparts. Because of their low toxicity, biodegradability, and renewable sources, they are positioned as sustainable alternatives that fit in with the global trend towards eco-friendly practices. Biosurfactants show promise not only for EOR but also for bioremediation, pharmaceuticals, cosmetics, and food production.

One important feature of biosurfactants is their versatility, as they can be derived from a variety of microorganisms and display a wide range of structures. Even though microbial biosurfactants, such as rhamnolipids, have been studied in great detail, investigating biosurfactants derived from plants provides new opportunities for investigation and potential uses.

Despite the apparent advantages, problems like yield problems and safety issues with specific kinds, like rhamnolipids, continue to exist. Growing corporate interest and ongoing research highlight biosurfactants' potential as affordable and environmentally friendly alternatives.

Examining biosurfactants in greater detail, particularly with regard to their capacity to increase oil recovery, demonstrates that their applications are not limited to the oil industry. These unique materials are excellent at decontaminating surfaces and producing environmentally friendly products. Biosurfactants are becoming more significant as regulations become more stringent and public concern for the environment increases. In order to fully realize their potential for creating a sustainable and eco-friendly future, ongoing research and innovation in this field are essential.

Within the broad field of biosurfactants, one can find sustainable solutions for various industries. Different classes, like lipopeptide biosurfactants and mannosylerythritol lipids, have unique properties and are used in everything from environmental protection to medicine. To stay competitive with surfactants made chemically, however, production scalability and cost-effectiveness issues must be addressed.

Conducting a life cycle analysis that takes into account social and economic factors emphasizes how important comprehensive assessments are when producing biosurfactants. Sustainable methods with the potential to improve social and environmental aspects include solid-state fermentation and the use of waste feedstocks. A comprehensive understanding of biosurfactant sustainability requires life cycle assessment methodologies, which take into account costs associated with raw materials, energy consumption, and societal impacts.

In EOR, biosurfactants show to be cost-effective and ecologically benign substitutes, potentially revolutionizing upstream operations. Their ability to adapt to different types of reservoirs, lower toxicity, and biodegradability make them important players in the pursuit of sustainable energy practices.

Biosurfactants are at the crossroads of innovation and sustainability, helping to create a future that is both ecologically friendly and more resilient. Biosurfactants are becoming more and more eco-friendly and adaptable in a variety of industries thanks to ongoing research that tackles production issues and enhances applications.

Biosurfactants show great promise across a wide range of industries as extremely adaptable and environmentally friendly materials. Their distinct attributes, such as their low toxicity, biodegradability, and renewable source, render them appealing for utilization in environmental remediation, pharmaceuticals, agriculture, nanotechnology, and enhanced oil recovery. Notwithstanding their advantages, obstacles like exorbitant manufacturing expenses and problems with purification prevent their widespread use.

Biosurfactants are still useful to the oil and gas industry for jobs like EOR, tank maintenance, and oil spill cleanup. Their capacity to tackle problems associated with the transportation of heavy crude oil suggests revolutionary opportunities for the industry.

Biosurfactants show great promise in environmental remediation, particularly in large-scale oil spills. They're useful tools for green cleaning methods because of their capacity to lower surface tension and promote microbial degradation.

The surfactant, antioxidant, and antimicrobial qualities of biosurfactants are advantageous to the pharmaceutical and cosmetic industries. Prospective directions for future application are opened by research on their possible uses in skincare, wound healing, and drug delivery.

Moreover, biosurfactants support growth promotion, seed protection, and animal nutrition in agriculture, demonstrating their versatility in promoting sustainability and efficiency.

Despite their potential, resolving concerns related to production costs and scalability is essential for wider commercial adoption. To get over these challenges, research into affordable raw materials, improved fermentation techniques, and alternative production methods is crucial.

Biosurfactants play a crucial role in meeting the growing global demand for sustainable and ecologically friendly solutions. Their backing of pollution prevention, carbon dioxide emission reduction, and eco-friendly technology is consistent with the more general objectives of sustainability and environmental preservation.

In conclusion, despite the difficulties that lie ahead, the future of biosurfactants in various industries seems bright. More research, ingenuity, and a dedication to eco-friendly practices are necessary to realize their full potential and make them the go-to solutions in a variety of applications.

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List of Abbreviation and Symbols

APG……………… Alkyl Polyglucosides

CMC……………… Critical Micelle Concentration

CO_2………………..Carbon dioxide

EOR………………..Enhanced Oil Recovery

EPS………………...Exopolysaccharides

GRAS……………...Generally Regarded as Safe

HLB………………..Hydrophilic Lipophilic Balance

IFT………………... Interfacial Tension

LCA………………..Life cycle assessment

LCC………………..Life Cycle Cost

LCSA………………Life Cycle Sustainability Assessment

LP…………………Lysophospholipids

MEOR……………..Microbial Enhanced Oil Recover

NRPS………………Non-ribosomal peptide synthetase

NaCl………………..Sodium Chloride

SLS………………....Sodium Lauryl Sulphate

sLCA……………… Social Life Cycle Assessment

SSF…………………Solid State Frérmentation