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Kartika Sharma
Editor

Bio-prospecting of Novel Microbial Bioactive Compounds for Sustainable Development

Management of Natural Resources Through Microbial Conversion into Valuable Products

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Editor
Kartika Sharma
Department of Biological Science
College of Basic Science
Bikaner, Rajasthan, India

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Preface

Microbes have been a valuable source of bioactive natural chemicals for over several years. Some of these compounds have been turned into medications to treat immune-system-related disorders, cancer, and infections. Novel compounds produced by microbes were traditionally found using traditional bioprospecting, which involved isolating possible producers and screening extracts from them using a range of bioassays. As a result of the discovery of the majority of the naturally occurring compounds identified by this method, the pipeline for novel medications derived from metabolites produced by microbes began to close.

The book *Bio-prospecting of Novel Microbial Bioactive Compounds for Sustainable Development: Management of Natural Resources Through Microbial Conversion into Valuable Products* covers recent advancements in the production of bioactive compounds, including therapeutics, pharmaceutical, biopesticides, enzymes, biosensors, biofertilizers, nutraceutical products. It offers a thorough understanding of how to use microbes or bioactive substances derived from microbes to create sustainable solutions. Additionally, the use of microbe-based goods in producing greener technology and controlling environmental pollution is highlighted. The book promotes the commercialization of bioactive substances obtained from microorganisms and their use in environmental protection research, agriculture, and the biochemical industries. The book also provides insightful information about the principles of microbial prospecting. Researchers, academics, and undergraduate and graduate students working in the field of microbial bioprospection of bioactive chemicals for conversion into useful products might use this as a reference book.

Bikaner, India — Kartika Sharma

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About the Editor

Dr. Kartika Sharma is Assistant Professor, Department of Biological Science, College of Basic Science, Bikaner, Rajasthan, India. Dr. Sharma completed her doctoral degree in Environmental Biology from Songkla University, Songkhla, Thailand, in 2023. Her specialization is bioactive compounds characterization and Heavy metal remediation. She is also working on the remediation of soil and water pollutants using recent technology like nanoparticles, biochar, etc. She has published more than 21 research articles in leading international and journals having high impact factors. She has received many awards and fellowships from different government organizations. She is involved in teaching and research and her area of research is plant and microbial biotechnology. She is an active reviewer for journals, including 3 Biotech, Chemosphere, Science of Total Environment, Gene, Journal of Hazardous Materials, PLoS One, etc.

Role of Microorganisms in Biosurfactant Production from Agricultural and Industrial Wastes

Asma Abid, Nour Elhouda Mekhadmi, Randa Mlik, and Kamilia Bireche

Abstract

Biosurfactants, characterized by their amphiphilic nature, are synthesized by a diverse array of microorganisms. These microorganisms possess the enzymatic capabilities to decompose complex organic molecules present in agricultural and industrial wastes. Through sophisticated fermentation and biodegradation processes, these substrates are converted into valuable biosurfactants. Agricultural residues, including crop remains, food processing by-products, and industrial effluents, serve as abundant feedstocks for microbial biosurfactant production. The resulting biosurfactants exhibit desirable properties such as biodegradability and low toxicity, making them highly suitable for various industrial applications. However, optimizing the production process remains challenging, necessitating careful consideration of factors such as microbial strain selection, fermentation conditions, and downstream processing. Continuous research is imperative to deepen our understanding of microbial metabolism and enhance bioprocess optimization, thereby promoting greater efficiency and sustainability in the production of biosurfactants from agricultural and industrial wastes. This chapter highlights the crucial role of microorganisms in converting agricultural and industrial wastes into biosurfactants, emphasizing the need for continued research to overcome production challenges and promote sustainable practices.

Keywords

Biosurfactants · Microorganisms · Agricultural wastes · Industrial wastes

1 Introduction

Surfactants are amphiphilic substances that lower the overall energy of a system by displacing high-energy bulk molecules at a contact. They possess a hydrophobic segment that has minimal attraction to the surrounding medium and a hydrophilic group that is drawn to the surrounding medium (Fig. 1). Surfactants have been employed in industrial applications for their sticky, flocculating, wetting, foaming, demulsifying, and penetrating properties (Abdel-Rahem, 2024). Biosurfactants, also known as tension-active biomolecules, are a type of surfactants biologically produced by various microorganisms. These include bacteria, filamentous fungi, yeast, and even some animals and plants (Ceresa et al., 2023). These compounds' amphiphilic characteristics and low molecular weight point to their genesis in microbes (Uzoigwe et al., 2015). To put it functionally, biosurfactants lower surface and interfacial tension by concentrating at water/air, oil/air, or oil/water interfaces. Although they have long been linked to hydrocarbon breakdown, new studies have revealed their broader functions in microbial physiology. Antibacterial and anticancer effects are among the therapeutic potentials of biosurfactants, which microbes make to alter cellular or environmental properties; these

A. Abid (✉) · K. Bireche
Laboratory of Valorization and Promotion of Saharan Resources (VPRS), Faculty of Mathematics and Matter Sciences, University of Ouargla, Ouargla, Algeria
e-mail: abid.asma@univ-ouargla.dz

N. E. Mekhadmi
Department of Biology, SNV Faculty, University of Chahid Hamma Lakhdar, El-Oued, Algeria

N. E. Mekhadmi
Laboratory of Biodiversity and Applications of Biotechnology in the Agriculture Field, University of Chahid Hamma Lakhdar, El-Oued, Algeria

R. Mlik
National Institute of Agronomic Research of Algeria, Adrar, Algeria

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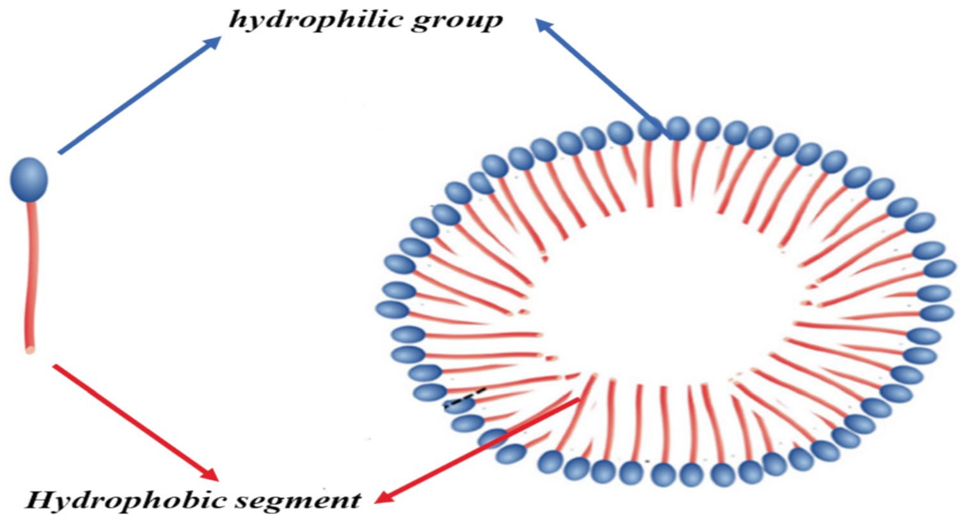

Fig. 1 The surfactant forms (hydrophobic segment and hydrophilic group)

biosurfactants are essential for microbial processes such as biofilm creation, cell motility, and fruiting body formation (Sharma et al., 2021).

With climate change and the increasing global population, pursuing innovative, efficient, and sustainable solutions is crucial. Biosurfactants from various microbes possess unique benefits compared to synthetic surfactants. These advantages include mild manufacturing conditions, adaptability, improved biodegradability, and minimized damage to living cells. Biosurfactants are in high demand due to their capacity to lower surface tension, stabilize emulsions, and biodegrade. They are widely used in diverse industries such as food, agriculture, and environmental restoration (Gayathiri et al., 2022). Furthermore, a wide variety of biosurfactants have the potential to be commercially produced and widely used in the pharmaceutical, cosmetics, and food industries. These biosurfactants are considered less environmentally harmful and have lower toxicity levels. Environmental microorganisms, especially in the rhizosphere and with plants, produce biosurfactants that aid mobility, communication, and biofilm formation. Thus, they profoundly affect plant-microorganism interactions. Biosurfactants eradicate plant diseases, boost beneficial microbial nutrient availability, and remediate agricultural soil (Das & Rao, 2024). According to Domínguez Rivera et al. (2019), biosurfactants made from agro-industrial wastes have advantages such as lower production costs, renewable materials, large-scale substrate production, product preservation, non-toxicity to microorganisms, and environmentally friendly constituents (Domínguez Rivera et al., 2019).

Biosurfactants' effectiveness and eco-friendliness make them highly sought after for use in biomedical and pharmaceutical applications. Due to their antioxidant, antibacterial, and anti-inflammatory qualities, they are appropriate for wound healing, immunomodulation, and medicine administration. However, the exorbitant manufacturing and purifying expenses hinder the extensive use of these chemicals. To address this issue, it is necessary to develop genetically modified strains that can create certain biosurfactants. Regulatory compliance and toxicity testing are required to ensure these strains' safe use. Although there are challenges, the engagement of key players in the market bodes well for biosurfactants in these industries (Ceresa et al., 2023).

The agro-industry generates lots of garbage with different qualities. The global agricultural wastes surpass 2 billion tonnes. Thus, exploring ways to exploit agro-industrial wastes better to maximize industry benefits is important. Inadequate handling of these waste materials negatively impacts the environment and the economic well-being of numerous countries. The current imperative is to develop effective and environmentally friendly waste management strategies. This involves two key aspects: firstly, the efficient transformation of wastes into valuable products and byproducts at reasonable treatment expenses, and secondly, evaluating the impact of these practices on soil quality and productivity (Singh et al., 2021). The literature discusses different types of wastes and byproducts resulting from agro-industrial processes utilized in biosurfactant production. These include wastes from oil processing, starch, sugar industry, fruits and vegetables, distilleries, animal fat, and petroleum byproducts. The utilization of industrial wastes offers several benefits, including cost reduction in production, increased availability of affordable and renewable substrates, large-scale substrate production, unchanged fundamental functional properties of the product, non-harmful nature of the product to microorganisms, and the eco-friendly and safe composition of all product components (Banat et al., 2014).

Historically, the predominant surfactants employed in industrial settings were derived from petrochemical sources.

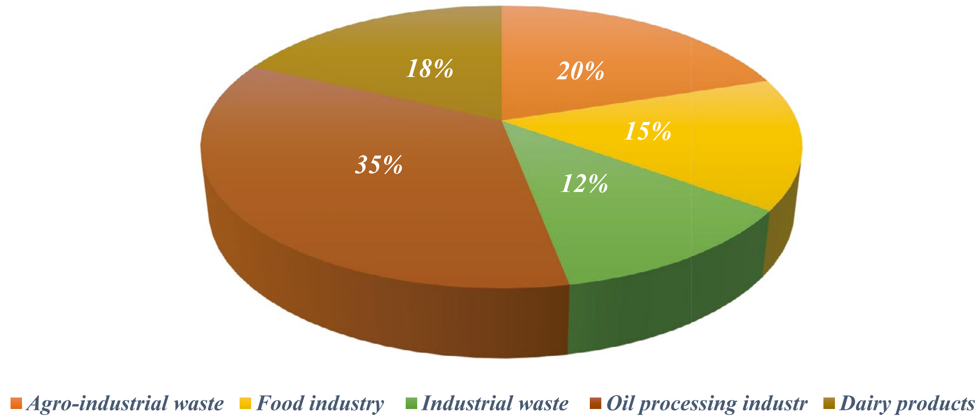

Fig. 2 The Contribution of different waste materials in biosurfactant production

However, these surfactants exhibit only partial biodegradability and toxicity towards living creatures, contributing to various environmental problems. In addition, the production of these items exhausts the Earth's finite petrochemical resources (Uzoigwe et al., 2015). The global output of synthetic surfactants surpasses 15 million tons annually (Fung et al., 2023), catering to diverse industrial sectors, including food processing, pharmaceuticals, cosmetics, detergent manufacturing, environmental cleanup (bioremediation), and enhanced oil recovery. In 2010, Reznik et al., (2010) published a study stating that the worldwide output of artificial surfactants reached 13 million tons in 2008. This production increased by 2% in 2009, resulting in annual revenue of US$2,433 billion. It was anticipated that the market would experience a consistent growth rate of 28% from 2009 to 2012, followed by an approximate increase of 3.5–4%. Nevertheless, numerous research studies have indicated that biosurfactants possess multiple advantages over petrochemical-based or synthetic surfactants. They demonstrate outstanding surface activity and emulsification characteristics while possessing little toxicity and enhanced biodegradability. They have high efficacy at low concentrations and can function well under various environmental circumstances, including pH, temperature, salinity, alkalinity, and acidity. Additional significant attributes of these biomolecules encompass enhanced environmental compatibility, reduced critical micelle concentration, heightened selectivity, specific activity, and the capacity to be synthesized from renewable, cost-effective resources (Rawat et al., 2020).

There has been a significant rise in the concern for environmental safety in recent years. The management of waste materials originating from diverse sources poses a formidable challenge. Utilizing garbage as a substrate for biosurfactant manufacturing offers a promising way to address wastes disposal issues (Yañez-Ocampo et al., 2017). Scientists have employed various waste products in varying amounts, as depicted in Fig. 2, to create biosurfactants for specific purposes. The distribution of waste sources is as follows: agro-industrial wastes account for 20%, the food industry contributes 15%, industrial wastes make up 12%, the oil processing industry is responsible for 35%, and dairy products contribute 18% (Jimoh & Lin, 2019).

In light of this, the chapter focuses on the considerable contribution that microorganisms make in the process of synthesizing biosurfactants from waste materials that are produced by industrial and agricultural processes.

2 Microbial Production of Biosurfactant

The dual nature of the biosurfactants, with both hydrophilic (water-loving) and hydrophobic (water-hating) regions, allows them to reduce surface tension at the interface between water and oil, making them valuable tools in various applications. Here's a closer look at the major types of biosurfactants produced by microbes. Different bacteria, yeast, and fungi species, especially those with filaments, create biosurfactants in varying quantities. They have roughly 60 distinct congeners and homologs. The primary category of microbes responsible for producing biosurfactants comprises *Pseudomonas* species, which were initially identified as producers of these secondary metabolites. *Acinetobacter sp., Arthrobacter sp., Bacillus sp.* and *Candida sp.* are more microbes that generate biosurfactants. It is commonly recognized that *Pseudomonas* species can create a wide range of bioactive metabolites on land and in the ocean (Abacha et al., 2016). Bhatnagar and Kim (2012) revealed that these unique bacteria generate around 800 bioactive compounds, the majority of which are antibiotic agents and others with a variety of other characteristics (Bhatnagar & Kim, 2012).

2.1 Bacterial Biosurfactant

Bacterial biosurfactants are amphiphilic compounds produced by various bacteria species like *Pseudomonas*, *Bacillus*, *Acinetobacter*, *Stenotrophomonas*, and *Burkholderia*, playing a crucial role in soil bioremediation by enhancing the degradation of hydrocarbons and heavy metals (Fardami et al., 2022). These biosurfactants exhibit excellent surface activity, emulsification properties, and biodegradability, making them environmentally friendly alternatives to chemical surfactants (Ingle, 2023). They are structurally diverse, including glycolipids, lipopeptides, fatty acids, and neutral lipids, with different functions and applications across industries like agriculture, petroleum, cosmetics, and medicine (Fatima et al., 2022). *Pseudomonas species*, known for producing rhamnolipids, have been studied for their effectiveness in cleaning applications and inhibiting pathogenic fungi like *Fusarium oxysporum*, showcasing the multifunctional properties of bacterial biosurfactants. Gaining a comprehensive understanding of the physiology, genetics, and biochemistry of strains that produce biosurfactants is crucial for improving production techniques and minimizing costs in many applications.

2.2 Biosurfactants Produced by Yeast

Yeast biosurfactants are popular due to their eco-friendliness and industrial applications. Yeasts like *Yarrowia lipolytica* and JAF-11 are effective biosurfactant makers, lowering surface tension and functioning as emulsifiers (Kim et al., 2023). These biosurfactants are attractive to pharmaceutical, food, cosmetic, and petrochemical industries because of their high biodegradability, low toxicity, and structural variety (Drumond de Souza et al., 2023). Screening, recovery, purification, and characterization methods are advancing to improve yeast-produced biosurfactant design, synthesis, and industrial use. Cleanly manufacturing biosurfactants using yeasts and low-cost substrates like agro-industrial byproducts should lower production costs and boost yields.

2.3 Biosurfactants Produced by Fungi

Fungal biosurfactants are used in pesticides, medicines, industrial materials, and environmental bioremediation (Drumond de Souza et al., 2023). These amphiphilic compounds with hydrophobic and hydrophilic moieties are biodegradable, low-toxic, and antibacterial, making them potential substitutes for chemically synthesized surfactants. Fungi, especially Candida species, produce biosurfactants with antibacterial, antifungal, antiviral, antiadhesion, and anticancer activities, making them useful in pharmaceutical and medicinal applications (Stainsby et al., 2022). Actinobacteria create biosurfactants with biomedical and environmental implications, particularly mycolic acid-containing *Rhodococcus*, *Corynebacterium*, *Dietzia*, *Gordonia*, and *Tsukamurella* (Galieva et al., 2023). Biosurfactants from *Bacillus* subtilis H1 can inhibit fungal plant diseases, suggesting biocontrol in agriculture (Fardami et al., 2022). Overall, fungal-produced biosurfactants are a valuable, ecologically benign resource with many industrial applications.

3 Classification of Biosurfactants

Biosurfactants are often categorized primarily by their chemical composition and microbial origin, in contrast to chemically synthesized surfactants, which are typically classified based on the type of their polar groups. In general, biosurfactants are divided into two groups: high and low-molecular-weight molecules. Glycolipids, lipopeptides, and phospholipids are examples of low-mass surfactants; polymeric and particulate surfactants are examples of high-mass surfactants, Table 1 summarizes the classification and the producing organism (Shoeb et al., 2013).

4 Biosurfactant Production Process

Carbon and nitrogen sources are essential factors in the production of these biosurfactants and greatly influence their cost of production, of which considerable efforts have been made to use sub-agro-industrial products and renewable resources as substrates in the production process. Studies have shown that using inexpensive substrates, such as raw materials or wastes, significantly affects biosurfactant production costs (Rawat et al., 2020). The different substrates from the wastes were used for the production of biosurfactants, especially the agricultural and industrial wastes. Figure 3 depicts the biosurfactant production process.

5 Factor Affecting on the Biosurfactant Production

The producer strain and the culture conditions impact the biosurfactant's composition and emulsifying activity. Therefore, the kind of polymer formed and the amount of biosurfactant produced are determined by various factors, including the carbon and nitrogen sources, their respective C:N ratios, dietary constraints, and chemical and physical

Table 1 Biosurfactants classification and the producing organism

	Class of Biosurfactant		Producing organism
Low molecular mass	Glycolipids	Rhamnoselipids	*Pseudomonas sp.*
		Trehalolipids	*Mycobacterium tuberculosis, Rhodococcus erythropolis*
	Lipopeptides	Corynomycolates	*Arthrobacter sp.*
		Surfactin Iturin Fengucin	*Bacillus licheniformis, Bacillus subtilis*
	Phospholipids and fatty acid	Spiculisporic acid Phosphatidylethanolamine Corynomycolic acid	*Penicillium spiculisporum, Acinetobacter sp., Rhodococcus erythropolis, Corynebacterium lepus*
High molecular mass	Polymeric	Emulsan Liposan Mannoprotein	*Acinetobacter calcoaceticus RAG-1* *Candida lipolytica* *Saccharomyces cerevisiae*
	Particulate surfactants	Vesicles Whole cells	*Acinetobacter ssp.* *Corynebacteria*

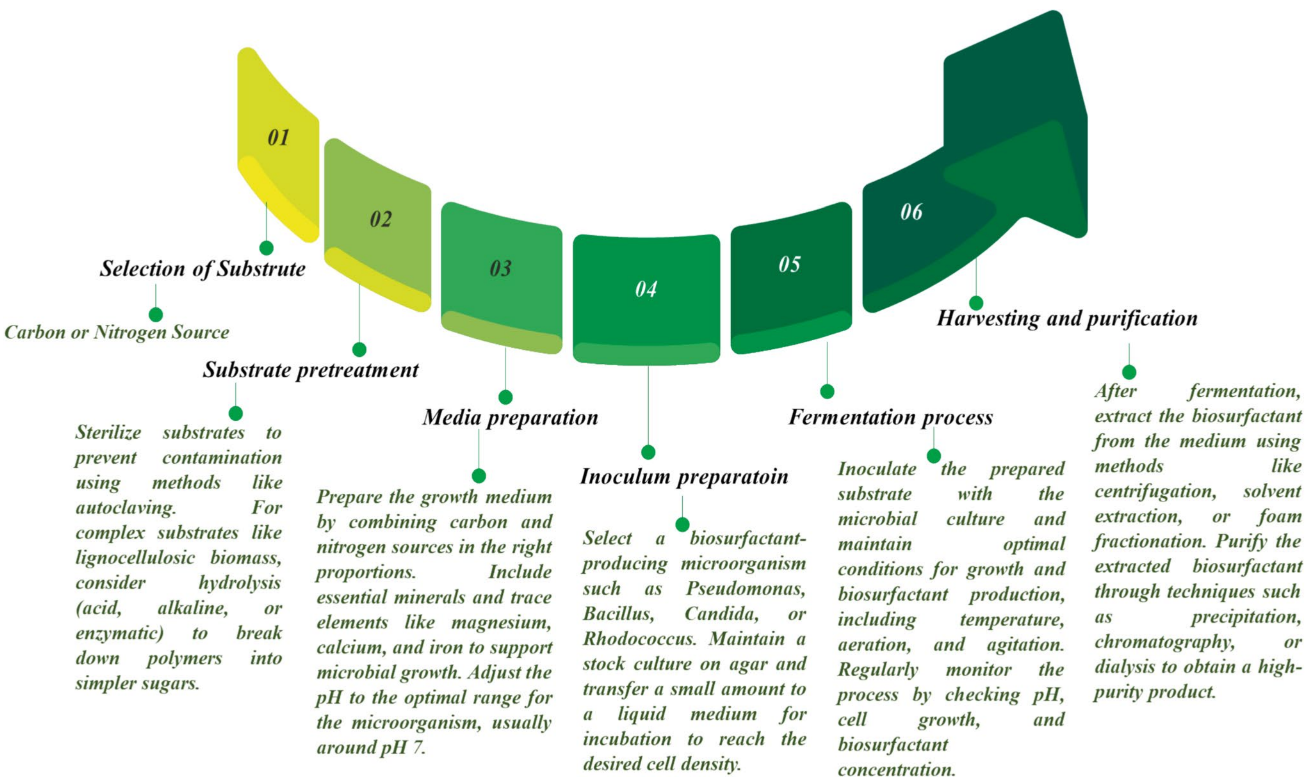

Fig. 3 Graphical depiction of biosurfactant production

characteristics, including pH, temperature, aeration, and divalent cations (2023b; Aslam et al., 2023a).

5.1 Carbon Sources

The nature of the carbon substrate influences and affects the quantity and quality of biosurfactant synthesis. We have already discussed the various carbon sources and how they affect the production of BSs. Several researchers have proposed using agro-industrial wastes as the primary source of carbohydrates to reduce production costs. According to reports, crude oil, diesel, glucose, sucrose, and glycerol are good sources of carbon substrate for the synthesis of biosurfactants (Jimoh & Lin, 2019).

5.2 Nitrogen Sources

Since protein and enzyme synthesis depend on nitrogen, it is critical for microbial development in the biosurfactant culture medium. Ammonium salts such as ammonium nitrate and ammonium sulphate, urea, peptones, meat and malt extract, yeast extract, and so on are examples of nitrogen sources. *Arthrobacter paraffineusprefers* ammonium salts and urea as nitrogen sources for biosurfactant synthesis, while *P. aeruginosa* produces the most significant amounts of surfactant when nitrate supplies nitrogen (Tripathi et al., 2019).

5.3 Environmental Factors

These significantly impact the yield and properties of the biosurfactant that is produced. It is always required to optimize the bioprocess to obtain significant quantities of biosurfactants since variations in temperature, pH, aeration, or agitation speed might alter the final product:

5.3.1 PH Factor

The growth of microbes and the fermentation of biosurfactants necessitate an optimal pH (Chen et al., 2018).

5.3.2 Temperature Factor

Temperature is a crucial environmental factor in the generation of biosurfactants. The development of each microorganism is linked to a specific temperature range, ideally between 25 and 30 °C. Both bacterial growth and carbohydrate fermentation require an optimal and carefully controlled temperature (Tripathi et al., 2019).

5.3.3 Agitation and Aeration Factor

In the case of the fermentation process, agitation is a crucial component since it affects a variety of processes, including the medium's viscosity, the growth of microorganisms' cells, and the distribution of heat, nutrients, and oxygen. Aeration, on the other hand, provides the oxygen gas required for fermentation and cell growth. It also lessens the amount of exhaust gases produced during the procedure. Adamczak and colleagues saw the highest production of BSs investigating how *C. antarctica* produces BSs. 50% of dissolved oxygen and a 1 vvm airflow rate were set as the parameters for the fermentation process. Because of the high foam formation 44, the increase in airflow rate suggested lower production of BSs. Wei and his colleagues 45 found that raising the agitation rate from 50 to 200 rpm boosted rhamnolipid production by about 80% and raised the rate of cell growth from 0.22 to 0.72 $h{-}^{1}$. They also found that microbial growth and rhamnolipid synthesis are positively impacted by increased dissolved oxygen levels (Wei et al., 2005).

6 Characterization of Biosurfactants

Various methods can be employed to discover biosurfactants, including haemolysis, axisymmetric drop shape analysis, rapid drop collapsing, colorimetry, and thin layer chromatography (Mouafo et al., 2023). Screening tests like surface tension measurement, emulsification index, oil displacement, drop collapse, and haemolysis are commonly used to detect biosurfactant activity. Techniques such as the hemolysis test, parafilm M test, lipase production test, CTAB agar plate method, and emulsification assay are routinely utilized for screening biosurfactant-producing strains (Alvionita et al., 2023). These diverse methods play a crucial role in identifying and studying the properties of biosurfactants.

The chemical characterization of purified biosurfactants involves various techniques to determine their structure and composition. The chemical nature of biosurfactants produced by diverse microbes has been studied using LC–MS, GCMS, FTIR, NMR, and thin-layer chromatography. (Mouafo et al., 2023). For example, LC–MS and GC–MS have identified glycolipids, whereas FTIR and NMR have confirmed biosurfactant chemical structures. Biosurfactants with lipopeptides have been analysed using thin-layer chromatography. Successful screening approaches such as oil spreading assay, blood agar hemolysis, emulsification assay, and foaming activity have identified biosurfactant-producing microorganisms in distinct strains. Biosurfactants are used in pharmaceuticals, detergents, and agriculture. Therefore, these methods help comprehend their molecular composition, functional groups, and structural features (Chauhan et al., 2022).

7 Properties of Biosurfactants

Microbial surfactants are characterized by their ability to travel across surfaces, withstand changes in pH, temperature, and ionic properties, degrade naturally, have minimal toxicity, possess emulsifying and demulsifying capabilities, and exhibit antimicrobial activity (Chandran & Das, 2010).

7.1 Surface and Interface Activity

Surfactants help decrease surface strain and interfacial pressure. *Pseudomonas aeruginosa* secretes rhamnolipids, which reduce the surface tension of water to 26 mN m^{-1} and the interfacial tension of water and hexadecane to less than 1 mN $m-^{1}$ (Chakrabarti, 2012). Biosurfactants have greater potency and efficacy and considerably lower Critical Micelle Concentration than chemical surfactants. A smaller quantity of biosurfactant is needed to achieve the highest possible decrease in surface tension (Chakrabarti, 2012).

7.2 Temperature and pH Tolerance

The utilization of extremophiles for the synthesis of biosurfactants has received considerable interest in recent years, owing to its significant potential for use in commercial settings. Several biosurfactants resist natural variables, such as temperature and pH, while maintaining their surface activity. The biosurfactant synthesized by *Arthrobacter protophormiae* exhibited stability throughout a wide range of temperatures (30–100 °C) and pH levels (2–12). Given the severe temperature, pH, and pressure conditions involved in industrial operations, it is essential to discover new microbial products that can perform well under these circumstances (Onyekonwu & Ogolo, 2010).

7.3 Biodegradability Property

Microbial-derived chemicals are more readily biodegradable than synthetic surfactants, which makes them well-suited for natural applications such as bioremediation and biosorption (Das & Mukherjee, 2007).

7.4 Low Toxicity Property

Although less research exists on the toxicity of biosurfactants, they are usually regarded as safe and suitable for use in the pharmaceutical, cosmetic, and food industries (Guerra-Santos et al., 1984).

7.5 Emulsion Framing and Emulsion

Biosurfactants function as substances that can either emulsify or de-emulsify. An emulsion is a mixture consisting of two fluids that do not mix well together. One fluid is scattered as droplets in the other fluid. The diameter of these droplets is usually larger than 0.1 mm. Emulsions can be classified into two types: water-in-oil or oil-in-water emulsions. These substances have low stability, but this can be improved by adding substances like biosurfactants. With the addition of these additives, the substances can be kept as stable emulsions for a considerable duration, ranging from months to years (Hu & Ju, 2001).

8 Agro-Industerial Wastes as Substrate Used for Biosurfactant Production

Agricultural wastes play a crucial role in impacting biosurfactant production efficiency by serving as low-cost substrates for microbial biosurfactant production, thus enhancing the economic viability of biosurfactant manufacturing. Utilizing agricultural wastes such as corncobs, sunflower stalks, cassava, palm kernel, and sawdust as substrates in submerged fermentation processes can lead to the production of high added-value biosurfactants with promising tenso-active and emulsifying properties (Sharon, 2023). The use of waste materials for biosurfactant production not only reduces environmental pollution but also contributes to cost-effective manufacturing processes, addressing the high production costs associated with biosurfactants and enhancing their commercialization potential. By optimizing production processes through the utilization of environment-friendly low-cost substrates and efficient product recovery methods, biosurfactant production efficiency can be significantly improved, making biosurfactants more competitive in the market. As Novel Methodologies and Approaches in Biosurfactant Production Research.

Environmental *Bacillus* sp. strains utilize potato waste water as a biosurfactant substrate, resulting in a cost-effective manufacturing process (Kavyarathna et al., 2023). This innovative method of biosurfactant manufacture utilizes inexpensive food wastes as substrates to mitigate environmental degradation and decrease manufacturing expenses effectively. The technique employs naturally occurring *Bacillus sp.* strains to enhance the effectiveness of biosurfactant synthesis from potato waste water. This approach utilizes inexpensive waste substrates to generate biosurfactants at a cost-effective rate, facilitating the production of sustainable and environmentally friendly food sector products.

The research conducted by Santos et al. (2023) explores the possible use of hemicellulosic liquors derived from corncobs and sunflower stalks as substrates for biosurfactant production. By employing submerged fermentation with *Bacillus* subtilis, we successfully generated biosurfactants from these agro-industrial wastes. Following the alkaline processing of hemicellulose-rich hydrolysates, we conducted tests on glucose and liquor concentrations to enhance the synthesis of biosurfactants. The sunflower stalk hemicellulose liquor demonstrated the maximum cell concentration and surface tension reduction, while the corncob liquor exhibited the highest emulsification index. These results were quite encouraging. 2.5% glucose, 20% hemicellulose liquor, and 1% mineral salts are the most favourable conditions for biosurfactant production. These results underscore the potential of these inexpensive substrates to be employed in the development of beneficial and valuable biosurfactants (Santos et al., 2023).

Factorial Designs (FD) and Response Surface Methodology (RSM) are statistical optimisation techniques employed to improve biosurfactant production by utilising refuse substrates. This approach leads to cost savings and increased market competitiveness. FD and RSM were extensively employed in this work to enhance the efficiency of biosurfactant production. FDs such as the Plackett–Burman Design and Taguchi design were used to evaluate the impacts and dependencies of factors. At the same time, RSM was employed to identify the best compositions of medium and culture conditions. Implementing Central Composite Design and Box-Behnken Design facilitated the optimisation of biosurfactant production in RSM by reducing the number of required testing runs. The integration of Artificial Neural Network demonstrated the ability of artificial intelligence to predict biosurfactant production, suggesting potential advancements in the future's cost-effective and efficient manufacturing of biosurfactants (Sharon, 2023).

9 Environmental and Economic Benefits of Biosurfactants

9.1 Environmental Benefits of Biosurfactants

Microbial surfactants, an example of a bio-economic product, have seen a growth in their utilization due to the recent push for ecologically friendly technologies, this is because of the environmental concerns raised over chemical surfactants. According to Georgiou et al. (1992), these biological molecules are seen as a sustainable and environmentally advantageous alternative to conventional surfactants manufactured using chemicals and fossil fuels (Georgiou et al., 1992). Thus, biosurfactants are also environmentally acceptable when used in waste treatment and bioremediation sectors. Biosurfactants are classified into four categories based on the chemical structure of the hydrophobic component: (1) glycolipid type, (2) fatty acid type, (3) lipopeptide type, and (4) polymer type. Because of their ability to reduce surface tension, stabilize emulsions, promote foam, and degrade biologically, there is much interest in using them instead of chemical surfactants (Gayathiri et al., 2022). In general, biosurfactants exhibit better qualities than chemically synthesized surfactants, making their usage in the oil recovery process safer for the environment. Their ability to endure harsh environments, their simplicity of culturing, their high-scale production capabilities, their eco-friendly nature, and their diverse nature render them sufficiently effective in the implementation of various domains, including microbial degradation (Gayathiri et al., 2022).

Biosurfactants are multifaceted substances that are found to be extensively used in biodegradation and bioremediation processes to eliminate harmful pollutants. They are also employed in the dairy, pharmaceutical, and other industries. Biosurfactants are still of interest due to their many applications and advantages. In agriculture, these compounds are employed to eradicate plant diseases and increase beneficial plant microbes' bioavailability of nutrients. Using biosurfactants for agricultural soil remediation can significantly enhance the quality of agricultural soil (Purwasena et al., 2019). Some of the ideas discussed are using sustainable by-products as substrates, cutting down on wastes, and eventually recycling treated wastes. This has led to increased exposure to these microbial products during production. Increased biodegradability and low toxicity are provided by whole surfactants, which mitigate the negative impacts of synthetic surfactants (Gayathiri et al., 2022).

Biosurfactants exhibit better qualities than chemically synthesized surfactants, making their usage in the oil recovery process safer for the environment. They are sufficiently effective in the implementation of different domains, including microbial degradation, due to their endurance in harsh environments, ease of culturing, high-scale production, eco-friendly nature, and diverse nature (Gayathiri et al., 2022). Biosurfactants are multifaceted substances that are found to be extensively used in biodegradation and bioremediation processes to eliminate harmful pollutants. They are also employed in the dairy, pharmaceutical, and other industries (Dadrasnia & Ismail, 2015). Biosurfactants are still of interest due to their many applications and advantages. In agriculture, these compounds are employed to eradicate plant diseases and increase beneficial plant microbes' bioavailability of nutrients. Using biosurfactants for agricultural soil remediation can significantly enhance the quality of agricultural soil (Purwasena et al., 2019). Some of the ideas discussed are using sustainable by-products as substrates, cutting down on wastes, and eventually recycling treated wastes. This has led to increased exposure to these microbial products during production. Increased biodegradability and low toxicity are provided by whole surfactants, which mitigate the negative impacts of synthetic surfactants (Gayathiri et al., 2022).

9.2 Economic Benefits of Biosurfactants

Large-scale production for most microbial surface-active agents has not reached a satisfactory economic level due to low yields. The raw resources they consume are essential in increasing the financial viability of bacteria-producing biosurfactants. For example, using waste products helps to maximize the production of the biosurfactant (over other metabolites) while lowering the cost of that resource (Bognolo, 1999). Optimizing reactor design is necessary for commercially successful biosurfactant production since it minimizes material loss and guarantees maximal biosurfactant extraction. It can produce biosurfactants more affordably and competitively than synthetic surfactants by using agro-industrial wastes from plants and animals to make biosurfactants. To obtain a more commercially viable production process, researchers have introduced an alternative approach using solid-state fermentation (Kapadia Sanket & Yagnik, 2013). Several studies have been conducted that will be important for developing economically efficient industrial-scale biotechnological processes in the future (Banat et al., 2014).

10 Applications of Biosurfactants

10.1 Environmental Applications

Figure 4 illustrates the various ways in which biosurfactants are used in environmental applications. Due to their

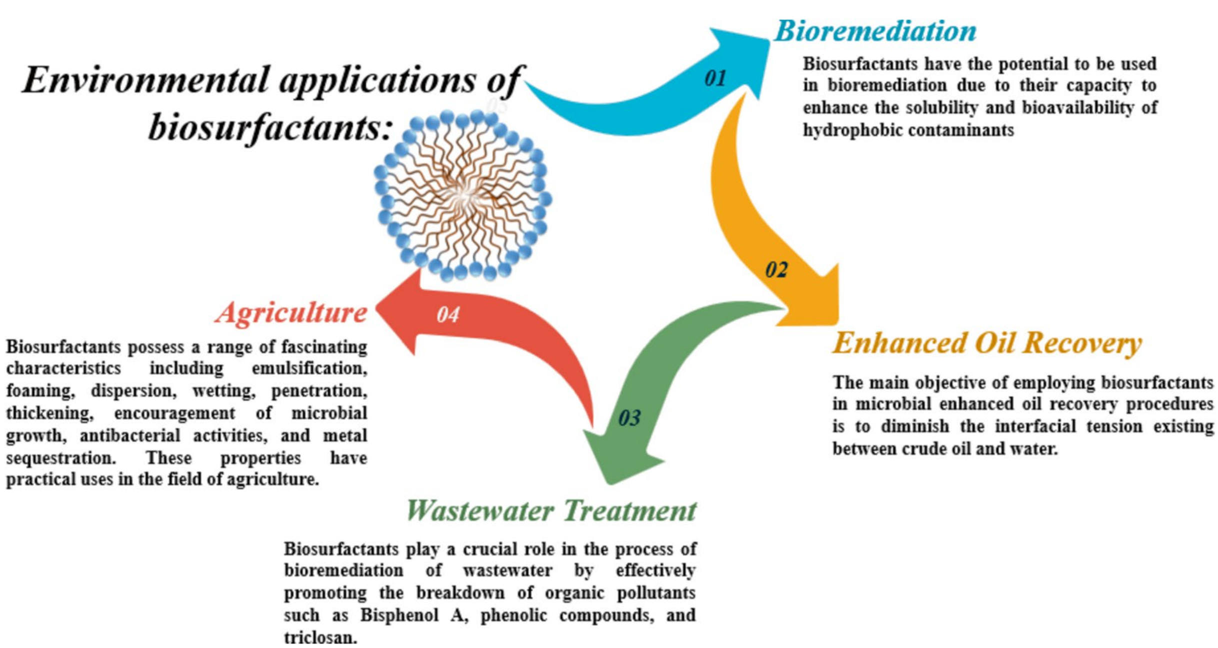

Fig. 4 Environmental applications of biosurfactant

biodegradable and non-toxic properties, these substances are highly suitable for a wide range of environmental uses; these encompass:

10.1.1 Bioremediation

Biosurfactants can improve hydrophobic pollutants' solubility and bioavailability, making them useful in bioremediation. Biosurfactants generate micelles that attach to heavy metal ions. Biosurfactants' metal binding and metal selectivity help transport and retrieve pollutants (Mishra et al., 2021). Biosurfactants improve mass transfer efficiency during biodegradation, making them essential in bioremediation. Biosurfactants can enhance, impede, or have no effect on mass transfer in microbial cells. The outcome depends on the bacteria's physiological traits and substrate features. Microorganisms can dissolve, pseudo-solubilize in biosurfactant micelles, or adhere to nonaqueous phases to access substrates. Biosurfactant micelles increase pollutant solubility, boosting soil desorption and biodegradation. This is demonstrated with *Pseudomonas* alcaligenes PA-10 and polyaromatic hydrocarbons. Increased micelles may weaken the contaminant by reducing mass transfer. Biosurfactants increase hydrophobic contaminants' pseudo-solubility, making them easier for microbes to digest and improve soil cleaning. This procedure can be in situ or ex situ. In situ methods are cheaper but slower and less uniform due to site heterogeneity. In contrast, ex-situ methods involve soil excavation and transfer. Research shows that biosurfactants remove organic contaminants and toxic metals from soils. Due to their lower environmental impact, they may be better than synthetic surfactants (Singh et al., 2009).

10.1.2 Enhanced Oil Recovery

Biosurfactants in microbial-enhanced oil recovery reduce crude oil–water interfacial tension. Flood recovery processes become more efficient, allowing them to obtain more oil. This requires identifying, developing, and synthesizing cost-effective biosurfactants. Biosurfactants with high surface activity, low CMC, and temperature and pH tolerance are ideal. They must dissolve quickly and form stable emulsions (Walter et al., 2010). Biosurfactants are used in microbial-enhanced oil recovery in two ways: (1) direct injection into the reservoir or (2) activating indigenous bacteria in the oil reservoir or injecting specialized microbes to produce biosurfactants on-site. Biosurfactants are sometimes mixed with metal ions. These additives promote polar interactions between ions and biosurfactant molecules, improving their efficacy. Lab trials using sand-packed columns have revealed that biosurfactants in Microbial Enhanced Oil Recovery may recover 95% of oil. This shows biosurfactants can boost oil recovery (Nikolova & Gutierrez, 2020).

10.1.3 Waste Water Treatment

Biosurfactants, especially rhamnolipids, help bioremediate waste water by breaking down organic contaminants such as Bisphenol A, phenolic compounds, and triclosan. Clearance rates reach 90%. These compounds change heavy metals like zinc and copper and lead to better dissolve and help remove them from polluted places. Rhamnolipids reduce surface tension and improve emulsification, enhancing oil–water separation. This is crucial in industrial or oil disasters (Liu et al., 2018). Rhamnolipids also boost enzymatic activity and pollutant accessibility, accelerating breakdown. Research shows they can boost laccase catalytic activity, reducing Bisphenol A by 65% in industrial waste water. They also modify enzyme structures to help decompose waste water pollutants, including phenolic compounds and petroleum hydrocarbons (PAHs and TPH). *Stenotrophomonas sp.* reduces pollutant concentrations by 70–90% using rhamnolipids (Patel & Patel, 2020). Personal care products contain triclosan, which rhamnolipids break down. Di-rhamnolipids break down 94% in water–sediment systems. Overall, rhamnolipids and other biosurfactants are a sustainable and adaptive waste water treatment system pollution solution. This highlights their environmental remediation potential and ability to reduce pollutants and safeguard human health (Malkapuram et al., 2021).

10.1.4 Agriculture Wastes Treatment

Biosurfactants have remarkable properties such as emulsification, foaming, dispersion, wetting, penetration, thickening, microbial growth, antibacterial activity, and metal sequestration. These qualities are helpful in agriculture. According to Thavasi et al. (2014), these compounds control plant diseases due to their antibacterial capabilities. Research has demonstrated that biosurfactants help fight plant diseases and improve resistance (Thavasi et al., 2014). This shows their potential to enhance agricultural pesticides and plant disease resistance:

Disease Control

Studies have shown that plants' biosurfactants can control fungi and other infections. Rhamnolipids and Sophorolipids lyse oomycete plant-pathogenic fungi zoospores. These fungi cause hydroponic plant diseases. Zoospore membranes rupture with biosurfactants, causing lysis and motility inhibition. This stops the disease from spreading. *Pseudomonas* and *Serratia strains* that produce biosurfactants have also been used on plant surfaces to limit fungal disease growth and spread (Thavasi et al., 2014).

Induced Systemic Resistance (ISR)

Biosurfactants can evoke amazement beyond their antibacterial properties. Rhamnolipids have been shown to boost plant systemic resistance. These chemicals cause plants to produce pathogenesis-related proteins and other defence mechanisms. This innate immune response, called ISR, helps plants resist several illnesses, lowering the requirement for pesticides (Salwan et al., 2023).

10.2 Therapeutic and Pharmaceutical Potential Applications

Medical and pharmaceutical applications for biosurfactants demonstrate their therapeutic potential. Commercial antibiotics contain powerful antibacterial and antifungal biosurfactants such as lipopeptides and glycolipids. They effectively prevent and stop biofilm buildup, which is crucial for reducing hospital device and surface infections (Sharma et al., 2019). Biosurfactants also disrupt microorganism cell membranes and biofilms, which may reduce doses and adverse effects while battling resistant strains. Since they affect the architecture of various enveloped viruses, they may be antiviral medications. Biological compounds like biosurfactants help wounds heal by encouraging cell development and tissue regeneration. This reduces infections and speeds healing (Balakrishnan et al., 2023). Some biosurfactants can also slow tumour cell proliferation, making cancer cells more susceptible to chemotherapy. Their immunomodulatory effects assist in treating immune-mediated illnesses and improve vaccine formulations, showing their potential to promote health and fight disease (Sajid et al., 2020).

10.3 Food Industry Applications

Biosurfactants are becoming more popular in food processing due to their natural origin and versatility. As emulsifying and stabilizing agents, they improve the stability of food emulsions such as dressings and sauces, protecting product quality and shelf life. Biosurfactants improve salad dressing consistency and thermal resistance compared to traditional emulsifiers. They also reduce calorie content and increase texture, volume, and quality in baked goods like bread and cookies. Despite limited coverage, biosurfactants may improve ice cream texture, creaminess, and physical properties during processing. These chemicals' antibacterial and anti-adhesive properties restrict microbe development and reduce their attachment to food surfaces, extending food shelf life. In dairy processing, this is beneficial. Biosurfactants contain antioxidants that limit food oxidation, improve product shelf life, and reduce the risk of oxidative stress-related disorders. Biosurfactants reduce synthetic chemicals, making them popular in the food business. This adoption enhances food quality, safety, and sustainability (Ribeiro et al., 2020).

10.4 Cosmetic Industry Applications

Biosurfactants like Sophorolipids, Rhamnolipids, and Mannosyl erythritol lipids are used more in cosmetics due to their natural and eco-friendly properties. Sophorolipids' hygroscopic qualities make them useful in moisturizers and emollients. They contain moisturizers, lipsticks, eye shadows, antibacterial acne treatments, and deodorants. Rhamnolipids, which produce less skin irritation, are utilized in insect repellents, acne treatments, antidandruff shampoos, and anti-wrinkle products. They are antimicrobial in cosmetics and personal hygiene. Pseudozyma yeasts produce mannosylerythritol, which has good industrial and biological qualities. These ingredients hydrate dehydrated skin, restore damaged hair, and fight ageing in skin care products. Their ceramide-like properties help maintain the skin's protective barrier. These biosurfactants indicate a shift towards eco-friendly cosmetics (Fracchia et al., 2014).

11 Challenges and Future Directions in Biosurfactant Research

Low yield, high manufacturing costs, and poor fermentation hinder biosurfactant commercialization. Future research could address these issues:

11.1 Improving Biosurfactant Yields

The biosurfactant-synthesis microbial strains used nowadays often have low yield and productivity. Scientists are employing metabolic and cellular engineering to improve biosurfactant synthesis by improving metabolic processes. Examples include enhancing biosynthetic gene expression and using molecular methods to boost microbial output. Intelligent methods, including artificial intelligence and statistical optimization, have improved culture medium composition to increase yields (Dhanya, 2021).

11.2 Enhancement of Process Economics

Biosurfactant manufacturing costs depend on raw material costs and downstream processing efficiency. Use cheap, sustainable resources and agricultural-industrial byproducts to cut costs. Downstream processing technologies like chemical-free recovery reduce production costs and environmental damage (Aslam et al., 2023b).

11.3 Advancements in the Fermentation Process

Are required for maximum biosurfactant production. Various fermentation methods, such as batch, fed-batch, and continuous fermentation, have been studied. Immobilized or resting cells and solid-state fermentation can boost production and streamline manufacturing. Notably, bioprocess coupling has shown promise in reducing manufacturing costs by synthesizing enzymes and biosurfactants (Beuker et al., 2014).

12 Conclusion

This chapter specifically examines the crucial role that microorganisms have in the conversion of agricultural and industrial waste materials into valuable biosurfactants. The objective of this chapter is to provide a comprehensive summary of the procedure. Biosurfactants refer to compounds that possess both hydrophilic and hydrophobic characteristics. A diverse range of bacteria, yeast, and fungus use complex fermentation and biodegradation processes to produce biosurfactants. These compounds provide many significant advantages, such as their ability to undergo natural degradation, their few adverse effects, and their remarkable reactivity with surfaces. Consequently, their skills are highly sought after in the food business, pharmaceutical manufacturing, cosmetic development, and environmental pollution cleanup. The use of waste materials generated by agro-industrial operations has the potential to reduce the production costs of biosurfactants. Consequently, the minimization of environmental pollutants leads to an enhancement in both the economic and ecological sustainability of the process. Nevertheless, obstacles have to be surmounted in order to enhance the efficiency of microbial strains, optimize fermentation conditions, and enhance downstream processing. Hence, it is essential to carry out continuous research to enhance the effectiveness and scalability of the biosurfactant manufacturing process. Such measures will promote environmentally conscious actions and protect the natural ecosystem.

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