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Review

Understanding Bio-Based Surfactants, Their Production Strategies, Techno-Economic Viability, and Future Prospects of Producing Them on Sugar-Rich Renewable Resources

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Abstract

Bio-based surfactants have demonstrated significant potential as economically viable and environmentally sustainable alternatives to petroleum-derived surfactants, with the global biosurfactant market expanding from USD 4.41 billion in 2023 to a projected USD 6.71 billion by 2032, representing a compound annual growth rate of 5.4%. While conventional surfactants such as alkyl aryl sulfates and alkyl benzene sulfonates exhibit extremely high aquatic toxicity and impose substantial ecological costs, biosurfactants including lipopeptides (surfactin, iturin, fengycin, lichenysin) produced by *Bacillus* species and glycolipids (rhamnolipids, sophorolipids, trehalose lipids, mannosylerythritol lipids) from *Pseudomonas* demonstrate superior biodegradability. However, current biosurfactant production costs, ranging from 5 to20 USD/kg, cannot compete effectively with synthetic surfactants, averaging approximately 2 USD/kg, necessitating comprehensive process improvements to achieve commercial viability. The utilization of renewable agricultural feedstocks containing 65–70% carbohydrates, including corn stover, sugarcane bagasse, rice bran, and palm oil mill effluent, has achieved production costs as low as 3.8 USD/kg through advanced optimized pretreatment technologies, enzyme catalysis, simultaneous saccharification and fermentation (SSF), and downstream processes, resulting in cost reductions compared to conventional methods. The implementation of artificial intelligence and machine learning algorithms for bioprocess optimization enables simultaneous optimization of genetic engineering, metabolic pathways, and fermentation parameters, achieving yield improvements and cost reductions, with projections indicating production costs below 2.50 USD/kg being needed in the next decade to achieve cost parity with synthetic surfactants, maintaining economic viability.

Keywords: biosurfactants; agricultural waste valorization; artificial intelligence optimization; rhamnolipids; surfactin; lipopeptides; glycolipids; renewable feedstocks; techno-economic analysis; circular bioeconomy

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1. Introduction

Surfactants are amphiphilic molecules that consist of hydrophobic tail groups and hydrophilic polar head groups that provide them with their unique properties such as (a) emulsification, (b) dispersion, (c) lowering of the surface tension of a liquid. The fundamental principle which leads to many of these surface-active properties is creation of micellic structures around the surfactant molecule in aqueous solutions, leading to prevention

of coalescence of particles. Besides these fundamental properties, surfactants have also been shown to possess antimicrobial activity and food-product-modifying characteristics, allowing them to be used as baking agents and nutrition retention agents. These properties of surfactants allow multiple chemical applications, including as detergents, wetting agents, foaming agents, or dispersants, and food applications, such as baking agents, emulsifiers, and preservatives. Surfactant consumption globally was estimated to grow from USD 47.36 billion in 2024 to USD 70.13 billion by 2032 at a CAGR of 4.9% [1]

Conventional petroleum-based surfactants pose significant environmental and health challenges due to their toxicity, resistance to degradation, and bioaccumulation concerns [2]. Due to their molecular properties, wastewater treatments are insufficient to remove all surfactants from water sources, with approximately 60% of surfactants remaining untreated, necessitating disposal of contaminated water [3]. These compounds cause multiple ecosystem impacts including aquatic species mortality with genetic deformities, human toxicity and irritation, reduced photochemical energy conversion in plants, decreased sunlight availability for marine plants due to foam accumulation, and suppression of bacterial populations [2].

Surfactants can also be produced using biological feedstock either by growing bacteria on them or via enzyme esterification reactions. The bio-based feedstocks currently employed for surfactant production via catalysis through industrial catalysts and enzyme-based esterification are mainly hydrophobes in the form of seed oil rich in acyl groups with chain lengths of 12–16 carbons. Due to the potential environmental and health risks of synthetic surfactants, which could leach into groundwater tables or end up in the sea, dispersants from biological sources (biosurfactants) are favored for their biodegradability and lower toxicity. These molecules comprise diverse structural configurations, with hydrophilic moieties including acids, peptides, or mono- to polysaccharides linked to hydrophobic fatty acid chains, creating extensive application potential across food and non-food sectors. Despite superior environmental performance and expanding applications, biosurfactant production costs of 5–20 USD/kg significantly exceed synthetic alternatives at 2 USD/kg, necessitating transformative process improvements to achieve commercial viability [4,5].

Recent advances in computational optimization and bioprocess modeling have shown significant potential for improving biosurfactant production efficiency while reducing costs. Artificial neural networks combined with response surface methodology achieved 90% reliability in predicting biosurfactant production parameters and optimal harvesting times, with neural network models demonstrating excellent correlation coefficients of 0.93–0.909 for predicting both biomass growth and surface tension reduction [6]. Genetic algorithm optimization proved effective for parameter estimation and kinetic modeling in rhamnolipid production systems, successfully modeling complex relationships between substrate consumption, biomass growth, and product formation using renewable feedstocks such as glycerol [7]. Machine learning approaches, including neural networks and polynomial models optimized through particle swarm algorithms, show promise for modeling biosurfactant production from agro-industrial residues, offering new approaches for economically competitive and environmentally sustainable surfactant production through waste valorization and intelligent bioprocess control [8].

1.1. Objectives and Scope

This review attempts to identify the gaps in the understanding of the relationship between biosurfactant technological potential and commercial viability by systematically evaluating recent advances in bioprocessing parameters, economic competitiveness, and value addition to biosurfactants. The analysis encompasses four interconnected domains:

(1) molecular characterization of major biosurfactant classes including lipopeptides (surfactin, iturin, fengycin, lichenysin) and glycolipids (rhamnolipids, sophorolipids, trehalose lipids, mannosylerythritol lipids); (2) strategic utilization of renewable agricultural feedstocks for cost-effective production; (3) integration of artificial intelligence and advanced computational methods for process optimization; (4) assessment of circular bio-economy opportunities and market transformation dynamics.

The review aims to demonstrate that biosurfactants have reached a critical inflection point where technological maturation, economic viability, and environmental imperatives converge to enable large-scale displacement of synthetic surfactants. Particular emphasis is placed on quantitative techno-economic analyses that identify pathways to achieve lower production costs through integrated optimization approaches, positioning biosurfactants competitively against petroleum-based alternatives while delivering superior environmental performance.

1.2. Novel Approach

This review examines the current state of biosurfactant production technologies, exploring connections between molecular structures, agricultural waste utilization, and computational optimization approaches. The analysis suggests that machine learning applications in bioprocess control show promise for improving production efficiency, though further research is needed to validate these approaches at commercial scale. Computational tools, including artificial neural networks and genetic algorithms, have demonstrated potential for optimizing fermentation parameters and predicting production outcomes in laboratory studies [6,7].

The development of biosurfactant technologies may contribute to broader sustainability goals through reduced reliance on petroleum-based surfactants and increased utilization of agricultural residues. However, significant challenges remain in scaling production processes and achieving cost competitiveness with conventional surfactants. Current research indicates that integrated approaches combining waste valorization with process optimization could help address some economic barriers, though more work is needed to understand the full commercial potential.

This review highlights opportunities for continued research in biosurfactant production, particularly in areas where computational optimization, strain engineering, and substrate diversification intersect. Future studies should focus on validating laboratory-scale improvements in industrial settings and developing more comprehensive economic models to guide technology development decisions.

1.3. Properties and Functions of Biosurfactants

To understand the properties and functions of surfactants produced by microorganisms of all varieties, and their potential for utilization in food and non-food applications, it is important to identify the biological functions of surfactants for the microbes that produce them in their proliferation, growth, and metabolic activities. The major roles that surfactants play in the growth and metabolism of microbes are as follows: (a) adhesion, (b) emulsification, (c) bioavailability and desorption, (d) defense strategy. Adhesion is the most significant role played by surfactants produced by microorganisms and is a physiological mechanism that allows them to grow in different environmental conditions by attaching themselves to surfaces. These surfaces vary in their properties, chiefly between hydrophobic and hydrophilic surfaces. Microorganisms produce different types of surfactants to allow them to interact with hydrophobic surfaces to use hydrophobic molecules for uptake and metabolism, and some microbes utilize surfactants to immerse themselves in water and proliferate [9]. One of the classic examples of microbial adhesion through surfactants is

how *Pseudomonas aeruginosa* increases its cell hydrophobicity through the membrane-bound rhamnolipid, allowing it to adhere to hydrophobic molecules for metabolic uptake [9].

Emulsification is required by microbes to grow on water-insoluble substrates, which requires synthesis and release of high-molecular-weight emulsifying molecules to lower the surface tension between immiscible hydrophobic and hydrophilic layers and allow better availability of substrates for the microbes to grow on.

High-molecular-weight hydrophobic substrates prevent their microbial degradation by sorption on surfaces, thereby lowering their water solubility and availability for uptake. Surfactants produced by microbes ensure desorption of these high-molecular-weight substrates and increase their bioavailability. Table 1 shows a breakdown of biological functions of microbial surfactants.

Table 1. Primary biological functions of microbial biosurfactants and their mechanisms.

Function	Mechanism	Biological Significance
Adhesion	Surface attachment facilitation through hydrophobicity modulation	Environmental adaptation and substrate access
Emulsification	High-MW molecule synthesis for surface tension reduction	Growth on water-insoluble substrates
Bioavailability Enhancement	Desorption and solubilization of hydrophobic compounds	Substrate accessibility and uptake
Defense Strategy	Integrated utilization of all surfactant properties	Survival in diverse environments

Bio-based surfactants can be broadly classified into six major categories based on their chemical structure and functional groups (Table 2). These categories are (a) glycolipids, (b) lipopeptides, (c) fatty acid biosurfactants, (d) polymeric biosurfactants, (e) emulsifying proteins, (f) particulate biosurfactants. This review focuses on glycolipids and lipopeptides, and a brief explanation of the structural and chemical classifications of these two categories of surfactants has been explored further.

Table 2. Classification of bio-based surfactants and their molecular features.

Category	Description	Key Examples
Glycolipids	Carbohydrate–lipid conjugates containing sugar moieties linked to fatty acid chains	Rhamnolipids, Sophorolipids, Trehalose Lipids
Lipopeptides	Amphiphilic compounds with lipid moieties bound to peptide sequences	Surfactin, Iturin, Fengycin
Fatty Acid Biosurfactants	Modified fatty acid derivatives with enhanced surface activity	Corynomycolic Acids
Polymeric Biosurfactants	High-molecular-weight biopolymers with emulsifying properties	Emulsan, Alasan
Emulsifying Proteins	Protein-based emulsifiers with amphiphilic amino acid sequences	Subtilisin, Protease Enzymes
Particulate Biosurfactants	Vesicle- and particle-forming compounds including membrane fragments	Cell Wall Fragments

1.4. Lipopeptides: Structure and Diversity

Lipopeptides are amphiphilic compounds comprising a hydrophobic lipid moiety covalently linked to a hydrophilic peptide chain. The lipid component typically consists of fatty acid chains ranging from 10 to 16 carbons in length, while the peptide portion exhibits variable composition and length. These biosurfactants are predominantly produced by bacterial genera, particularly *Bacillus* and *Streptomyces*, as secondary metabolites with primary antimicrobial functions. The antimicrobial spectrum of lipopeptides encompasses antibacterial, antifungal, and hemolytic activities, with specific bioactivity profiles determined by carbon chain length and overall molecular architecture.

Surfactin is one of the most extensively studied lipopeptides that is synthesized by *Bacillus* species, most efficiently by *Bacillus subtilis*. It is a cyclic lipopeptide that contains a varying chain length (10–16 carbons) β-Hydroxy fatty acid nonpolar chain connected to a ring of amino acids forming the polar part of the amphiphilic molecule (Figure 1) [10]. Iturin is another class of lipopeptides synthesized by *Bacillus subtilis*, which is a cyclic lipoheptapeptide similar to surfactin, connected to a β-amino fatty acid chain, instead of a β-Hydroxy fatty acid in surfactin, as the nonpolar component of the molecule [11]. Fengycin is a class of lipopeptides generated by *Bacillus subtilis*, which again contains a β-Hydroxy fatty acid chain with C15-C17 variants in its isoforms connected to an Ala-Val dimorphy in the heptapeptide amino acid ring [12]. Lichenysin, another class of lipopeptides which is synthesized by the bacterial species *Bacillus licheniformis*, with a structure very similar to surfactin, contains a β-Hydroxy fatty acid chain connected to a cyclic ring of amino acids, with the main difference between the amino acid rings of surfactin and lichenysin being the presence of glutaminyl residue in position 1 instead of the glutamic acid residue in the cyclic peptide ring of surfactin [13].

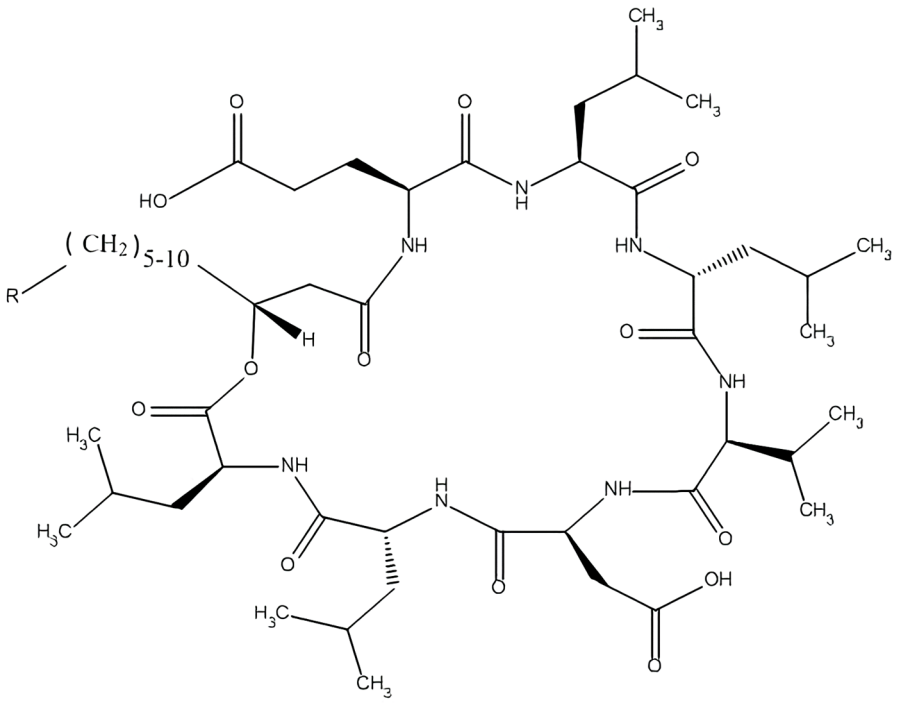


Figure 1. Molecular structure of surfactin.

1.5. Glycolipids

Glycolipids are a category of carbohydrates that are combinations of saccharide chains joined with long-chain aliphatic acids or hydroxy aliphatic acids. These saccharides can be mono-, di-, tri- and tetrasaccharides, including sugars such as glucose, mannose, galactose,

glucuronic acid, rhamnose, and galactose. Among glycolipids, rhamnolipids, trehalose lipids, sophorolipids, and mannosylerythritol lipids are selected as the main subjects as they hold the prime market share, attributed to high demand from end-use sectors, especially the cosmetic and personal care industries [14].

The major examples of glycolipids that have been characterized and studied extensively are trehalose lipids, rhamnolipids, sophorolipids, diglycosyl diglycerides, and mannosylerythritol lipids. Some of the other lesser-known reported glycolipids are glycoglycerolipid, sugar-based bioemulsifiers, and many different hexose lipids (Table 3). Glycolipids are mainly metabolized by two major categories of enzymes: (a) Glycosyltransferases, (b) Glycoside hydrolases. These biosurfactants are found on the surface of cell membranes extending out into the extracellular environment from the phospholipid bilayer. The main function of glycolipids is to act as cellular interaction recognition sites, where the saccharide unit of the glycolipid binds to complimentary carbohydrates to generate immune responses [15–17].

Rhamnolipids are glycolipids produced by *Psuedomonas aeruginosa*, along with other bacterial species, where the glycosyl unit is always a rhamnose sugar attached to a 3-(hydroxyalkanoyloxy) alkanoic acid (HAA) fatty acid tail (Figure 2). The two types of rhamnolipids produced are mono-rhamnolipids and di-rhamnolipids [16]. Trehalose lipids have been classified in many structural types where the C-6 and C-6′ positions in the trehalose sugar moiety are esterified by two or three hydroxyl groups and branched-chain fatty acids, such as α-branched and β-branched mycolic acids. These glycolipids have been reported to be synthesized by *Mycobacterium*, *Nocardia*, and *Corynebacterium* [18]. Sophorolipids have been reported to be mainly produced by yeasts such as *Torulopsis bombicola*, which can be structurally defined as a sophorose unit attached to a long-chain hydroxy fatty acid. These glycolipids are extremely low-toxicity compared to other biosurfactants and are highly biodegradable in nature [19]. Mannosylerythritol lipids are mannosylerythritol-sugar-containing glycolipids that are produced by yeast like *Candida antarctica* and other *Candida* species. In these glycolipids the sugar molecule is combined with different fatty acid components, mainly hexanoic, dodecanoic, tetradecanoinc, or tetradecenoic acids [20].

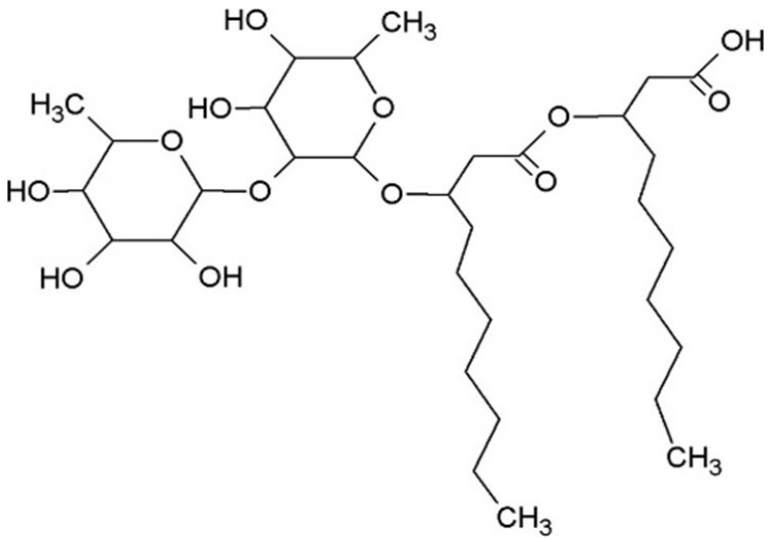


Figure 2. Molecular structure of di-rhamnolipid.

Table 3. Classification of major biosurfactant types, structural characteristics, and recent advances.

Category	Biosurfactant Type	Key Structural Features	Producing Microorganisms	Distinctive Properties and Applications	References
LIPOPEPTIDES	Surfactin	Cyclic heptapeptide with β-hydroxy fatty acid (C13–C16)	*Bacillus subtilis*, *B. amyloliquefaciens*, *Micromonospora marina*	Most extensively studied; excellent surface activity; strong antimicrobial properties	[10]
	Iturin	Cyclic lipoheptapeptide with β-amino fatty acid (C14–C17)	*Bacillus subtilis*, *Paenibacillus polymyxa*	Strong antifungal activity; hemolytic properties; biocontrol applications	[21]
	Fengycin	Cyclic decapeptide with β-hydroxy fatty acid (C15–C17)	*Bacillus subtilis*, *Paenibacillus polymyxa*	Antifungal activity; cell membrane interaction; agricultural biocontrol	[22]
	Lichenysin	Cyclic heptapeptide with β-hydroxy fatty acid; Gln at position 1	*Bacillus licheniformis*	Similar to surfactin; enhanced oil recovery applications; thermostability	[13]
GLYCOLIPIDS	Rhamnolipids	Mono/di-rhamnose linked to 3-(hydroxyalkanoyloxy) alkanoic acid	*Pseudomonas aeruginosa*, *P. putida*	Most commercialized; excellent emulsification; environmental applications	[23]
	Sophorolipids	Sophorose disaccharide with hydroxy fatty acid; acidic/lactonic forms	*Starmerella bombicola*, *Wickerhamiella domercqiae*	Low toxicity; high biodegradability; cosmetic and pharmaceutical uses	[24]
	Trehalose Lipids	α-1,1-linked glucose with esterified mycolic acids at C-6/C-6′	*Mycobacterium*, *Nocardia*, *Rhodococcus*, *Corynebacterium*	High pH and temperature stability; bioremediation applications	[25]
	Mannosylerythritol Lipids (MELs)	Mannose-erythritol with fatty acids; variable acetylation (MEL-A to MEL-D)	*Pseudozyma* sp., *Candida antarctica*, *Ustilago maydis*	Anti-inflammatory; antimicrobial; anticancer; drug delivery; skin repair	[26,27]
	Cellobiose Lipids	β-1,4-linked glucose with fatty acid esters; optional acetyl groups	*Ustilago* species	Excellent surface activity; co-produced with MELs; industrial applications	[28]

2. Production of Bio-Based Surfactants

2.1. Production of Bio-Based Surfactants Through Enzymatic Synthesis

Enzymatic biosurfactant synthesis from sustainable and secondary feedstocks offers a promising approach for producing environmentally friendly surface-active compounds. This enzymatic approach can transform waste streams into valuable biosurfactants while addressing environmental disposal challenges. The synthesis of these molecules by enzymatic activity is an opportunity in accordance with the need for more sustainable and greener processes [29]. Various enzyme classes including lipases, glucosidases, phospholipases, and proteinases have been successfully employed to catalyze the formation of biosurfactants from renewable feedstocks such as agricultural waste, food processing residues, and industrial by-products. Table 4 presents a summary of enzyme catalyzed biosurfactants and reaction schemes.

Lipases represent the most widely studied enzyme class for biosurfactant production, operating through esterification and transesterification reactions to produce sugar fatty acid esters from waste cooking oils, lactose whey, and lignocellulosic sugars [29,30]. Glucosidases, particularly through transglycosylation mechanisms, enable the synthesis of alkyl glucosides and glyceryl glycosides from sucrose-rich waste streams, with reported al-

coholysis/hydrolysis ratios reaching 5.1 under optimal conditions [31,32]. Phospholipases and proteinases have also demonstrated potential for converting phospholipid-rich waste and protein-containing residues into functional biosurfactants, respectively [33,34].

Table 4. Summary of enzyme-catalyzed biosurfactants and reaction schemes.

Enzyme Class	Feedstock Examples	Reaction Type	Examples	Features	Reference
Lipases	Waste cooking oils, lactose whey, mixed hardwood xylose/glucose	Esterification/ transesterification	Sugar fatty acid esters, lactose esters	High selectivity, mild conditions	[29,30]
Glucosidases	Sucrose-rich waste (molasses), glyceryl caprylate/caprate	Transglycosylation	Glyceryl glycosides, alkyl glucosides	Alcoholysis/ hydrolysis	[31,32]
Phospholipases	Phospholipid-rich waste, biodiesel co-products	Hydrolysis of sn-1 ester bonds	Lysophospholipids, modified phospholipids	Compatible with lipase systems	[34]
Proteinases	Protein-rich waste, metagenomic sources	Hydrolysis/ modification	Protein-derived biosurfactants, peptide surfactants	Oil degradation activity, detergent compatibility	[33]

2.2. Microbial Production of Bio-Based Surfactants: A Comparison of Metabolic Frameworks and the Role of Growth Media in Surfactin and Rhamnolipid Synthesis

Both *Bacillus* and *Pseudomonas* species have evolved intricate genetic strategies for producing biosurfactants. Figure 3 shows that both rely on two quorum-sensing systems (QSSs), the way these systems are organized and regulated differs markedly between the two genera [35,36].

In *Bacillus*, surfactin synthesis is managed through two linked QSSs that act together to regulate the srfA operon—the central hub for surfactin production [37,38]. The first system revolves around four open reading frames (srfAA, srfAC, sfp, and Sfp) within the srfA operon. These genes are directed by nonribosomal peptide synthetases (NRPSs), which assemble β-hydroxytetradecanoic acid, the hydrophobic tail of the surfactin molecule [10,39]. The enzymes and binding proteins they encode influence transcription across all srf genes, while also determining how amino acids are incorporated into surfactin's distinctive seven-amino-acid ring [40,41]. The second system operates through a "Com" signaling cascade involving ComQ, ComP, phosphorylated ComA, and ComS. Its signal molecule, ComX, senses cell density and interacts with membrane-bound ComP, which then works with ComA to activate srfA expression when the population reaches a critical threshold [42–45].

In *Pseudomonas* species, rhamnolipid production follows a more layered, hierarchical QSS design. Two systems, positioned at different locations on the chromosome, work together to form a complex regulatory network [46,47]. The rhl system plays the direct role in synthesis: rhlA and rhlB encode inner membrane proteins for rhamnosyltransferase I and II, while rhlR produces a transcriptional activator and rhlI generates the autoinducer N-butanoyl-L-homoserine lactone (PAI-2), enabling the production of both mono- and di-rhamnolipids [48,49]. Overseeing this, the las system regulates rhlR via its own autoinducer, N-(3-oxodecanoyl)-L-homoserine lactone (PAI-I). This allows not only upstream gene regulation but also post-translational control through PAI-II binding prevention, with environmental responsiveness mediated by cyclic AMP levels [50–52].

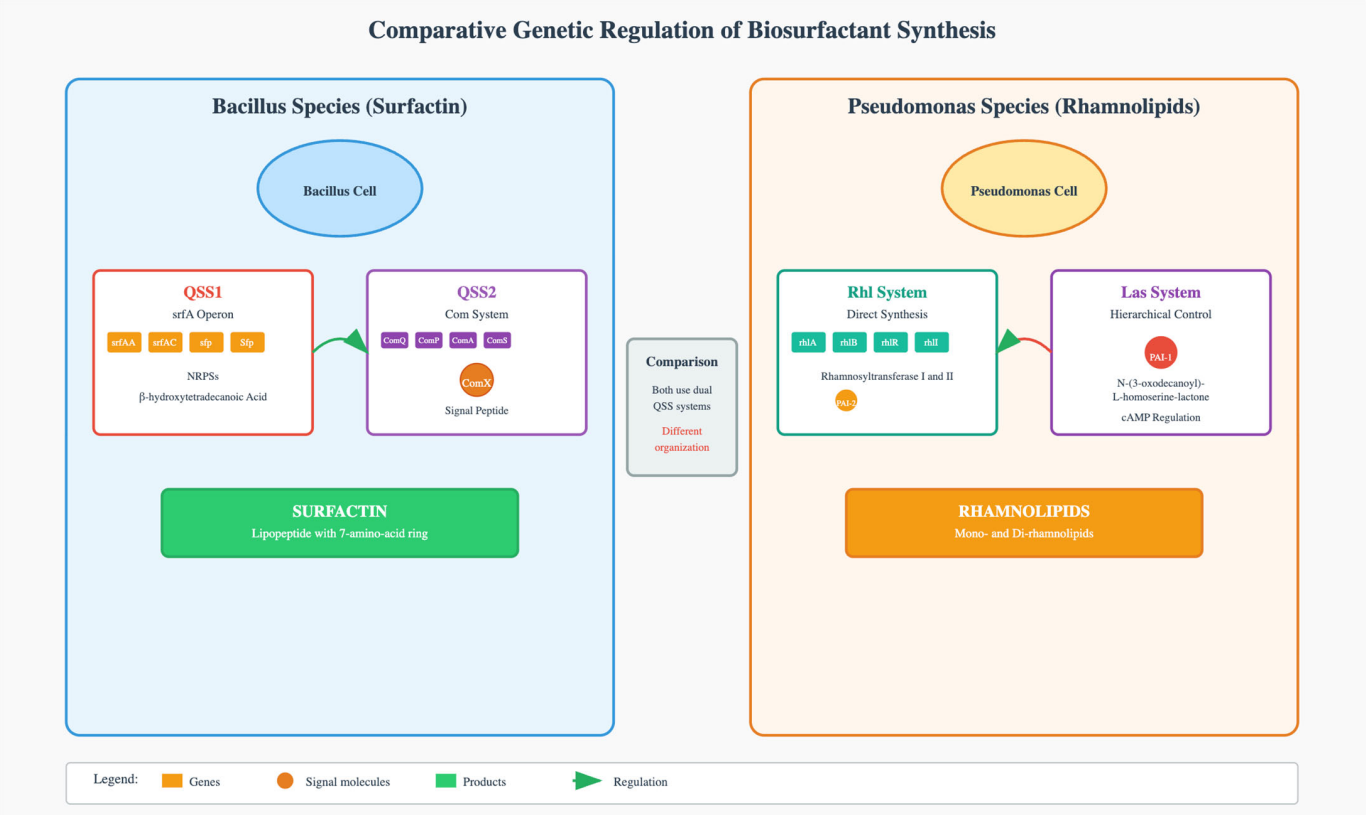


Figure 3. Comparative genetic regulation of surfactin and rhamnolipids.

The enzymatic differences between *Bacillus* and *Pseudomonas* appear to reflect distinct evolutionary pathways, each presenting unique characteristics and constraints worth investigating further [44,53]. In *Bacillus*, surfactin synthesis involves NRPSs in assembling the amino acid ring and fatty acid chain, creating a structurally complex molecule. This pathway demonstrates notable sensitivity to fermentation media composition—factors such as hexose sugar concentration, pH, and trace element content appear to significantly influence yields [54,55]. While this sensitivity may present production challenges, it also suggests opportunities for optimization through media manipulation. Wu et al. (2019), for instance, observed a 20-fold yield increase to 8.5 g/L through deletion of biofilm-associated genes and enhancement of branched-chain fatty acid supply [56]. Zhang et al. (2020) reported even more substantial improvements, documenting a 678-fold enhancement in *B. amyloliquefaciens* through targeted srfA operon engineering [57]. However, surfactin's low water solubility—attributed to the five hydrophobic amino acids in its polar ring—appears to remain a persistent constraint. Investigations aimed at improving solubility, such as those described by Reznik et al. (2009), achieved their intended goal but resulted in titer reductions from 3–4 g/L to 0.2–0.3 g/L, suggesting inherent trade-offs in biosurfactant optimization [58].

In contrast, *Pseudomonas* rhamnolipid synthesis appears to rely on specialized rhamnosyltransferases for glycolipid backbone construction and may benefit from the adaptability of its hierarchical quorum-sensing regulation. The las pathway's ability to modulate rhl activity via cyclic AMP suggests a mechanism that enables dynamic responses to environmental changes [59,60]. This regulatory flexibility appears to support the utilization of diverse renewable substrates.

Comparative analyses suggest that each biosynthetic approach holds particular advantages for different research objectives [61,62]. *Bacillus*-based production demonstrates considerable potential for yield improvement through targeted genetic modifications,

though their integrated quorum-sensing architecture and NRPS dependence may create sensitivities to environmental and media variables—alongside solubility limitations [63]. The *Pseudomonas* approach, characterized by spatially separated regulatory circuits and dual autoinducer networks, appears to provide greater flexibility in substrate utilization and environmental adaptability, potentially making it well-suited for sustainable production using renewable feedstocks [64,65].

Recent research continues to explore the practical implications of these mechanistic differences [66,67]. Understanding each approach's characteristics and limitations may help researchers select appropriate biosurfactant platforms for specific research objectives and experimental constraints [68,69].

2.3. Media Optimization and Upstream and Downstream Processing in Biosurfactant Production

While understanding the genetic regulatory mechanisms underlying biosurfactant synthesis may provide a foundation for strain improvement, optimizing production appears to require comprehensive approaches that address both upstream fermentation conditions and downstream processing challenges. The complex quorum-sensing mechanisms described for both *Bacillus* and *Pseudomonas* species demonstrate notable sensitivity to media composition [70,71], suggesting that the selection and optimization of carbohydrate sources represents a critical factor worth investigating in achieving higher production titers. This sensitivity appears to create both opportunities and constraints that warrant careful consideration when exploring the genetic potential of engineered strains.

The choice of carbohydrate source in fermentation media appears to significantly influence both cellular growth and the synthesis of biosurfactant structural components, particularly given the metabolic demands of the complex regulatory networks governing surfactin and rhamnolipid production [72]. Traditional approaches utilizing purified carbohydrates like glucose and glycerol have provided valuable insights into optimal growth conditions, though economic and environmental considerations increasingly suggest exploring renewable, non-purified carbohydrate sources derived from agricultural wastes and fibrous biomass such as switchgrass [72,73]. However, utilizing these complex carbohydrate sources may present significant challenges, particularly the potential need for effective lignin degradation and cellulosic decrystallization through physical, chemical, or enzymatic pretreatment to generate fermentable sugars. The metabolic complexity appears to increase further when considering how biosurfactant-producing microbes might process composite sugar mixtures, pentose sugars, and various polysaccharide structures commonly found in renewable feedstocks. Given that the *Bacillus* ComX signaling pathway and *Pseudomonas* hierarchical quorum-sensing networks demonstrate sensitivity to hexose availability, pH, and trace elements [70,74], successful implementation of renewable carbohydrate sources may require careful optimization that complements these genetic regulatory requirements while maintaining the delicate balance of media components necessary for maximum biosurfactant expression.

The transition from laboratory flasks to bench-scale bioreactors represents a necessary step in understanding biosurfactant production feasibility and identifying the technical considerations that would influence eventual commercial development. While flask cultivation provides initial insights, bench-scale bioreactors (typically 2–50 L) allow researchers to examine how process parameters interact under more controlled conditions and begin to assess whether the production economics might support larger-scale operations [75]. Bench-scale systems introduce several variables that are not present in flask studies. Temperature, pH, oxygen supply, and nutrient feeding can be monitored and adjusted continuously, but this also reveals new challenges such as foam formation and the importance of mass transfer rates. Most bench-scale studies use stirred-tank reactors because they are well-

characterized and allow systematic parameter variation, though air-lift reactors are being explored to understand whether different mixing approaches might offer advantages [75].

From the available literature, operating conditions for bench-scale biosurfactant production generally fall within predictable ranges: aeration rates of 1–1.5 vvm, agitation speeds of 100–250 rpm, and temperatures of 28–37 °C for common bacterial and yeast producers. However, pH requirements vary considerably depending on the organism—bacterial systems typically operate at around pH 6–8, while some Candida species prefer pH 5.3–5.5, and alkaliphilic bacteria may require pH 8–9 [75]. These studies help identify which parameters are most critical for maintaining productivity and begin to address questions about substrate costs—a key factor in any future commercial assessment. Many researchers are investigating waste materials like used cooking oils and agricultural by-products as alternatives to pure substrates, with bench-scale concentrations of 10–40 g/L being reported under optimized conditions [76,77]. Recent bench-scale investigations have provided useful insights into how different organisms respond to various operational approaches, revealing some interesting patterns that were not apparent in flask studies. For instance, work with Salibacterium sp. 4CTb in stirred-tank reactors found that lower aeration conditions (0.48 vvm) actually supported better biosurfactant production than higher oxygen supply rates, achieving 74.55% emulsification efficiency at modest agitation speeds (540 rpm) [78]. This suggests that the relationship between oxygen availability and productivity is not always linear, which has implications for understanding energy costs in any future scale-up.

Similarly, studies comparing air-lift reactor performance found that *Bacillus atrophaeus* responded differently to operational parameters than organisms in stirred-tank systems, performing optimally at 1.00 vvm aeration and 34 °C [79]. These differences highlight how reactor design choices could influence both productivity and operating costs at larger scales. These bench-scale studies begin to address several questions that would be critical for any commercial biosurfactant production: substrate flexibility, process robustness, and productivity levels. The successful use of waste materials like animal fats and food processing by-products in several studies suggests that raw material costs—typically a major factor in bioprocess economics—might be manageable. Concentrations in the 10–40 g/L range, while still modest compared to some chemical surfactants, indicate productivity levels that could potentially support commercial operations if downstream processing costs can be controlled.

The variability in optimal operating conditions across different organisms also suggests that strain selection might be as important as process optimization in determining commercial viability. Some organisms appear more tolerant of operational variations, which could reduce process control costs, while others achieve higher productivities under specific conditions that might require more sophisticated control systems. Perhaps most importantly, these bench-scale studies reveal that biosurfactant production involves trade-offs between productivity, substrate costs, and process complexity that are not apparent in flask studies. Understanding these relationships will be essential for determining whether any particular biosurfactant–organism combination might eventually support commercial production and under what economic conditions that might become viable.

One persistent challenge in bench-scale biosurfactant production has been foam management, which becomes more problematic as vessel size increases. Xu and colleagues (2020) explored an ex situ foam control approach that reduced foam accumulation by 51–73% while maintaining rhamnolipid concentrations of 48.67 g/L [80]. Their work with repeated fed-batch operation suggests that it might be possible to work with foam formation rather than simply trying to prevent it, potentially reducing the need for chemical additives that could complicate downstream processing. The use of automated mini-bioreactor

systems has also provided insights into parameter sensitivity. Work with *Pseudomonas* marginalis indicated that mixing intensity (300 rpm) had a greater impact on production than oxygen supply rates, suggesting that understanding mass transfer characteristics might be more important than simply maximizing dissolved oxygen levels [81].

Beyond fermentation optimization, downstream processing appears to represent another critical area of investigation that could significantly impact the feasibility of biosurfactant production, reportedly accounting for approximately 70–80% of total production costs [66,67,82] and requiring sophisticated separation strategies that complement the molecular diversity produced by different genetic approaches. The downstream processing workflow typically involves clarification of fermentation broth through homogenization, centrifugation, or membrane filtration, followed by solubilization and concentration using various solvent extraction methods, including chloroform–methanol, dichloromethane–methanol, and other organic solvents [83,84], and culminating in purification steps that may achieve greater than 90% purity through removal of cellular debris, unwanted proteins, and ionic contaminants. Recovery yields for surfactin have been reported to range from 2.4 to 6.0 g/L in batch fermentations [85], with Chen & Juang (2008) [86,87] achieving approximately 97% recovery through combined liquid–liquid extraction and dead-end filtration after acid precipitation, while rhamnolipid recovery has demonstrated 84% efficiency using ultrafiltration strategies [88]. However, what appears to be the most challenging aspect of biosurfactant purification involves molecular separation of target compounds from structurally similar molecules produced by the same microorganisms, a problem particularly evident in *Bacillus*-based production where surfactin synthesis occurs alongside other lipopeptides like iturin and fengycin [89,90] and in the separation of surfactin isoforms that differ in methyl group positioning (C10–C16 variants) [91]. These purification challenges appear to relate directly to the genetic complexity discussed earlier, as the sophisticated regulatory networks that enable high production titers also seem to result in the simultaneous synthesis of multiple related compounds, potentially requiring advanced separation techniques such as preparatory HPLC to achieve the molecular purity necessary for various applications [84,91]. Understanding both the genetic basis for this molecular diversity and developing appropriate downstream processing strategies may represent a critical integration point where metabolic engineering achievements could be translated into feasible production processes [66,67,92].

3. Use of Renewable Agricultural Feedstocks and Food Residues as Nutritional Inputs for Biosurfactant Production

The exploration of agricultural waste as feedstock sources presents promising possibilities for biosurfactant production within biorefinery frameworks. Research suggests that substrates account for 10–30% of total production costs, making the investigation of low-cost waste materials particularly important for developing cost-effective strategies [93]. Agricultural residues offer substantial potential due to their availability and composition, though extracting fermentable components presents several challenges related to their complex lignocellulosic structure.

Understanding the structural complexity of agricultural biomass appears essential for effective utilization. The recalcitrant nature of lignocellulosic materials often requires pretreatment approaches to enhance accessibility for microbial conversion. Researchers have identified various pretreatment methods including physical approaches (size reduction, ultrasonication), chemical methods (acid/alkaline hydrolysis), and biological treatments using enzymes. Each approach presents distinct advantages and limitations in terms of efficiency, cost, and downstream processing requirements [93].

Research demonstrates that various agricultural waste streams can serve as substrates for biosurfactant production. Table 5 presents examples from verified studies exploring different feedstocks. Studies have shown potential with fruit and vegetable wastes for rhamnolipid production using *Pseudomonas aeruginosa*, with orange peel producing 9.18 g/L of rhamnolipid and achieving surface tension reduction to 31.3 mN/m [94]. A variety of bio-based substrates have been reported to produce biosurfactants through fermentation, including glycerol, starch, soybean meal, sucrose, biodiesel–glycerol, orange peels, banana peels, corn pith, and fermented soybeans. Studies show significant variation in yields: *Bacillus velezensis* strain H3 achieved 0.88 g/L surfactin production on 2% starch, while higher yields of 1.8 g/L were observed with composite carbon sources using cheese whey and glucose compared to pure sugars [95,96]. Remarkably, *Lactobacillus delbrueckii* produced glycolipids at 5.35 g/L using peanut oil, and *Brevibacterium aureum* MSA13 achieved an 18 g/L lipopeptide yield using pretreated molasses [97–99]. However, several factors contribute to variability, including feedstock heterogeneity, pretreatment requirements, microbial strain variations, and complex interactions between substrate composition and fermentation parameters. These inconsistencies in product yield and substrate uptake patterns may result from differences in molecular characterization methods, fundamental understandings of substrate uptake mechanisms, potential substrate/product toxicity, and interactions with other media components [93]. Table 6 presents a list of various agricultural wastes and fibrous biomasses for biosurfactant production.

Table 5. Summary of recent advancements in bioreactor performance and optimization parameters.

Microorganism	Biosurfactant	Optimized Parameters	Reactor Type	Performance Highlights	References
Salibacterium sp. 4CTb	Lipopeptide	540 rpm, 0.48 vvm, 37 °C, pH 9.0	Stirred-Tank	E_{24}% = 74.55%, Yield = 0.76 g/g, kLa = 31 1/h	[78]
B. atrophaeus ATCC-9372	Iturin	1.00 vvm, 34 °C, pH 7.0	Air-Lift + Foam Fractionation	E_{24}% = 66.9%, Productivity = 967.5% mL h^{-1}	[79]
P. marginalis C9	Rhamnolipid	300 rpm, pH 8.5, 25 °C	Mini-Bioreactor (DASbox®)	7.40 g/L, CMC = 48.9 mg/L, E_{24}% = 66.9%	[81]
P. aeruginosa KT1115	Rhamnolipid	400 rpm, 1 vvm, 30 °C, pH 7.0	Ex Situ Foam Control + Fed-Batch	48.67 g/L, Yield = 0.67–0.83 g/g	[80]
C. lipolytica UCP0988	Glycolipid	200 rpm, 28 °C, pH 5.3, 120 h	50 L Batch Bioreactor	40 g/L (Scale-Up from 10 g/L at 2-L)	[75]

Table 6. Summary of utilization of various agricultural wastes and fibrous biomasses for biosurfactant production.

Feedstock	Microorganism	Biosurfactant Type	Yield/Key Findings	References
Orange peel	*Pseudomonas aeruginosa* MTCC 2297	Rhamnolipid	9.18 g/L yield; surface tension reduced to 31.3 mN/m	[94]
Banana peel	*Halobacteriaceae archaeon*	Lipopeptides	Used as sole carbon source for biosurfactant synthesis	[100]
Cashew apple juice	*Acinetobacter calcoaceticus*	Cellular polyanionic amphipathic heteropolysaccharide	Surface tension reduction up to 17%	[101]
Feather meal, potato peel, and rape seed cake	*Bacillus subtilis* PF1	Lipopeptide	Simultaneous production with protease and amylase	[102]
Cassava wastewater	*Pseudozyma tsukubaensis*	Mannosylerythritol lipids (MELs)	Novel production and purification approach	[103]
Starch (2% *w*/*v*)	*Bacillus velezensis* strain H3	Surfactin	Maximum yield of 0.88 g/L	[96]
Peanut oil	*Lactobacillus delbrueckii*	Glycolipid	Yield of 5.35 g/L	[98]
Pretreated molasses (4% *w*/*v*)	*Brevibacterium aureum* MSA13	Lipopeptide	Yield of 18 g/L	[97]

The utilization of agricultural residues for biosurfactant production represents an interesting intersection of waste valorization and biotechnology. While challenges exist in terms of feedstock variability, pretreatment requirements, and process optimization, continued research in bioconversion methods may help unlock the potential of these abundant renewable resources. Understanding the fundamental relationships between feedstock composition, pretreatment conditions, and biosurfactant production appears essential for advancing this field [93]. The complexity of agricultural biomass conversion suggests that successful implementation will require interdisciplinary approaches addressing both technical and economic considerations for sustainable production systems.

Techno-Economic Viability of Biosurfactant Production Through Renewable Feedstock

Contemporary techno-economic analyses have identified downstream processing as the primary cost driver in biosurfactant production, accounting for 60–80% of total manufacturing expenses [4]. Recent studies employing advanced process modeling and optimization strategies have demonstrated significant improvements in economic competitiveness for agricultural waste-based production systems. Process integration strategies, including simultaneous saccharification and fermentation (SSF), in situ product recovery, and enzyme recycling systems, have promised significant processing and operational

costs. The implementation of these technologies has the potential to lower processing time, downstream costs, and enzyme-related expenses [104].

A techno-economic assessment of surfactin production from soy hull conducted by our team [105] demonstrates remarkable improvements through process intensification strategies. The analysis considers a 200-metric-tonne biomass processing facility incorporating advanced unit operations including optimized pretreatment, enzymatic hydrolysis with enzyme recycling, fed-batch fermentation, and integrated downstream processing.

The enhanced biorefinery model achieves production costs of 3.83 USD/kg for surfactin, representing a 42.2% reduction compared to the original process design. This cost structure positions soy-hull-derived surfactin competitively against commercial sophorolipids (2.95 USD/kg) and rhamnolipids (5.00 USD/kg), while providing superior environmental benefits including reduced carbon footprint and waste stream minimization [5].

The integration of agricultural waste utilization for bioenergy and value-added biochemical production represents a strategically important development in the transition toward circular bio-economy principles. Technological convergence points toward achieving cost parity with synthetic surfactants for optimized biorefinery operations, particularly those utilizing high-yielding feedstocks such as palm oil mill effluent and rice bran. Critical success factors for commercial viability include the following: (1) establishment of reliable feedstock supply chains through long-term contracts with agricultural cooperatives; (2) continuous process optimization focusing on conversion efficiency and product recovery; (3) development of premium market segments emphasizing sustainability attributes; (4) leveraging regulatory advantages through environmental compliance requirements; (5) integration of advanced technologies including artificial intelligence for process optimization and predictive maintenance [106,107].

4. Future Scope

The integration of artificial intelligence and machine learning technologies has emerged as a promising approach for optimizing biosurfactant production processes, addressing the critical challenge of high production costs that limit commercial viability. Recent advances demonstrate that AI-driven optimization can achieve significant improvements in both process efficiency and product quality. Neural network models combined with response surface methodology have shown remarkable predictive accuracy, achieving 90% reliability in forecasting biosurfactant production parameters and optimal harvesting times [6]. These models demonstrate excellent correlation coefficients of 0.93–0.909 for predicting biomass growth and surface tension reduction, with optimized conditions yielding a 48% surface tension reduction in fermentation broth and a 63% reduction in isolated products [6].

Machine learning algorithms, particularly genetic algorithms, have proven effective for parameter estimation and kinetic modeling in biosurfactant production systems. These approaches successfully model complex relationships between substrate consumption, biomass growth, and product formation, with genetic algorithm optimization demonstrating superior performance in rhamnolipid production kinetics using renewable feedstocks such as glycerol [7]. The application of AI tools extends beyond single-parameter optimization to multi-objective bioprocess enhancement, where artificial neural networks can simultaneously predict multiple output parameters including optical density and surface tension [6]. However, comprehensive studies on AI-driven optimization for large-scale biosurfactant production remain limited, representing a significant opportunity for future research and development in achieving cost-competitive biosurfactant manufacturing.

5. Conclusions

This comprehensive review demonstrates that bio-based surfactants have reached a critical inflection point where technological maturation, economic viability, and environmental imperatives converge to enable large-scale market displacement of conventional surfactants. The strategic utilization of renewable agricultural feedstocks containing 65–70% carbohydrates has achieved sub-competitive production costs for various biosurfactants, with advanced process integration demonstrating potential cost reductions compared to conventional approaches, positioning biosurfactants competitively against synthetic surfactants (2–4 USD/kg). The detailed characterization of biosurfactant molecular structures, including lipopeptides and glycolipids, reveals remarkable structural diversity that enables superior performance characteristics, enhanced stability across pH and temperature ranges, complete biodegradability, and minimal environmental toxicity compared to synthetic alternatives.

The integration of artificial intelligence, machine learning, and digital twin technologies represents a quantum leap opportunity for biosurfactant production optimization, enabling simultaneous optimization of multiple process variables and achieving yield improvements and cost reductions. The implementation of integrated biorefinery concepts demonstrates the potential to achieve system-wide cost reductions through optimized resource flows and AI-enabled process integration, addressing the multi-variable nature of biosurfactant production challenges while creating economically resilient and environmentally sustainable production networks. Current market analysis indicates rapid growth in the biosurfactant sector, with projections reaching USD 6.71 billion by 2032 at a 5.4% CAGR, driven by the convergence of technological maturation, regulatory support for bio-based products, and increasing corporate sustainability commitments.

Future research priorities should focus on integrated systems optimization that simultaneously addresses genetic engineering, metabolic pathway optimization, and downstream processing integration, alongside development of AI-enabled bioprocess intelligence incorporating real-time sensor data and predictive models for autonomous process control. The establishment of robust supply chains through blockchain-enabled traceability systems and strategic partnerships with agricultural cooperatives represents a critical success factor, while proactive regulatory framework development will facilitate market acceptance and provide competitive advantages for bio-based products. The widespread adoption of biosurfactants derived from agricultural waste represents a transformative opportunity to address multiple societal challenges simultaneously, contributing directly to waste reduction, rural economic development, and greenhouse gas emission mitigation.

The evidence presented demonstrates that bio-based surfactant production from renewable agricultural feedstocks has the potential to achieve technological and economic readiness for large-scale commercial implementation, with the convergence of advanced biotechnology, AI-driven optimization, and favorable market dynamics creating unprecedented opportunities for sustainable chemistry transformation. The quantum leap in production efficiency enabled by integrated optimization approaches, combined with the inherent environmental advantages of biosurfactants, positions this technology as a cornerstone of the emerging bio-based economy that delivers superior performance while advancing environmental stewardship and economic prosperity. As the global community confronts the urgent challenges of climate change, resource depletion, and environmental degradation, bio-based surfactants represent a tangible pathway toward sustainable industrial chemistry, with the time for transformation having arrived and the tools for success within reach.

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