

Review

Biosurfactants: An Overview of Their Properties, Production, and Application in Mineral Flotation

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Abstract: The quest for sustainable mining processes has directed research towards environmentally friendly alternatives to conventional beneficiation practices, with biosurfactants emerging as a viable option due to their lower environmental impact. This study reviews the application of biosurfactants as bioreagents in mineral flotation, exploring their production, their mechanisms of action, and the sustainability benefits they offer. Methods include a decade-long text mining analysis of relevant literature, utilizing software tools like Zotero on platforms like Web of Science to extract and analyze data. The results underscore the growing interest in biosurfactants over the last ten years, highlighting their increasing relevance in industrial applications such as mineral flotation, where they replace synthetic surfactants. Particularly, biosurfactants have shown effectiveness in enhancing the froth flotation process, leading to more efficient mineral recovery while mitigating environmental harm. In conclusion, the adoption of biosurfactants in mineral processing not only aligns with sustainability goals but also demonstrates potential improvements in operational efficiency, offering a dual benefit of environmental protection and enhanced resource recovery.

Keywords: biotechnology; biomining; surfactants; sustainable minerals; sustainability



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1. Introduction

The mining industry plays a key role in economic development, supplying essential raw materials to various sectors of society. However, mineral exploitation can often present significant environmental challenges, such as the generation of waste and excessive consumption of water and energy [1]. In this context, the search for more sustainable practices has driven studies into alternatives that minimize environmental impact without compromising the efficiency of beneficiation processes. One promising approach is the use of biosurfactants to replace synthetic surfactants in mineral flotation, which is an environmentally friendly alternative [2].

This article aims to provide a comprehensive overview of the use of biosurfactants as bioreagents in mineral flotation, considering their mechanisms of action, production factors, and the positive implications in terms of sustainability and environmental aspects. With increasing interest in more sustainable practices in the mining industry, biosurfactants have emerged as a promising alternative for improving the efficiency of froth flotation processes and, at the same time, reducing the environmental impact associated with this essential activity for global economic development.

To this end, a text mining method was chosen to conduct this review on the use of biosurfactants in mineral flotation, motivated by the need to examine and synthesize information dispersed across a wide variety of academic sources over 10 years. Text mining offers an effective approach for identifying trends, patterns, and relevant information

“adsorption”, “application” and “bacteria”. This result indicates that these biosurfactants have attracted more attention due to their adsorption properties and ability to modify surface characteristics, making them fundamental for industrial and ecological development in various industrial applications. Interestingly, there has been an increase in interest in the use of these biosurfactants as bioflocculants and additives. At the same time, terms such as “environmental”, “anionic” and “air” are mentioned less frequently over the years, which can be attributed to the redundancy of these concepts. In abstracts of articles, the most frequently mentioned terms are “adsorb”, “availability” and “behavior”. This highlights the search for studies on biosurfactant behavior in various applications. However, the difficulty in obtaining these biosurfactants persists, and research continues to be conducted in this direction, reflecting continued interest [4–8].

Table 1. Correlations between biosurfactants and second terms—Titles and Abstracts (2013–2023).

Fixed Term	Titles			Abstract		
	2° Term	Correlation	Significance (<i>p</i>)	2° Term	Correlation	Significance (<i>p</i>)
Biosurfactants	Adsorption	0.84	0.0020	Adsorb	0.82	0.003
	Application	0.79	0.0070	Availability	0.82	0.003
	Bacteria	0.64	0.0460	Behavior	0.79	0.006
	Bioflocculant	0.01	0.9800	Biodegradable	0.00	0.990
	Additives	0.01	0.9800	Access	−0.01	0.988
	Environmental	−0.83	0.0030	Acids	−0.54	0.105
	Anionic	−0.87	0.0010	Amino	−0.55	0.100
	Air	−0.91	0.0002	Auxiliary	−0.65	0.044

However, for a more detailed analysis, an annual investigation into the progression of studies related to biosurfactants was carried out. For this purpose, Voyant software was again used to examine the most pertinent terms from each year. In Table 2, the correlations of the term “biosurfactants” with specific keywords are highlighted, year by year, to gain a deeper understanding of their study and development over time.

From 2013 to 2023, research on biosurfactants has evolved significantly, with initial studies in 2013 focusing on their behavior and applications, particularly in bioremediation, to understand their biological characteristics and potential to replace chemical products. By 2014, emphasis shifted towards their roles in adsorption and biosorption, enhancing industrial process efficiency. In 2015, research expanded to their use as foaming agents and production methods. Subsequent years saw a deepening focus on their application in mineral flotation, especially with hematite in 2016, and a variety of studies in 2017 exploring the effects of biosurfactant concentration and their amphoteric properties. By 2018, research spotlighted their role as collectors in froth flotation, while 2019 emphasized their alternative uses in industries like metallurgy and pharmaceuticals. The focus in 2020 was on their efficacy as emulsifiers and potential replacements for synthetic reagents. In 2021, this trend continued with studies aimed at improving biosurfactant production and applications, notably in heavy metal removal. Exploration of new chemical compositions, particularly with chitosan, marked 2022’s research, leading to 2023, when the interaction of biosurfactants with heavy metals like copper was a key focus, underscoring their potential as environmentally friendly alternatives in metal recovery and the froth flotation process in mining, reflecting a growing trend towards sustainable industrial practices [9–39].

Biosurfactants show promising results for the recovery of metals such as iron ores, which are among the most widely used worldwide. In addition, the search has grown for biosurfactants to replace synthetic reagents currently used in froth flotation, the main process for concentrating these ores in the mining industry.

Table 2. Correlations between biosurfactants and second terms year on year from 2013–2023.

Year	Titles			Abstract		
	2° Term	Correlation	<i>p</i>	2° Term	Correlation	<i>p</i>
2013	Application	0.65	0.043	Behavior	0.76	0.010
	Activated	−0.16	0.667	Bioremediation	−0.12	0.746
	Biological	−0.55	0.102	Biodegradation	−0.37	0.294
2014	Application	0.78	0.007	Allows	0.70	0.023
	Biosorption	−0.05	0.901	Improve	0.04	0.907
	Adsorption	−0.41	0.242	Adsorption	−0.68	0.031
2015	Foam	0.86	0.001	Application	0.67	0.035
	Bioremediation	0.04	0.907	Bacterial	0.01	0.978
	Production	−0.59	0.075	Aqueous	−0.72	0.019
2016	Hematite	0.83	0.003	Benefits	0.69	0.027
	Soil	0.04	0.904	Evaluation	0.20	0.583
	Microalgae	−0.21	0.565	Application	0.17	0.629
2017	Concentration	0.70	0.024	Agents	0.81	0.004
	Agriculture	−0.04	0.919	Adsorbents	−0.01	0.971
	Degradation	−0.79	0.006	Amphoteric	−0.41	0.235
2018	Collector	0.77	0.005	Air	0.65	0.044
	Air	−0.03	0.930	Biomass	0.03	0.041
	Metal	−0.23	0.521	Appropriate	−0.69	0.026
2019	Alternative	0.55	0.047	Bioremediation	0.94	0.000
	Bacteria	−0.10	0.788	Air	−0.02	0.955
	Agents	−0.59	0.075	Aeruginosa	−0.54	0.105
2020	Emulsifiers	0.73	0.016	Action	0.83	0.003
	Processes	0.05	0.889	Biodegradation	0.01	0.984
	Synthesis	0.00	1.000	Progress	−0.72	0.019
2021	Enhanced	0.84	0.002	Skill	0.70	0.024
	Biomass	−0.02	0.959	Amina	0.01	0.030
	Based	−0.39	0.271	Affects	−0.54	0.106
2022	Chitosone	0.73	0.016	Arrangements	0.78	0.008
	Characteristics	0.15	1.000	Applications	−0.01	0.042
	Approaches	−0.37	0.289	Agents	−0.45	0.190
2023	Copper	0.77	0.009	Activities	0.80	0.006
	Bioproducts	−0.01	0.471	Biodegradable	−0.01	0.048
	Activated	−0.71	0.022	Biofilm	−0.50	0.1390

3. Surfactant

Surfactants are chemical substances capable of altering surface properties. This is achieved due to the molecular structure of surfactants, which have a hydrophilic part and a hydrophobic part. They play an essential role in various applications, acting as detergents, wetting agents, emulsifiers, and foaming agents. They are present in a wide range of consumer and industrial products, including food, health products, paints, and so on, as well as being crucial components in many industrial processes, such as oil recovery and mineral concentration.

Two decades ago, global production of surfactants was estimated at 7 million metric tons per year [40]. This figure rose to 12.5 million metric tons in 2006 and reached 14.1 million metric tons in 2017. In 2022, there was a further 18 per cent growth in the estimated figure [41]. These figures reflect the growing demand and continuous development of the surfactant sector in the global market.

The use of surfactants in various applications is due to their surface-active properties. Their molecular structure, with a hydrophilic head and a hydrophobic tail [41,42], allows the molecules to group at an interface, such as the air/water interface, reducing surface tension

and stabilizing the system, such as an emulsion or foam. Above a certain concentration, known as the critical micellar concentration (CMC) [43], further increases in surfactant concentration do not result in a further reduction in surface tension [44]. Above the CMC, surfactant molecules aggregate in the bulk phase in a process called micellization [45], forming micelles with different shapes, such as spherical, cylindrical, or discoidal, or even more complex shapes. The micelle shape influences the rheological and dynamic properties of the surfactant solution. In some applications, the presence of micelles is fundamental to the functional performance of the surfactant; for example, in a study on a household cleaning product, greater amounts of foam were produced at concentrations above the CMC [46].

The antibacterial and solubilization properties of surfactants are also characterized by the CMC point [46,47]. The CMC provides a clear reference point for surfactant concentration, allowing direct comparison of the performance of different surfactants based on their relative CMCs. There are different groups of surfactants, classified according to the charge of the hydrophilic head of the molecule: anionic (negative charge), cationic (positive charge), amphoteric (negative and positive ions), and non-ionic (no charge) [43,44]. These characteristics often determine the applications for which surfactants are best matched.

Concerning mineral concentration, surfactants play a crucial role in promoting the separation of minerals of interest and gangue. Anionic surfactants have a negative charge on the hydrophilic head of the molecule. They are widely used in flotation as collectors since they have an affinity for positively charged minerals. The most common anionic surfactants used in flotation include alkyl sulfates and alkyl ether sulfates, such as sodium dodecyl sulfate (SDS) [48,49]. These surfactants help to promote selective adsorption on the surfaces of minerals of interest, making them hydrophobic and facilitating their adherence to air bubbles during the flotation process [46,47,50,51].

On the other hand, cationic surfactants have a positive charge on the hydrophilic head of the molecule. They are often used as mineral surface modifiers to improve selectivity in flotation. Cationic surfactants can interact with negatively charged minerals, improving their adhesion to air bubbles and promoting flotation [52–54].

Amphoteric surfactants can change their charge depending on the pH of the medium. They can be positively charged at an acidic pH and negatively charged at an alkaline pH. Non-ionic surfactants have no charge on the hydrophilic head of the molecule. They are widely used as collectors in flotation, especially in processes involving minerals that do not interact strongly with ionic surfactants. Non-ionic surfactants help to reduce the surface tension between air and water, improving foaming and the adhesion of mineral particles to air bubbles during flotation [43,55].

In addition to conventional surfactants, a promising alternative in froth flotation is the use of biosurfactants [2]. Biosurfactants are emerging as a promising option, offering environmental advantages and potential applications in froth flotation. Continued research in this area is essential to understand the potential of biosurfactants as substitutes for conventional ones. For example, biosurfactants not only reduce the environmental impacts caused by synthetic surfactants but also share similar characteristics, making their use a differentiated option for mineral flotation [56–59].

4. Biosurfactants

Biosurfactants are considered biodegradable, biocompatible, non-toxic, and environmentally friendly compared to synthetic surfactants, which pose environmental risks and are generally difficult to degrade [60]. Moreover, biosurfactants offer considerable advantages over synthetic surfactants including lower toxicity, greater biodegradability, better environmental compatibility, higher foaming capacity, and the ability to be produced from renewable resources [61].

Biosurfactants can be produced from various substrates, such as potato peel, industrial waste, cassava flour, palm oil, and glycerol, among others [62]. In contrast, the production of synthetic surfactants involves chemical processes that generally incur high costs and

environmental risks [63]. Table 3 presents the advantages and disadvantages of synthetic and biological surfactants.

Table 3. Advantages and disadvantages of biological and synthetic surfactants.

Biosurfactants		Synthetic Surfactants	
Advantages	Disadvantages	Advantages	Disadvantages
High biodegradability	Difficulty in production at scale	Capable of generating foam	Low biodegradability
Low production cost	Sensitive boundary conditions (Temperature, pressure)	Soluble in water	High production cost
Non-toxic		Ease of production at scale	Toxic
Capable of generating foam			
Soluble in water			

Biosurfactants have various industrial applications, including in agriculture, cosmetics, detergents, oil and gas, environment, food, textiles, and mineral processing [64]. In mineral processing, biosurfactants are used in froth flotation due to their hydrophobic properties, derived from long-chain fatty acids, and their hydrophilic nature, stemming from sugars, phosphates, carboxylic acids, amino acids, and cyclic peptides. These characteristics promote selective adsorption, usually through chemical and/or physical interactions with mineral surfaces, enabling selectivity and good recovery of the target minerals. Biosurfactants can serve as substitutes for synthetic surfactants due to their surface-active properties, where they are capable of reducing surface tension similarly to synthetic surfactants. Moreover, the possibility of obtaining a biosurfactant with a chemical composition similar to synthetic surfactants, containing both polar and non-polar compounds, allows for maintaining the quality of the final product at a low production cost with biodegradable residues.

Although there are no precise indicators of the quantity of surfactants used in mineral flotation, it is estimated that millions of tonnes are used annually, posing a significant challenge due to the health and ecosystem risks associated with synthetic surfactants [65]. Biosurfactants are promising substitutes for more sustainable mining. However, their use on an industrial scale is not yet common, being primarily based on glycolipids, lipopeptides, phospholipids, and polymeric surfactants. Large concentrations of surfactants are required for mineral flotation, which would entail considerable volumes of biosurfactants and the potential generation of by-products from their biodegradation. These by-products need to be investigated and, if possible, reprocessed to minimise environmental risks. The large-scale production of biosurfactants remains a significant challenge due to its complexity, which has spurred various research efforts.

5. Microorganisms and Biosurfactant Production

As far as the global market is concerned, the production of biosurfactants reached a value of 4.2 billion USD in 2017 and experienced an increase to approximately 5.5 billion USD in 2022, with an annual growth rate of 5.6% [66]. A variety of microorganisms, including plants, animals, and microbial species, show potential for producing biosurfactants, which play a key role in promoting the diffusion of insoluble substances, such as hydrocarbons, into the cell [2,67,68].

Biosurfactants and biological surfactants are categories that often overlap but have distinct nuances in their definitions and applications. Biosurfactants are a specific subcategory of biological surfactants produced by microorganisms during their growth or metabolism. These molecules have the unique ability to reduce surface tension and facilitate the emulsification of liquids, like synthetic surfactants, but with the added advantage of being biodegradable and less toxic. While biosurfactants are typically generated by bacteria, yeasts, and fungi, the term “biological surfactants” encompasses a broader range, including compounds produced by plants and animals. The main similarity between them is functionality—both reduce surface tension and stabilize emulsions. However, the difference lies in their origin and method of production: biosurfactants are a direct result

of microbial biotechnology, while biological surfactants can come from a broader variety of biological sources. Microbial biosurfactants, preferred over other biological surfactants, stand out for their instant production, multifunctional characteristics, accessibility, and ability to be scaled up [1,69].

Studies reveal the presence of biosurfactant-producing microorganisms in both contaminated and uncontaminated soils. In unpolluted soils, approximately 2–3% of microorganisms are recognized as biosurfactant producers, while this fraction increases to 25% in contaminated soils. Among the bacterial genera notable for their production of biosurfactants are *Actinobacteria*, *Pseudomonas*, *Sphingomonas*, *Bacillus*, *Halomonas*, *Pseudoalteromonas*, *Mycobacterium*, *Alcanivorax*, *Rhodococcus*, and *Arthrobacter*. Despite extensive studies on bacterial species, there is a gap in research exploring the potential of fungi to produce biosurfactants. *Candida lipolytica*, *Candida bombicola*, *Candida batistae*, *Candida ishiwadae*, *Aspergillus ustus*, and *Trichosporon ashii* are prominent examples of biosurfactant-producing fungi [70–72].

With an average molecular mass ranging from 500 Da to 1500 Da, biosurfactants are categorized into low molecular weight and high molecular weight. Low molecular weight biosurfactants are effective in reducing surface tension and stabilizing emulsions, while high molecular weight biosurfactants are more effective in stabilizing oil-in-water emulsions and are often referred to as bioemulsifiers [68]. Examples of low molecular weight biosurfactants include glycolipids, lipopeptides and phospholipids [73,74].

Among the low molecular weight biosurfactants, glycolipids are the most extensively studied class. Their structure comprises a hydrophilic carbohydrate portion linked to hydrophobic fatty acid chains. The most prevalent subclasses include rhamnolipids, trehalolipids, mannosylerythritol lipids and sophorolipids.

5.1. Classification and Factors Influencing Production

The classification of biosurfactants depends on the diversity of microorganisms and their biological and chemical activity. The main types of biosurfactants include glycolipids, phospholipids, liposaccharides, lipopeptides, fatty acids, and neutral lipids [75–77]. In this context, different classes of biosurfactants have been identified and studied for their unique characteristics. Table 4 shows the main classes of biosurfactants and their sources. These advances in the understanding of microorganisms and the production of biosurfactants highlight the growing importance of these molecules on the industrial and environmental scene.

Table 4. Main classes of biosurfactants and their sources.

Class	Subclass	Microorganisms	References	
Glycolipids	Rhamnolipids	<i>Pseudomonas aeruginosa</i>	[67,71]	
		<i>Pseudomonas cepacia</i>	[78]	
		<i>Pseudomonas</i> spp.	[79,80]	
		<i>Lysinibacillus sphaericus</i>	[81]	
		<i>Serratia rubidaea</i>	[82]	
	Trehalolipids	<i>Nocardia farcinica</i>	[83]	
		<i>Rhodococcus</i> sp.	[84]	
		<i>Candida bombicola</i>	[85,86]	
	Sophorolipids	<i>Candida sphaerica</i>	[87]	
		<i>Starmerella bombicola</i>	[88]	
		<i>Cutaneotrichosporon mucoides</i>	[89]	
	Mannosylerythritol Lipids	Not informed	<i>Pseudozyma aphidis</i>	[90]
			<i>Meyerozyma guilliermondii</i>	[91]
<i>Saccharomyces cerevisiae</i>			[92]	
<i>Candida utilis</i>			[93]	

Table 4. Cont.

Class	Subclass	Microorganisms	References
Lipopeptides	Surfactin	<i>Marinobacter hydrocarbonoclasticus</i>	[94]
		<i>Bacillus subtilis</i> , <i>Bacillus nealsonii</i>	[95,96]
	Lichenysin	<i>Bacillus licheniformis</i>	[97]
		Not informed	<i>Pseudomonas azotoformans</i>
	<i>Bacillus velezensis</i>		[99]
	<i>Virgibacillus salarius</i>		[100]
	Phospholipids		<i>Bacillus pumilus</i>
<i>Halomonas</i> sp.			[102]
<i>Thiobacillus thiooxidans</i>			[103]
<i>Klebsiella pneumoniae</i>			[104]
Polymeric Surfactants	Liposan	<i>Candida lipolytica</i>	[105]

5.1.1. Glycolipids

Glycolipids are widely studied biosurfactants and are divided into three groups: rhamnolipids, sopholipids and trehalolipids. These compounds have an aliphatic hydrophobic part, made up of long chains of aliphatic hydroxy acids, linked to a hydrophilic sugar, which can be a mono-, di-, tri- or tetra-saccharide, through an ether or ester bond [106,107].

- Rhamnolipids

Rhamnolipids consist of one or two fatty acid chains, with 8 to 16 carbons, linked to one or two rhamnose sugar molecules [108]. The Gram-negative bacterium *Pseudomonas aeruginosa* is the main producer of rhamnolipids, although other bacterial species can also actively synthesize these biosurfactants [109,110]. The types of rhamnolipids produced vary according to the bacterial strain, the carbon source used, and the cultivation conditions. Due to their advantageous characteristics, rhamnolipids are considered one of the most interesting classes of biosurfactants. Various renewable substrates, such as used oils or waste from the food industry, have been identified as suitable carbon sources. These biosurfactants can reduce the surface tension of water/air from 72 mN.m⁻¹ to values close to 30 mN.m⁻¹, as well as tension at the water/oil interface from 43 mN.m⁻¹ to values close to 1 mN.m⁻¹. The critical micellar concentration of pure rhamnolipids and their mixtures ranges from 50 to 200 mg.L⁻¹ [111].

In addition, rhamnolipids containing one and two rhamnose molecules are respectively designated as mono-rhamnolipids and di-rhamnolipids [112]. Their chemical structures are observed in the manuscript presented by Abdel-Mawgoud et al. [108]. These compounds are classified based on the number of rhamnose molecules present and have a hydrophobic tail made up of fatty acid chains, giving them amphiphilic properties [113,114].

Rhamnolipids are directly influenced by the composition of the mixture and can reduce the surface tension of water to approximately 29 mN.m⁻¹ [115]. *Pseudomonas aeruginosa* stands out as one of the main producers of these biosurfactants, with a remarkable production capacity that can reach up to 100 g.L⁻¹, making the process of obtaining them economically attractive [71,72,116].

The production process of rhamnolipid biosurfactants (RL) is described by Santa Anna et al. [116]. This process is based on the sequence of the glycosyl group, with synthesis carried out by rhamnosyltransferase 1 enzymes. These enzymes transfer thymidine diphosphate-L-rhamnose to form dTDP-L-rhamnose.

L-rhamnose has a key role in the synthesis of rhamnolipids, mediated by the rhlA, rhlB and rhlC genes. The rhlA gene produces the enzyme responsible for producing fatty acids and free 3-(3-hydroxyalkanoxyloxy) alkanolic acid (HAA). In turn, rhamnosyltransferases encoded by the rhlB and rhlC genes transfer dTDP-L-rhamnose to 3-(3-hydroxyalkanoic) alkanolic acid, resulting in complete rhamnolipids [117,118].

Kronemberger [119] conducted a study on the production of rhamnolipids in a bioreactor using *Pseudomonas aeruginosa* for aerobic fermentation with glycerol as a substrate.

The results indicated that approximately 17 g.L^{-1} of rhamnolipids was obtained, with a productivity of around $44 \text{ mg.L}^{-1}.\text{h}^{-1}$ and a yield of 34%. Recently, Zhao et al. [120] observed differences in the synthesis of rhamnolipids through aerobic and anaerobic routes using *Pseudomonas aeruginosa*, with the latter demonstrating anaerobic production capacity using glycerol as a substrate.

Optimizing macronutrients and micronutrients in the rhamnolipid production process is crucial for obtaining high yields and suitable molecular compositions. *Pseudomonas aeruginosa* can produce a mixture of RL molecules in different proportions during cultivation [118]. Studies have explored different carbon sources, such as industrial waste (residual carbon from refineries), food waste (frying oil, molasses), and waste from distillation processes [121]. In addition, organic compounds such as sucrose, glucose, alkanes, and glycerol have been used as substrates to produce rhamnolipids. The concentration of nutrients, especially the carbon/nitrogen (C/N) ratio, plays a significant role in stimulating RL biosynthesis by *Pseudomonas aeruginosa*. Despite advances in research into the production of rhamnolipids, production on an industrial scale is still a challenge, requiring further studies and developments to optimize and make viable their production on a large scale. Continued research in these areas is essential to exploit the full potential of these versatile and sustainable biosurfactants in various industrial and environmental applications [122].

- Sophorolipids

Sophorolipids comprise a hydrophilic disaccharide called sophorose, made up of two monomers joined by β -1,2 bonds. Internally, the sophorose is linked to C16 or C18 hydroxylated fatty acid chains, which can be acetylated or non-acetylated [123,124].

These compounds have two main congeners: the acidic form and the lactonic form [125]. Their chemical structures are observed in the manuscript presented by Van Bogaert et al. [126]. In the acidic form, the fatty acid tail is free, while in the lactonic form, the carboxyl group of the fatty acid chain is linked via an intramolecular ester bond with the hydroxyl group of the sophorose. These different forms influence their biological properties and activities [127,128].

Sophorolipids are the second-most-studied compounds in terms of properties and applications. The acidic form contributes to solubility and foaming capacity, while the lactonic form significantly affects the antimicrobial activity of these compounds [125]. Microbial production of sophorolipids results in a natural mixture of around 40 different types of these biomolecules and their isomers, with variations in structures [129,130].

The biosynthesis of sophorolipids by *Candida bombicola* begins with glucose as the precursor molecule for the hydrophilic part of the sophorolipids. The precursors for the hydrophobic part can be alkanes, triglycerides, or fatty acid methyl esters. The fatty acids used vary, including fatty acid n-alkanes, alcohols, or fatty acid esters, which are metabolized to their corresponding fatty acids. In the absence of a carbon source, they are formed via synthesis from Acetyl-CoA provided by the glycolytic pathway [124].

The fatty acid chains are oxidized by the enzyme cytochrome P450 monooxygenase to form hydroxylated fatty acids. These are linked to the first and second glucose molecules by the enzymes glycosyltransferase I and II, respectively. The glycosylation reaction results in FS in their acid form. Subsequent reactions, including acetylation, generate structural variations. Lactonization occurs by esterification, converting the acid form into its lactonic form [131]. The production of these biocompounds is described by Kobayashi et al. [126] and Baccile et al. [127]. Sophorolipids are recognised for their surfactant and emulsifying properties, making them valuable in various industrial applications. Production reached 400 g.L^{-1} , highlighting the commercial potential of these compounds [131].

Oliveira [132] carried out a study on the efficient production of sophorolipids by *Candida bombicola* ATCC 22214 using cells immobilized in calcium alginate. After optimization, production of 8.45 g.L^{-1} of sophorolipids was achieved with immobilization efficiency of 90.92%. The immobilized cells remained stable for three cycles, maintaining an efficiency of around 70.75%. Structural analysis revealed a predominance of acidic forms (70.95%)

and a smaller proportion of lactonic forms (29.05%), indicating a promising method for the economical production of sophorolipids with broad industrial applications.

- Trehalolipidis

Trehalolipids are compounds formed by the association of trehalose disaccharides with mycolic acid, the latter being a chain of branched β -hydroxy fatty acids found in some Gram-positive bacteria. This class of compounds displays considerable structural diversity and is predominantly produced by species of the genera *Rhodococcus*, *Nocardia*, *Mycobacterium* and *Corynebacterium* [123]. Notably, trehalolipids from *Arthrobacter* spp. and *Rhodococcus erythropolis* can reduce surface and interfacial tensions in culture media to values of 25–40 $\text{mN}\cdot\text{m}^{-1}$ and 1–5 $\text{mN}\cdot\text{m}^{-1}$, respectively [111]. Trehalose, on the other hand, is a disaccharide composed of two glucose molecules [84,133]. Its chemical structure is observed in the manuscript reported by Cameotra et al. [134]. The combination of these hydrophilic and hydrophobic groups gives trehalolipids surfactant properties, making them useful in various applications, such as emulsifiers and detergents. Bacteria such as *Nocardia*, *Mycobacteria*, and *Corynebacteria* are recognised as major producers of these biosurfactants [135].

Trehalolipids are produced by yeasts and are notable for forming extremely stable emulsions under adverse conditions, such as wide variations in temperature (20 to 100 °C), pH (2 to 10), and salinity (5 to 25% *w/v*). This remarkable stability in extreme environments gives them value in various industrial applications [136].

The synthesis of trehalose occurs through enzymes located in the cytoplasm using glucose as a substrate [137]. The production of trehalose by yeasts is detailed by Ping et al. [136]. Initially, glucose is converted into glucose-6-phosphate and, through the action of the enzyme trehalose-6-phosphate synthase (TPS1), condenses with UDP-glucose, resulting in trehalose-6-phosphate and UDP. Subsequently, trehalose-6-phosphate phosphatase (TPS2) removes the phosphate group, resulting in trehalose and inorganic phosphate [137,138]. Besides yeasts, other forms of trehalose biosynthesis are found in various organisms, such as bacteria, higher fungi, insects, and plants [139].

Trehalolipids have the remarkable ability to reduce the surface tension of water from 72 to approximately 36 $\text{mN}\cdot\text{m}^{-1}$, demonstrating their emulsifying properties and ability to stabilize mixtures of immiscible liquids such as water and oil. An essential parameter for assessing their emulsifying activity is their Critical Micellar Concentration (CMC), which varies between 4 and 200 $\text{mg}\cdot\text{L}^{-1}$, depending on the conditions and the specific structure of the compound [140].

Colla [141] conducted a study with two yeast strains, *Rhodotorula dairenensis* and *Rhodospiridium paludigenum*, selected to produce trehalose, a cell protection compound. The cultivation conditions were optimized, resulting in 19 $\text{g}\cdot\text{L}^{-1}$ of dry mass for *Rhodotorula dairenensis* and 31 $\text{g}\cdot\text{L}^{-1}$ for *Rhodospiridium paludigenum*. The production of trehalose under thermal stress was investigated, showing that temperature and exposure time affect yields. This study highlights promising strategies for the efficient production of trehalose, with implications for cosmetic and pharmaceutical applications.

Recent studies indicate that the sigma factor plays a crucial role in regulating the biosynthesis of corinomycolate and associated compounds in *Corynebacterium Glutamicum*, a related bacterium. This regulator is fundamental in the expression of genes involved in the synthesis of trehalolipids. In addition to their emulsifying properties, trehalolipids have shown significant potential in bioremediation, increasing the bioavailability of contaminants in the environment, making them useful in removing pollutants from soil and water. In addition, these molecules exhibit relevant antimicrobial activity against Gram-positive bacteria and some pathogenic fungi, making trehalolipids promising in the control of pathogenic microorganisms and the development of new antimicrobial agents. Due to all these characteristics, trehalolipids have aroused great interest in industry and scientific research, especially for their emulsifying properties and their applications in bioremediation and control of pathogenic microorganisms [142].

5.1.2. Lipopeptides

Lipopeptides are compounds produced by fungi, bacteria, and yeasts, characterised by a unique structure consisting of a peptide chain, composed of amino acids linked together, joined to a lipid chain made up of fatty acids or lipids. The link between the peptide part and the lipid part gives these compounds their unique properties. A notable example of a lipopeptide is surfactin, which has a structure composed of a peptide chain of seven amino acids joined to a lipid chain made up of fatty acids, as studied by Banat et al. [143].

Lipopeptides can modify the hydrophobicity of surfaces, making them more hydrophobic, and they interact with some mineral surfaces, making them valuable in various industrial applications, including the detergent, cosmetics, cleaning products and metallurgy industries [144–151].

Surfactin is a lipopeptide produced from culture broth of the bacterium *Bacillus subtilis*. There are three known variants of surfactin, called surfactin-A, surfactin-B and surfactin-C, which differ in the amino acids present in their rings [152].

The production of surfactin is detailed by Sullivan et al. [153]. In this process, multi-enzyme thio-templates synthesise the surfactin enzyme. The surfactin synthetase complex is composed of four enzyme subunits, including SrfA, SrfB, SrfC, and SrfD. SrfD plays a crucial role in the initiation cycle of production, while SrfA is an inducible operon for surfactin, stimulating sporulation and growth. Surfactin possesses remarkable surfactant properties, being able to reduce the surface tension of water by up to $27 \text{ mN}\cdot\text{m}^{-1}$.

Optimization of the production process allowed us to achieve approximately $860 \text{ mg}\cdot\text{L}^{-1}$ of biosurfactants from *Bacillus licheniformis*, a significant and promising achievement for commercial applications. Obtaining substantial quantities of biosurfactants is crucial for their industrial viability and large-scale use [154]. In addition to their industrial applications, these biosurfactants also have potential in environmental contexts, such as the bioremediation of contaminated soils and the removal of toxic compounds from aquatic environments. Liquesin's structural similarity to surfactin suggests that it may also exhibit antimicrobial properties and other interesting biological activities, further expanding its possible applications in various areas [152].

Zhao et al. [152] studied *Bacillus amyloliquefacies* for the synthesis of lipopeptides and revealed that the maximum yield in the production of these substances was consistently maintained in neutral and alkaline conditions. In contrast, acidic environments (with a pH below 5.0) resulted in a significant reduction in production, reaching zero, indicating a lack of lipopeptide synthesis under these conditions. Oliveira [155] investigated the production of lipopeptides by *Bacillus subtilis* R14 under different aeration and temperature conditions. The microorganism demonstrated the ability to produce antimicrobial compounds and surfactants during the growth phase, with the best results under conditions of oxygen restriction and a temperature of $30 \text{ }^\circ\text{C}$. In addition, the production of spores was observed and compounds such as surfactin and an antimicrobial compound were characterised by means of thin layer chromatography (SLC).

5.1.3. Fatty Acids, Phospholipids and Neutral Lipids

Phospholipids are substances widely produced during the growth of bacteria and yeasts on n-alkanes. Notable species, such as *Acinetobacter* spp. and *Thiobacillus trioxidans*, are recognized for their ability to synthesize phospholipid biosurfactants [123].

These molecules play a crucial role as essential components of cell membranes, especially when n-alkanes are used as a carbon source during the cultivation of these microorganisms. Phospholipids are fundamental to structural and functional integrity, presenting a basic structure composed of a glycerol molecule to which two fatty acid molecules are linked by ester bonds. In addition, a phosphate group is anchored to the glycerol molecule, providing a variety of phospholipids due to variations in their constituents [42].

Among the main types of phospholipids are phosphatidylinositol, whose chemical structure is observed in the manuscript presented by Motta [156], phosphatidylglycerol,

and phosphatidic acid. Each of these types varies in its structure and composition of fatty acids and phosphate groups [78,157].

The production of fatty acid surfactants occurs through the oxidation of alkanes, where microorganisms convert alkanes into fatty acids. These fatty acids are used in the synthesis of surfactants, compounds with a hydrophobic part represented by the fatty acid chain and a hydrophilic part made up of the polar functional group.

On the other hand, phospholipids play a dynamic and vital role as essential components of cell membranes in microorganisms and other cells [111]. Their structure, like the one mentioned above, comprises a glycerol molecule linked to two fatty acid molecules via ester bonds, as well as a phosphate group. This configuration gives phospholipids amphiphilic properties, making it possible to form lipid bilayers in cell membranes. A specific example is observed in the bacterium *Acinetobacter* sp. HOI-N, which, when using hexadecane as a substrate, produces phospholipids of the phosphatidylethanolamine type. However, it is important to note that this is just one of many possible phospholipid compositions, as different types can be synthesized by microorganisms in response to environmental conditions and available substrates [111].

5.1.4. Polymeric Biosurfactants

Polymeric biosurfactants, presented by Desai et al. [42], are high molecular weight biosurfactants that have been widely studied. In addition to emulsan, other examples include liposan, mannoprotein, and polysaccharide–protein complexes [158]. Various microorganisms, such as *Pseudomonas*, *Arthrobacter*, *Bacillus*, *Acinetobacter*, *Halomonas*, and *Candida*, can produce these biosurfactants. Each type of polymeric biosurfactant has unique structures and properties, which allow for a wide range of applications [159].

Due to their emulsifying properties and ability to reduce the surface tension between liquids and solids, polymeric biosurfactants have many potential applications. They can be used in a variety of industrial sectors, including oil, cosmetics, food, and agriculture, among others. In addition, polymeric biosurfactants have the advantage of being biodegradable and, in general, less toxic compared to traditional synthetic surfactants. This makes them more environmentally friendly and promising for use in bioremediation applications, where they can aid in the removal of pollutants and the recovery of contaminated soils [160].

Emulsan, a variety of polymeric biosurfactant, is classified as a heterolipopolysaccharide. Its intricate structure combines carbohydrate groups (polysaccharides) and lipid groups (fatty acids), linked by ester and amide bonds. This compound is predominantly produced by the bacterium *Acinetobacter calcoaceticus*. Its large-scale production can lead to a considerable molecular weight, reaching values of around 1000 kDa (kilodaltons) [122]. This high molecular weight is a fundamental characteristic of polymeric biosurfactants, resulting from the presence of several monomeric units connected in a continuous structure.

6. Application of Biosurfactants in Froth Flotation

With technological advances, environmental awareness has increased, resulting in the emergence of new legislation. As a result of this context, the demand for new biodegradable and non-toxic reagents in products has intensified [161]. Biosurfactants have emerged as a sustainable alternative to replace synthetic surfactants, which are often derived from petroleum resources and present significant environmental risks [162]. Due to their amphiphilic properties, surfactants play a crucial role in the metallurgical industry and are especially used in the froth flotation process for metal recovery [157].

Jia et al. [163] investigated a new biocollector, the biodegradable multiligand biosurfactant sodium myristoyl glutamate (SMG), developed for the flotation of smithsonite in zinc oxide ore. Smithsonite, a refractory ore, is difficult to separate from calcite with traditional flotation collectors. Microflotation experiments showed that SMG was an effective collector for smithsonite, achieving recovery of over 95% at a specific concentration. The addition of calcium lignosulfonate (CLS) as a calcite depressant resulted in a significant difference in flotation recovery rates between smithsonite and calcite. Adsorption analyses of the

collector on the mineral surface, including contact angle, zeta potential, Fourier transform infrared spectroscopy (FTIR), X-ray photoelectron spectroscopy (XPS), and atomic force microscopy (AFM), confirmed the strong adsorption of SMG on smithsonite. Furthermore, CLS was strongly adsorbed on the calcite surface and less adsorbed on the smithsonite surface. Calculations using density functional theory (DFT) confirmed that the amino group in SMG promoted the binding of carboxyl groups adjacent to metal sites on the mineral surface. These results indicate that SMG is a promising collector for the selective recovery of smithsonite from calcite through flotation due to its biodegradability and efficacy.

Hu et al. [164] studied a biosurfactant, Sodium Lauroyl Methyl Isethionate (SLMI), which was employed for the first time in an ion flotation process to remove heavy metal ions (HMs) from simulated wastewater, and compared to the conventional surfactant Sodium Dodecyl Sulphate (SDS). Operational parameters such as surfactant concentration, flotation time, initial pH, and ionic strength were investigated. A concentration of 200 mg/L of SLMI was effective in the removal of Pb, and a flotation time of 30 min proved efficient for Ni and Cu, with removal rates of up to 97.9% and 97.8%, respectively. The removal efficiency was above 98% at an initial pH above 8 and remained stable at low ionic strengths (0 to 0.5 g/L NaCl), but decreased at higher concentrations. The study suggests that SLMI could be an environmentally friendly alternative to SDS in ion flotation for the removal of HMs.

Chakankar et al. [165] investigated the effect of metallic ions, both individually and in a mixed system containing gallium (Ga) and arsenic (As), on the interfacial and foam formation properties of rhamnolipids, as well as rhamnolipid–metal interactions using isothermal titration calorimetry. The potential of rhamnolipids to recover and separate Ga from As was evaluated using bioionflotation. Ga, both alone and in a mixed system, had a notable effect on the properties of rhamnolipids compared to As alone. Operational parameters such as pH, rhamnolipid concentration, and air flow rate significantly influenced separation performance, with almost 74% of Ga removed at a rhamnolipid concentration of 0.85 mM, pH 6, and air flow rate of 80 mL/min. The selectivity of Ga over As was highest (17.2) at a rhamnolipid concentration of 0.85 mM, pH 6, and air flow rate of 40 mL/min. The selective separation of Ga depended on water recovery from the foam. The results provide insights into the properties of rhamnolipids and their efficiency as ion collectors for Ga, suggesting that optimised process parameters could provide efficient separation and recovery of the target metal through ion flotation.

Miettinen et al. [166] investigated the impact of enriched process microorganisms on flotation at Kevitsa mine, Finland, and the application of ion exchange in removing sulphur and microorganisms. An increase in microbial load improved flotation selectivity, especially for nickel. Two types of water, process water (PW) and final tailings (FT), exhibited different behaviours. Microorganisms did not affect Cu recovery from FT but reduced Cu recovery from PW. Ni recovery in Cu concentrate decreased, while Ni recovery in Ni concentrate increased with microorganism addition. Flotation of Ni with microorganisms produced a larger and more stable foam layer. Sulphate and thiosulphate ions did not significantly influence flotation. IX treatment effectively removed sulphur and microorganisms with DAF as a successful pretreatment. Microorganisms are often overlooked in process design and water cleaning techniques, but their consideration can lead to even better results.

Wang et al. [167] investigated microbial flotation as a green technology for mineral separation, specifically as an environmentally friendly depressant for chlorite. Exopolysaccharides (EPS) were extracted and purified from *Azotobacter vinelandii* (Av) and compared with commercial alginate. The results revealed that Av-derived EPS from different fermentation substrates exhibited various surface structures, compositions, and morphologies. Only some EPS variants showed effective chlorite inhibition, with scanning electron microscopy (SEM) analysis indicating that EPS with effective inhibition had a rough and porous surface morphology, similar to spherical structural units. EPS composition was investigated using colorimetric methods, identifying total carbohydrates, uronic acids, acetyl and pyruvyl groups, and proteins. Functional groups, such as acetyl groups (CH₃CO) and pyruvic acid (COCOOH), were detected in certain EPS variants and associated with the observed

inhibition effect on chlorite. These findings highlight the potential of Av-derived EPS as an environmentally friendly chlorite depressant.

Legawiec et al. [168] investigated how the biosurfactant rhamnolipid (RL) produced by *Pseudomonas aeruginosa* influences bubble adhesion to model surfaces with varying levels of hydrophobicity. The attachment time of a single bubble to solid surfaces with contact angles ranging from 6 to 80° was assessed at RL concentrations from 0 to 500 mg·dm⁻³ at pH 5 (non-ionic) and pH 10 (anionic). It was observed that increasing RL concentration prolonged the formation time of the triple-phase contact (TPC) due to increased film drainage time. Additionally, RL had a significant effect on TPC expansion (at a lower rate) and on the size of the contact area between the bubble and the surface (with a smaller surface area). This study contributes to a better understanding of the role of one of the most commonly used biosurfactants in the fundamental flotation process: the attachment of particles to bubbles.

Jia et al. [169] conducted research into the flotation of hemimorphite and quartz using the biosurfactant *N-lauroylsarcosinate* (LS). This compound is notable for having amide and carboxyl groups, giving it high reactivity and biodegradability. The study used microflotation tests to evaluate the froth flotation process, as well as fundamental analyses to clarify interaction mechanisms between the mineral surface and the collecting agent. Due to the presence of the amide and its shorter carbon chain, LS stands out as a soluble biosurfactant, reducing the likelihood of micelle formation, which is a favorable factor for flotation efficiency. LS showed significant selectivity for hemimorphite, especially when applied at a concentration of 3.4×10^{-4} mol./L⁻¹ at a pH of 7. Contact angle and zeta potential analyses indicated that LS interacted selectively with the surface of hemimorphite. Furthermore, the use of X-ray Photoelectron Spectroscopy (XPS) revealed that the dominant interaction is of a chemical nature and occurs between LS and hemimorphite.

Arias et al. [170] undertook a study focused on the flotation of copper sulfide, using microbial communities and indigenous bacteria as collecting agents for pyrite. Several bacterial strains were tested as biosurfactants, using both freshwater and seawater as media. The results showed that bacterial communities are highly influenced by the characteristics of the water used during the flotation process. The researchers found that native bacteria exhibited a striking and remarkable affinity for the pyrite mineral, making them promising candidates for the role of pyrite collectors.

Mwewa et al. [171] investigated the use of surfactin as a collecting agent in the flotation of sulfide minerals. As part of this study, fundamental analyses were carried out to understand the interaction between the mineral surface and surfactin. Using techniques such as zeta potential and FTIR, the researchers identified that surfactin adsorbed onto the surface of pyrite, showing a more significant interaction at neutral and alkaline pH. The predominant mode of this interaction was chemical. FTIR analysis suggested that adsorption occurs preferentially on the iron hydroxide sites present on the surface. The authors observed that, as the concentration of the biosurfactant was increased, there was an increase in metallurgical recovery, indicating a process of hydrophobization of the particles. The best metallurgical recovery rates were achieved at pH 10 and a concentration of 15 mg.L⁻¹, resulting in an approximate yield of 82%.

Legawiec et al. [67] conducted research into the influence of the biosurfactant rhamnolipid (RL) obtained from *Pseudomonas aeruginosa* on quartz flotation. In this study, the researchers investigated various factors, including interaction time, different concentrations, and pH, using contact angle techniques to analyze angle formation and solid–gas interactions at the interface. A central observation of this work was that pH proved to be a critical parameter in flotation using the rhamnolipid, with non-ionic interactions having the ability to stabilize the foam films. The application of the biosurfactant rhamnolipid increased the stability of the bubbles, which consequently prolonged the residence time, promoting greater adhesion and transport of the particles. The authors reported that very high concentrations of the biosurfactant harmed flotation kinetics, reducing the size of the bubbles and thus impairing the efficiency of the flotation process.

Zhang et al. [172] carried out a study on the reverse flotation of quartz present in iron ores, using different collectors: sodium oleate (NaOL), octylphenol ethoxylate (OP-10), nonylphenol ethoxylate (NP-10) and fatty alcohol ethoxylate (AEO-9). According to the results obtained by the authors, the recovery of minerals increased following the sequence OP-10, NP-10 and AEO-9. To better understand the interactions between these collectors and the surface, experiments involving FTIR analysis, contact angle measurements, and surface tension evaluations were carried out. These analyses revealed that NaOL adsorbed onto the quartz surface, increasing the hydrophobicity of the particles, followed by the order mentioned, OP-10, NP-10 and AEO-9. This trend was consistent with the floatability results observed. The authors concluded that the use of NaOL in combination with one of the alcohol ethoxylates increased floatability. This improvement was explained by the increase in hydrophobicity and better adsorption on the quartz surface. In addition, the surface tension results of the mixed system showed a decrease in surface tension and average surface area per NaOL molecule at the gas–liquid interface, which contributed to improved flotation performance.

Jia et al. [36], conducted a study on a new biosurfactant, sodium N-lauroyl sarcosinate (LS), for copper, lead, and chromium flotation. In this study, the authors compared the biosurfactant with a synthetic surfactant, sodium dodecyl sulfate (SDS). It was observed that LS showed superior recovery compared to the synthetic collector, achieving a remarkable 95% efficiency in the flotation of metal ions in isolation and 70% in the flotation of mixed ions. The researchers pointed out that the strategy used involved precipitating metal ions in an acidic medium, followed by separation through bubbles in the flotation process. Through XPS and FTIR analysis, it was elucidated that the sulfonic acid group of SDS and the carboxyl and amide groups of LS reacted in a complex way with the metal ions. Results from DFT calculations showed that LS has a more intense coordination reaction capacity with lead (Pb (II)) than SDS. Specifically, the carboxyl O in LS interacted with Pb (II) to form a stable bidentate coordination ring structure composed of two oxygen atoms and one Pb (II). The researchers concluded that LS showed superior performance in removing heavy metal ions from wastewater, emphasizing its degradable and environmentally friendly properties, which confer significant benefits to its application.

Biosurfactants, like synthetic surfactants, can modify the surface characteristics of mineral particles, making them more hydrophobic or hydrophilic depending on the properties of the ore and the flotation process used. This adjustment influences the adherence of air bubbles to mineral particles, playing a crucial role in the selectivity and effectiveness of the separation. However, it is crucial to note that the practical application of biosurfactants in mineral flotation is an intricate and constantly evolving field. The effectiveness of these substances in this context is influenced by several factors, including the nature of the ore, the chemical composition of the biosurfactants, and the process conditions.

On the other hand, it is important to recognize that the use of biosurfactants in flotation also presents challenges and limitations. One of the main advantages is that they are less toxic and more biodegradable than synthetic surfactants.

Despite these benefits, the industrial implementation of biosurfactants faces considerable challenges. These include the high cost of production, variations in chemical composition that can directly impact flotation efficiency, compatibility with conventional reagents, and stability under different pH values, concentrations, and temperatures. As such, the successful incorporation of biosurfactants into flotation requires meticulous approaches to overcome these issues and maximize their benefits.

7. Sustainability and Environmental Aspects

Biosurfactants have proven to be a highly favorable option in terms of environmental sustainability, especially when compared to traditional chemical surfactants. In addition to their natural and renewable origin, these biological molecules offer a few environmental benefits that contribute to preserving ecosystems and reducing the environmental impact of human activities [173,174].

One of the main advantages of biosurfactants, according to Baccile et al. [175], is their biodegradability. This characteristic results in a lower persistence of these substances in the environment, reducing the risk of contamination and accumulation in sensitive ecosystems. On the other hand, conventional chemical surfactants tend to be more persistent and can cause long-term environmental damage.

The use of biosurfactants in industrial processes such as mineral flotation not only reduces the release of toxic substances into the environment but can also lead to a reduction in the amount of waste generated. The efficiency of biosurfactants in separating minerals can result in greater recovery of valuable minerals, reducing wasted natural resources and the need for treatment and disposal of large volumes of solid and liquid waste [176].

In addition, the production of biosurfactants can have a significantly lower impact on greenhouse gas emissions. As these compounds are produced by microorganisms using renewable carbon sources, the manufacturing process can generate fewer CO₂ emissions compared to chemical surfactants derived from petroleum. This contributes to reducing the carbon footprint of industries that adopt biosurfactants, in line with the goals of combating climate change and the search for more sustainable practices [177].

Thus, biosurfactants offer a highly promising prospect for boosting sustainability and environmental aspects in various industrial applications, including mineral flotation. Their natural and renewable origin, biodegradability, waste reduction, and lower impact on greenhouse gas emissions position these molecules as an environmentally friendly and effective alternative to traditional chemical surfactants, contributing to a more bearable and well-adjusted future for our sustainability and circular economy regarding mineral resources [177].

8. Conclusions

After an in-depth analysis of the application of biosurfactants in mineral flotation, a clear vision of their transformative potential in mining practices emerges. Replacing synthetic surfactants with biosurfactants not only aligns the mining industry with environmental sustainability imperatives but also enhances the efficiency of mineral beneficiation processes. This study highlighted the superiority of biosurfactants across several key parameters, including biodegradability, reduced toxicity, and effectiveness in flotation environments. Therefore, the adoption of biosurfactants represents a significant advance for the mineral industry, promoting a balance between economic efficiency and environmental responsibility. Future research must focus on optimizing processes and reducing the production costs of biosurfactants, ensuring their economic viability and widespread adoption in the sector.

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