International Journal of Agricultural Technology 2026 Vol. 22(6):2589-2622
DOI: https://doi.org/10.63369/ijat.2026.22.6.2589-2622
Available online http://www.ijat-aatsea.com
ISSN 2630-0192 (Online)

Microbial biosurfactants: Sustainable solutions for post-pandemic challenges in agriculture, healthcare, and the environment

Eshwarnath, V. S.[1], Radhakrishnan, M.[1*], Priyanka, K.[2]., Kumar, S. M.[1], Gopikrishnan, V.[1], Poveda, S. L.[3], Soytong, K.[4], Song, J. J. [4,5] and Kumar, A. K.[1]

[1]Centre for Drug Discovery and Development, Sathyabama Institute of Science and Technology, Chennai 600119, Tamil Nadu, India; [2]Department of Biotechnology, Sathyabama Institute of Science and Technology, Chennai 600119, Tamil Nadu, India; [3]Institute of Biochemistry and Microbiology, Universidad Austral De Chile, Valdivia, Chile; [4]Research Institute of Modern Organic Agriculture (RIMOA), King Mongkut's Institute of Technology Ladkrabang (KMITL), Thailand; [5]Department of Agricultural Technology, King Mongkut's Institute of Technology Ladkrabang (KMITL), Prince of Chumphon, Thailand.

Eshwarnath, V. S., Radhakrishnan, M., Priyanka, K., Kumar, S. M., Gopikrishnan, V., Poveda, S. L., Soytong, K., Song, J. J. and Kumar, A. K. (2026). Microbial biosurfactants: Sustainable solutions for post-pandemic challenges in agriculture, healthcare, and the environment. International Journal of Agricultural Technology 22(6):2589-2622.

Abstract Biosurfactants are amphiphilic molecules produced by microorganisms and are of natural origin; the production, structure and biological functions are strongly linked to the physiology of the producer. In this review, we offer a microbiological overview of biosurfactants, including the organisms that produce them, the genetic and environmental factors that regulate their synthesis, their characterization, the evolutionary relationships that exist between them and their importance at the interface between microbiology and biotechnology in the post-pandemic era. The review covers the genetic basis (biosynthetic gene clusters, quorum sensing), ecological roles (rhizosphere function, anti-biofilm activity, hydrocarbon degradation, occurrence in extreme environments) of the literature from 2010–2026, and applications, economic perspectives, emerging technologies, and current challenges. Bacillus lipopeptides and Pseudomonas rhamnolipids are significant in agricultural biocontrol and hydrocarbon bioremediation, respectively, and surfactin exhibits strong anti-biofilm activity against drug-resistant pathogens. Challenges include limited in vivo data, sparse field trials, and regulatory uncertainty. CRISPR based genome editing, metagenomic mining and artificial intelligence-driven process optimisation hold promises to improve biosurfactant utility and scalability.

Keywords: Biosurfactants, Microbial biosynthesis, Antimicrobial resistance, Biocontrol, Environmental remediation

[*] **Corresponding Author:** Radhakrishnan, M.; **Email:** mrkactinos@gmail.com

Introduction

Background of Biosurfactants

Surfactants are surface active agents mainly derived from petrochemical sources that are widely used in detergents, agrochemicals, oil recovery and pharmaceuticals. However, they are not environmentally friendly because of their toxicity and carbon footprint. In contrast, biosurfactants are surface-active molecules produced by microbes which are attracting attention as sustainable alternatives. They can decrease surface and interfacial tension because of their amphiphilic nature with hydrophilic and hydrophobic parts. These molecules have important biological roles such as inhibition of pathogen adhesion, antimicrobial activity, and microbial interactions in natural environments. Owing to their broad functional capabilities, biosurfactants are generally less toxic, biodegradable, and effective under extreme environmental conditions, making them strong alternatives to synthetic surfactants. A better understanding of their biological roles could further enhance their versatility and promote wider adoption of biosurfactants (Théatre *et al.,* 2021; Ongena and Jacques, 2021; Roelants *et al.,* 2019). Since their discovery several decades ago, research has shifted from a primary focus on their chemical properties to deeper biological insights. Regulatory pathways, genetics, and microbial ecology are now recognised as key to uncovering novel biosurfactants with higher yields and more advanced, application-specific formulations.

Importance of Sustainability in the Post-Pandemic Era

Since the COVID-19 pandemic, considerable attention has been directed towards biosurfactants from a microbiological perspective. The disruptions we saw during the pandemic showed that we need to move more forcefully towards sustainable development. Antibiotic use increased during this period, contributing to the rise in antimicrobial resistance (AMR). This highlights the potential value of biosurfactant-based anti-biofilm agents. These concerns have stimulated the interest in the identification of environmentally friendly biosurfactants effective against resistant pathogens (Langford *et al.,* 2021; Murray *et al.,* 2022). The vulnerabilities of the petrochemical supply chains also strengthened the need for bio-based alternatives, and microbial biosurfactants are a renewable and sustainable alternative. Additionally, the pandemic and post-pandemic period has sped up the development of bioinformatics and genomics that have enabled the discovery and development of biosurfactants. The significance of bio-based chemicals including biosurfactants has been further emphasized through initiatives like the European Commission Bioeconomy Strategy and the WHO Global AMR Action Plan (2022), and national

bioeconomy programmes in countries such as India, Brazil and South Korea (WHO, 2022; European Commission, 2018).

Biosurfactants: An overview

Classification

Biosurfactants can be classified according to the microorganisms that produce them, their genetic characteristics, and their biosynthetic pathways, all of which are shaped by ecological adaptation. Glycolipids consist of carbohydrate moieties glycosidically linked to hydroxylated fatty acid chains. Among them, rhamnolipids are the most extensively studied and are primarily synthesised by *Pseudomonas aeruginosa*. Their biosynthesis involves sequential enzymatic reactions regulated by quorum sensing (Reis *et al.,* 2022). In contrast, sophorolipids are produced through a distinct eukaryotic pathway in *Starmerella bombicola*, involving fatty acid hydroxylation by CYP52M1, glycosylation by UGTA1 and UGTB1, and acetylation by AT (Roelants *et al.,* 2019). Lipopeptide biosurfactants are synthesised by non-ribosomal peptide synthetases (NRPS) and may be either cyclic or linear, consisting of both lipid and peptide components. In *Bacillus subtilis*, the biosynthetic genes are organised in the large srfAA-AB-AC-AD operon (~26 kb). NRPS enzymes function in a modular manner, with each module containing adenylation, condensation, and thiolation domains. Among these, the adenylation domain, which selects a specific amino acid substrate, is the feature most frequently exploited for biosurfactant modification (Théatre *et al., 2021*). Other important lipopeptides, such as iturin A and fengycin, are produced through related NRPS systems. Phospholipid biosurfactants are produced particularly during growth on hydrocarbons by bacteria such as *Thiobacillus thiooxidans* and *Acinetobacter calcoaceticus*. These include compounds such as phosphatidylethanolamine and cardiolipin, which modify cell surface properties and enhance hydrophobic interactions (Markande *et al.,* 2021).

High-molecular-weight complexes such as emulsan, produced by *Acinetobacter venetianus* RAG-1, are classified as polymeric biosurfactants (Smyth *et al.,* 2010). Particulate biosurfactants, including outer membrane vesicles from Gram-negative bacteria, possess amphiphilic bilayers that enable the transport of both hydrophobic and hydrophilic molecules. These systems are attracting increasing interest for biomedical and drug delivery applications (Zhang *et al.,* 2026; Wen *et al.,* 2026). The major classes of biosurfactants, their representative molecules, producing microorganisms, key properties, and application domains are summarized in Table 1.

Table 1. Classification and Key Properties of Biosurfactant Classes

Class	Example Molecules	Key Producing Organisms	Key Properties	Application Domains
Glycolipids	Rhamnolipids, sophorolipids, trehalose lipids, mannosylerythritol lipids (MELs)	*Pseudomonas aeruginosa*, *P. putida*, *Starmerella bombicola*, *Rhodococcus erythropolis*, *Moesziomyces aphidis*	Low critical micelle concentration (CMC; 10–200 mg/L), strong emulsifying activity, biodegradability, antifungal properties	Agriculture, bioremediation, medicine, personal care
Lipopeptides	Surfactin, iturin A/C, fengycin, lichenysin, polymyxin	*Bacillus subtilis*, *B. amyloliquefaciens*, *B. licheniformis*, *B. velezensis*	Potent antimicrobial activity, anti-biofilm effects, quorum-sensing inhibition, reduction of surface tension to <27 mN/m	AMR mitigation, biocontrol, wound care, medical coatings
Phospholipids	Phosphatidylethanolamine, cardiolipin	*Acinetobacter calcoaceticus*, *Thiobacillus thiooxidans*, *Micrococcus* spp.	Hydrocarbon emulsification, modulation of cell-surface hydrophobicity	Bioremediation, metal bioleaching
Polymeric	Emulsan, alasan, liposan, mannan–lipid–protein complex	*Acinetobacter venetianus* RAG-1, *A. radioresistens*, *Candida lipolytica*	High molecular weight (>1 MDa), exceptional emulsion stability, activity at 0.001% (w/v)	Oil-spill response, wastewater treatment, enhanced oil recovery
Particulate	Membrane vesicles, hydrophobic protein complexes	*Acinetobacter calcoaceticus*, diverse marine gamma-proteobacteria	Vesicular architecture, nanocarrier properties, self-assembly	Drug delivery, nanomedicine, targeted antimicrobial delivery

Key microbial producers

Hydrocarbon-contaminated sites such as refinery soils, oil-storage areas, marine seep regions and roadside environments have often produced rhamnolipid and polymeric biosurfactant producers, possibly because biosurfactants increase the bioavailability of hydrophobic substrates and so benefit hydrocarbon-utilising strains (Cameotra and Singh, 2009; Fenibo *et al.,* 2019; Sachdev and Cameotra, 2013).

Agricultural soils, particularly the rhizosphere of stressed or pathogen-affected plants, also harbour biosurfactant-producing species of *Bacillus*, *Acinetobacter*, *Thiobacillus thiooxidans*, *Micrococcus*, and *Pseudomonas*, which

are involved in pathogen suppression and root colonisation. Marine ecosystems, including deep-sea sediments, hydrothermal vents, hypersaline coasts, and polar ice, also offer largely untapped potential for the discovery of novel biosurfactants (Kubicki *et al.,* 2019). Yeasts such as *Moesziomyces aphidis*, *Ustilago maydis*, and *Starmerella bombicola* are among the most industrially favoured biosurfactant producers because of their high sophorolipid yields and safe fermentation profiles. In addition, fungi such as *Moesziomyces aphidis* and *Schizonella melanogramma* can produce mannosylerythritol lipids with distinct structures and bioactivities, including the promotion of nerve growth factor, suggesting potential biomedical applications beyond conventional uses (Wang *et al.,* 2019). Understanding the ecological niches that favour high-yield strains is important for the efficient prospecting of biosurfactant-producing microbes. Knowledge of microbial traits such as surface adherence, hydrocarbon utilisation, and interspecies competition, all of which confer survival advantages, is essential for identifying effective biosurfactant producers (Ullah *et al., 2026;* Déziel *et al.,* 2026). Members of the genus *Pseudomonas*, including *P. chlororaphis*, *P. fluorescens*, *P. putida*, and *P. aeruginosa*, have been extensively investigated for rhamnolipid production. Some strains, e.g. P. aeruginosa PAO1 and PA14, are widely used in regulatory studies but restricted in food and pharmaceutical applications due to their biosafety level 2 classification. Conversely, P. putida KT2440 is being increasingly used as a soil bacterium for rhamnolipid gene expression, synthetic biology and metabolic studies (Tiso *et al.,* 2017). Lipopeptide biosurfactants produced by members of the genus Bacillus, such as B. subtilis 168, B. amyloliquefaciens FZB42, B. licheniformis BAS50, and B. velezensis QST713, have been studied extensively. The organisation of non-ribosomal peptide synthetase (NRPS) gene-clusters varies, resulting in different lipopeptide types and yields (Théatre *et al.,* 2021; Ongena and Jacques, 2021).

Physicochemical properties relevant to global challenges

The performance of biosurfactants is dictated by their physicochemical behavior in complex environmental conditions, such as wound exudates, marine sediments, industrial fermentation systems, and rhizosphere soil wetness. The aqueous systems used for assessment in the lab are often simplified and differ greatly from the actual circumstances. The critical micelle concentration (CMC) is the minimum concentration at which biosurfactants reduce the surface and interfacial tensions and form micelles. These micelles have ability for drug delivery, metal-ion binding and solubilization of hydrophobic compounds. Glycolipid CMCs in clean water are generally in the range of 10–200 mg/L and are influenced by temperature, ionic strength and the presence of organic matter.

(Jahan *et al.,* 2020) Many studies evaluating the efficiency of biosurfactants neglect these environmental aspects. A major advantage biosurfactant has over synthetic surfactants is their biodegradability. For instance, rhamnolipids are degraded aerobically inaround 10 days days by processes like beta-oxidation due to their structural likeness to cellular lipids (Thakur *et al*., 2021) Although rapid breakdown is beneficial for the environment, it may limit its efficacy in applications such as bioremediation, where continual production may be required. Sophorolipids are stable between pH 3 and 9 and can endure temperatures up to 60°C. As such they are appropriate for moderately hot and acidic environments. However, many lipopeptides are less stable at temperatures greater than 45°C and at high concentrations of divalent metal ions, unless appropriately prepared, thus limiting their application in metal-contaminated environments (Roelants *et al.,* 2019). The resistance of lipopeptides is dependent on their special ingredients and formulation. The different lipopeptides can withstand high temperatures and the divalent cations (such as Ca2+) significantly affect the micellization of lipopeptides, which in turn affects their effectiveness in metal-rich environments (Femina Carolin et al., 2021; Ravindran et al., 2020).

Post-pandemic perspective: why biosurfactants?

Increased demand for eco-friendly products after COVID-19

The pandemic accelerated trends in sectors such as personal care, agriculture, household products and others in favor of biodegradable and clean-label alternatives. The problem of disposable personal protective equipment (PPE) pollution has raised a keen interest towards sustainable alternatives (Banat *et al.,* 2021). Furthermore, the widespread use of disinfectants raised microbiological concerns about antimicrobial resistance, especially because quaternary ammonium compounds can induce efflux pump-mediated resistance in pathogens such as *Staphylococcus* and *Klebsiella* (Murray *et al.,* 2022). Rather than targeting specific receptors, biosurfactants generally act through physical disruption, which could reduce the risk of resistance development. Biosurfactants produced by members of the human microbiota, including *Lactobacillus*, *Streptococcus*, and *Bacillus*, have therefore attracted increasing interest. They represent a promising intersection of clinical and industrial microbiology because of their potential to prevent pathogen adhesion (Gudiña *et al.,* 2021).

Green chemistry and circular bioeconomy trends

The circular bioeconomy gained momentum after the pandemic by prioritising the recycling of biological materials, the reduction of emissions, and

the conversion of waste into value-added products. The use of agro-industrial waste as a fermentation substrate can reduce production costs, which remains a major barrier to commercialisation, while also helping to address waste-management challenges. However, such substrates also present important limitations, including variable composition and microbiological challenges such as lignocellulosic residues, heavy metals, and competing microorganisms. These factors can affect microbial growth and the quality of the biosurfactant produced (De Almeida *et al.,* 2016). The yeast *Starmerella bombicola* can grow on crude glycerol containing impurities such as methanol and can achieve sophorolipid titres exceeding 12 g/L under optimised conditions (Roelants *et al.,* 2019). Similarly, B. subtilis and B. amyloliquefaciens can be evolved in the laboratory to ferment substrates including wheat bran hydrolysate in the presence of inhibitors, and to produce lipopeptides similar to those produced in defined media (*Gudiña et al.,* 2021). Bacillus spp. is particularly suitable for fermentation of starchy and lignocellulosic wastes due to their ability to secrete extracellular enzymes including amylases, proteases, xylanases and cellulases but this potential is largely untapped.

Biosurfactants as replacements for synthetic surfactants

To replace synthetic surfactants commercially, biosurfactants must be equally effective, competitively priced and readily available. From the microbiological point of view, strain stability is one of the most important factors affecting the product consistency. This is especially the case for engineered strains with high production, which often have multiple genetic modifications or plasmids. This frequently leads to reduced yields because of metabolic burden, particularly for energy-intensive lipopeptides synthesized by large non-ribosomal peptide synthetase (NRPS) clusters (Tiso *et al.,* 2017). Several strategies have been proposed to tackle this problem, including chromosomal integration of biosynthetic genes, the use of strong constitutive promoters and genetic stabilisation tools such as addiction cassettes. Another significant challenge is product heterogeneity. Most microorganisms produce mixtures of biosurfactants instead of a single compound, which complicates their purification, especially for pharmaceutical applications. In Pseudomonas aeruginosa, the production of mono- and di-rhamnolipids is regulated by the expression of rhlB and rhlC genes, which are regulated by quorum sensing systems such as RhlI and RhlR, as well as repressors such as RsaI, carbon source availability, and growth stage (Reis *et al.,* 2022). Engineering the promoter regions in alternative hosts such as P. putida provides a potential route to more uniform biosurfactant profiles. The major applications and underlying

mechanisms of biosurfactants across different industrial and environmental sectors are summarized in Figure 1.

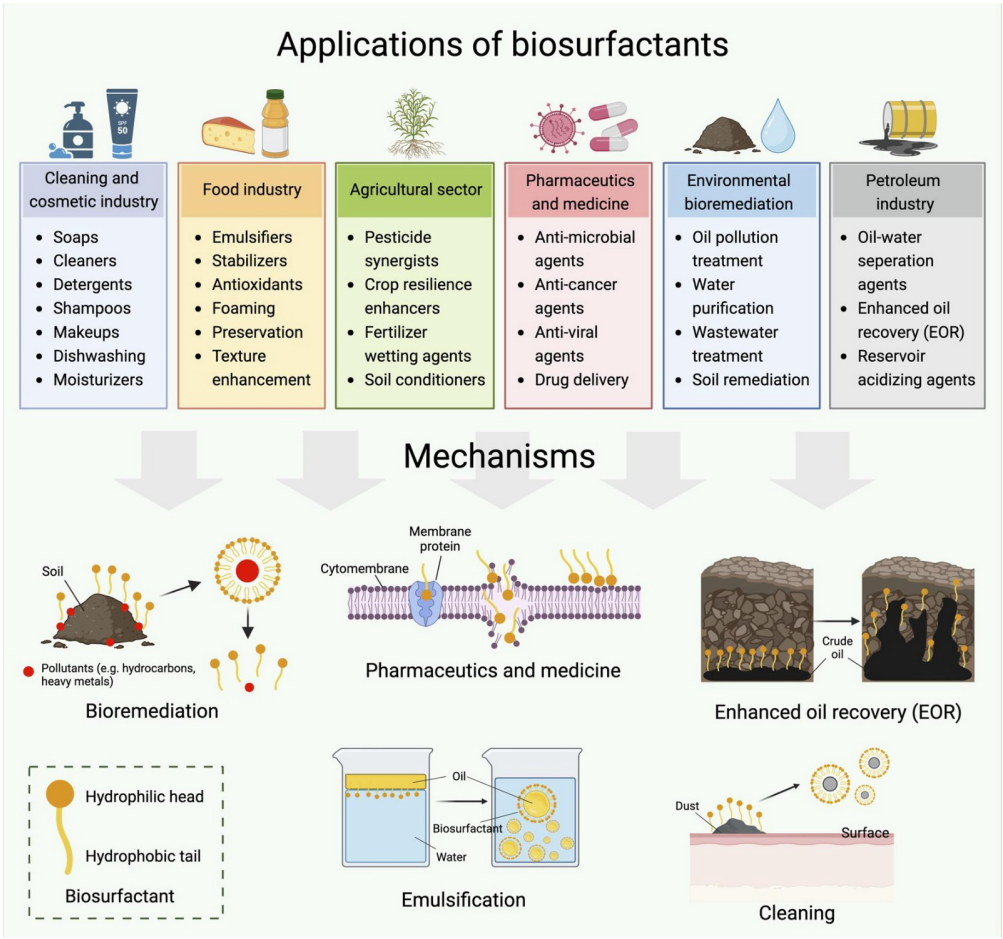


Figure 1. Major applications and mechanisms of microbial biosurfactants

Biosurfactants in sustainable agriculture

Role in soil health and nutrient cycling

Agricultural soils, typically containing 10^8 to 10^9 cells per gram, harbour dense and diverse microbial communities that are essential for plant growth and soil fertility. Biosurfactant-producing microorganisms actively influence ecological interactions, nutrient cycling, mineral dissolution, and the decomposition of organic matter. Rhizosphere bacteria that promote plant growth, including *Pseudomonas fluorescens*, *Bacillus amyloliquefaciens* FZB42, *Serratia marcescens*, and *Arthrobacter* species, play particularly important roles.

P. fluorescens produces rhamnolipids that reduce the surface tension of soil water, thereby enhancing root water uptake and the transport of nutrients such as iron and phosphate. (Sachdev and Cameotra, 2013). Phosphorus solubilisation can also be facilitated by sophorolipids, which reduce surface tension at the calcium phosphate interface and chelate calcium ions, thereby increasing phosphorus availability without the risks associated with excessive fertiliser use. Biosurfactants may also influence the native soil microbiota. However, long-term metagenomic studies are still needed to clarify these effects, which appear to be highly dependent on soil conditions.

Enhancing plant stress tolerance: drought, salinity, and heavy metals

Research on biosurfactant-producing microbes that improve plant stress tolerance is advancing rapidly. *Bacillus amyloliquefaciens* FZB42 produces surfactin, which facilitates root colonisation by reducing surface tension and enabling bacterial motility along root surfaces, an important step in effective plant growth promotion. (Théatre *et al.,* 2021). Under saline conditions, biosurfactant-producing bacteria can enhance plant sodium exclusion through activation of H+-ATPases. This helps protect photosynthesis by reducing sodium accumulation in shoots. Treated plants also accumulate osmolytes such as proline, indicating activation of stress-response pathways that may involve hormonal signalling. (Hamid *et al.,* 2023). *Pseudomonas aeruginosa* produces rhamnolipids that bind heavy metals such as calcium, copper, lead, and zinc. This can accelerate phytoremediation by mobilising metals from soil particles and enhancing their uptake by hyperaccumulator plants and mycorrhizal fungi. However, careful management is required because increased metal mobility may also raise the risk of groundwater contamination (Liu *et al.,* 2018). The major agricultural functions of biosurfactants, their mechanisms, producing microorganisms, and target crops are summarized in Table 2.

Table 2. Biosurfactants in Sustainable Agriculture: Microbial Producers and Mechanisms

Function	Mechanism	Producing Organism & Biosurfactant	Crop/Target	Ref.
Drought stress tolerance	Reduces rhizosphere soil–water surface tension and improves root hydraulic conductivity and water-film continuity	*Pseudomonas fluorescens* (rhamnolipids)	*Zea mays*, *Triticum aestivum*	Sachdev and Cameotra, 2013
Salinity tolerance	Reduces shoot Na+ accumulation through SOS1 modulation and	*Bacillus amyloliquefaciens* FZB42 (surfactin)	Tomato, wheat	Hamid *et al*., 2013

	upregulates osmolyte biosynthesis, including proline and glycine betaine			
Heavy metal phytoremediation	Complexes Cd2+, Pb2+, and Cu2+ through carboxylate coordination and desorbs metals from soil colloids into rhizosphere solution	*Pseudomonas aeruginosa* PAO1 (di-rhamnolipids)	Hyperaccumulator species, contaminated agricultural soils	Liu *et al*., 2018
Antifungal biocontrol	NRPS-derived lipopeptides (iturin, fengycin) interact with fungal membranes, causing pore formation and loss of membrane integrity	*Bacillus subtilis*	*Fusarium oxysporum*, *Botrytis cinerea*, *Rhizoctonia solani*	Gharsallah *et al.,* (2025)
Phosphorus solubilisation	Reduces surface tension at calcium phosphate mineral interfaces, chelates Ca2+, and improves phosphorus bioavailability	*Starmerella bombicola* (sophorolipids)	Calcareous soils, cereal crops	Borah *et al.*,2018
Biofertiliser synergy / PGPR consortium	Facilitates arbuscular mycorrhizal fungal hyphal extension through hydrophobic soil aggregates and enhances rhizosphere phosphorus transfer	*Pseudomonas putida* + AMF consortium (mono-rhamnolipids)	Semi-arid wheat rhizosphere	Sachdev and Cameotra, 2013

Biocontrol and antifungal activity

Bacillus species produce lipopeptides, including iturin A and iturin C, which bind to ergosterol in fungal cell membranes. This interaction disrupts membrane integrity resulting in ion leakage and cell death. This mechanism is somewhat selective, as ergosterol is not found in plant and mammalian cells, thus helping to limit toxicity. Fengycin works via a different mechanism including inhibition of fungal enzymes and induction of oxidative stress. It is particularly effective against pathogens which are less sensitive to iturins (e.g. *Phytophthora infestans* and *Pythium ultimum*). Biocontrol agent effectiveness is highly dependent on strain genetics. The expression and presence of non-ribosomal peptide synthetase (NRPS) gene clusters are strain dependent and influenced by rhizosphere conditions and regulatory networks. Therefore, the effective strains should be selected by the comprehensive screening such as gene-expression

analysis and quantification of biosurfactant. (Mulk *et al.,* 2022; Ongena and Jacques, 2021). Various mechanisms including direct inhibition of pathogens, competition for nutrients such as iron and induction of systemic resistance in plants are involved in biocontrol by rhamnolipid producing *Pseudomonas* spp. These effects can strengthen plant defence even without direct contact with the pathogen.

Integration with biofertilisers and biopesticides

To improve agricultural performance, biosurfactant-producing microorganisms can be combined with other beneficial microbes in multi-species consortia. Such consortia can integrate nitrogen fixation, phosphate solubilisation, hormone production, and disease suppression, thereby more closely mimicking natural soil microbiomes. Co-inoculation with rhamnolipid-producing *Pseudomonas* can support mycorrhizal hyphal extension and improve soil structure, thereby enhancing plant nutrient acquisition (Sachdev and Cameotra, 2013*).* Challenges remain in the development of multi-strain formulations, including interspecies competition during storage and application, as well as the dominance of fast-growing organisms. Even so, microbial consortia that include biosurfactant producers represent a promising and sustainable biotechnological strategy for improving crop productivity while maintaining soil health.

Biosurfactants in antimicrobial resistance (amr) mitigation

Anti-biofilm and quorum-quenching activities

Biosurfactants primarily disrupt biofilms by altering surface properties and reducing surface free energy, thereby interfering with the initial bacterial adhesion process. They are also closely associated with quorum-sensing pathways, which regulate different stages of the biofilm life cycle. Rhamnolipids play an important role in biofilm architecture by maintaining internal channels and enabling cell release during dispersal in *Pseudomonas aeruginosa*, a major biosurfactant producer (Reis *et al.,* 2022). At concentrations above the critical micelle concentration, exogenous mono-rhamnolipids can trigger premature biofilm dispersal, shifting bacteria from protected sessile communities to planktonic states that are more susceptible to antibiotics. At lower concentrations, however, they may promote biofilm formation, making dose optimisation essential in therapeutic contexts. Surfactin produced by *Bacillus subtilis* can, at sub-inhibitory concentrations, interfere with the agr quorum-sensing system in *Staphylococcus aureus*. By reducing the expression of

adhesion-related genes, it acts at the early stage of biofilm formation without exerting bactericidal effects, which may help reduce the risk of resistance development *(*Théatre *et al., 2021*). Certain *Bacillus* strains also produce AHL-lactonases, enzymes that degrade quorum-sensing signalling molecules. This disrupts microbial communication, attenuates virulence, and reduces biofilm formation. The combination of biosurfactant production and quorum-quenching activity therefore represents an effective microbial strategy for suppressing pathogenic competitors (Nickzad and Déziel *et al.,* 2021*).* The major mechanisms underlying the antiadhesive, antibiofilm, and antibiotic activities of biosurfactants are illustrated in Figure 2 and 3.

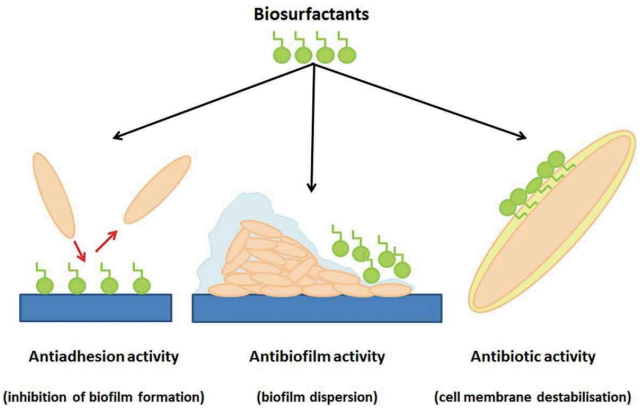


Figure 2. Antimicrobial mechanisms of biosurfactants against pathogenic microorganisms

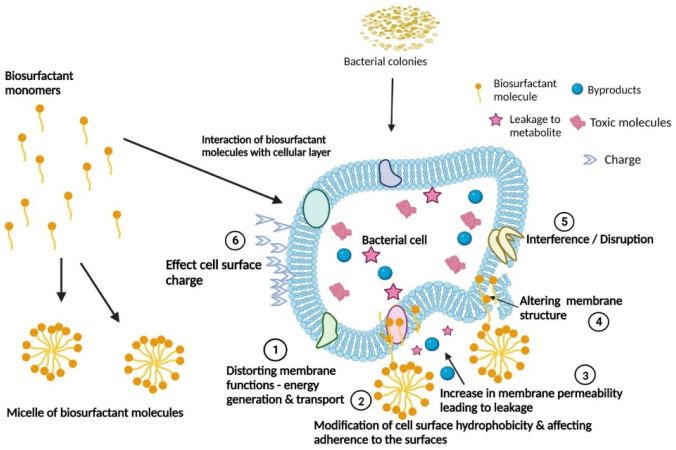


Figure 3. Molecular mechanisms of antimicrobial activity of microbial biosurfactants

Synergistic potential with antibiotics

Biosurfactants may improve the activity of antibiotics through increasing the permeability of bacterial membranes, facilitating the uptake of the drug, inhibiting efflux pumps, destabilising cell membranes and other mechanisms. These effects may help to enhance the antimicrobial performance against resistant microorganisms. For example, a lipopeptide biosurfactant derived from Bacillus licheniformis showed synergistic activity with conventional antibiotics against Escherichia coli CFT073 biofilms, resulting in a significant increase in biofilm eradication compared with treatment with antibiotics alone (Rivardo *et al.,* 2011). Similar findings have been reported with the combination of sophorolipids and nisin, which reduced mixed biofilms of Staphylococcus aureus and Candida albicans by disrupting the biofilm matrix and inducing damage to cellular membranes (Sana *et al.,* 2023). These synergistic approaches are clinically relevant because many infections are caused by more than one microbial species. However, considerable gaps remain, for instance, sparse data regarding the pharmacokinetics of biosurfactants, their susceptibility to enzymatic degradation, their interactions with host proteins and their impact on host tissues. These uncertainties point to the need for further investigation prior to widespread clinical application. The major roles of biosurfactants in AMR mitigation, their molecular mechanisms, producing organisms, and applications are summarized in Table 3.

Table 3. Biosurfactants in AMR Mitigation: Producing Organisms, Mechanisms, and applications

Role	Molecular Mechanism	Biosurfactant	Producing Organism	Application	Ref.
Anti-biofilm activity (adhesion phase)	Competes with adhesins at the substratum, reduces cell-surface hydrophobicity, and suppresses agr quorum-sensing and fnbA/clfA expression	Surfactin	*Bacillus subtilis* ATCC 21332	Medical implant surface protection, MRSA prevention	Leistikow *et al.,* 2024
Biofilm dispersal induction	Triggers premature dispersal of mature biofilm microcolonies and converts sessile AMR-tolerant cells into antibiotic-susceptible planktonic cells	Mono-rhamnolipids	*Pseudomonas putida* KT2440 (*rhlAB* expressed)	Anti-virulence therapy, pre-antibiotic biofilm sensitisation	Passos and Nitschke 2024
Quorum-sensing inhibition	Suppresses rhlI/rhlR and lasI/lasR acyl-homoserine lactone-mediated gene	Rhamnolipids (sub-CMC)	*Pseudomonas* spp., *Bacillus* spp.	Anti-virulence therapy, chronic	D'Aquila *et al*.,2024

quorum quenching	networks and reduces pyocyanin, elastase, and rhamnolipid-associated virulence factors			lung infection in cystic fibrosis	
Antibiotic synergy	Promotes outer-membrane permeabilisation through lipopolysaccharide disruption and suppresses efflux pumps such as TetA and MexAB via altered membrane fluidity	Rhamnolipids combined with tetracycline or ciprofloxacin	*Pseudomonas aeruginosa*; uropathogenic *Escherichia coli*	Urinary tract infection, wound infection, CAUTI prevention	Gdaniec *et al*., 2021
Anti-adhesion coating	Modifies device polymer surfaces to become more hydrophilic and prevents conditioning-film formation	Sophorolipids (acidic form)	*Starmerella bombicola*	Catheter and orthopaedic implant coatings	Ceresa *et al.,*2020
Membrane disruption / antifungal AMR mitigation	Targets ergosterol-containing fungal membranes, causing pore formation, ion leakage, and mitochondrial membrane depolarisation in *Candida* and *Aspergillus*	Iturin A, fengycin	*Bacillus amyloliquefaciens* FZB42	Antifungal wound care, mucosal candidiasis	Wang *et al.,* 2025

Application in wound healing and medical coatings

Chronic wounds such as diabetic ulcers often contain persistent polymicrobial biofilms that sustain inflammation and delay healing (Armstrong *et al.,* 2020). Biosurfactants, especially lipopeptides produced by *Bacillus* species, may help manage these infections by inhibiting biofilm formation and promoting biofilm dispersal. In addition, biosurfactants can reduce inflammation, stimulate fibroblast and keratinocyte activity, and modulate immune responses, thereby supporting tissue regeneration and wound repair (Fracchia *et al.,* 2020). To prevent biofilm-associated infections on medical devices, biosurfactants have also been investigated as antimicrobial coatings. These studies have shown reduced bacterial adhesion on coated surfaces, including catheters and implants (Ceresa *et al.,* 2020). Despite these promising findings, several factors must be thoroughly evaluated before clinical translation, including long-term stability under physiological conditions, resistance to fluid exposure, and compatibility with sterilisation procedures.

Biosurfactants and climate change solutions

Bioremediation of hydrocarbons and microplastics

Microbial degradation is the primary natural mechanism for the cleanup of petroleum contamination, but the limited availability of hydrophobic hydrocarbons often restricts this process. By emulsifying these compounds and increasing microbial cell-surface hydrophobicity, biosurfactants facilitate substrate uptake. In such environments, microbial consortia often outperform individual strains. Cooperative interactions occur among hydrocarbon-degrading bacteria in petroleum-polluted marine environments, including *Alcanivorax borkumensis*, aromatic-compound degraders such as *Cycloclasticus* species, nitrogen-fixing organisms that support growth under nutrient-limited conditions, and biosurfactant producers such as *Marinobacter* and *Rhodococcus erythropolis* (Prince, 2015). The major environmental challenges addressed by biosurfactants, together with their mechanisms and producing microorganisms, are summarized in Table 4.

Table 4. Biosurfactants and Climate Change Solutions: Producing Organisms and Mechanisms

Environmental Issue	Role of Biosurfactant	Biosurfactant	Producing Organism	Ref.
Crude oil / aliphatic hydrocarbon spills	Promotes pseudosolubilisation through mixed micelle formation, enhances emulsification, and increases hydrocarbon bioavailability to degrader consortia	Emulsan	*Acinetobacter venetianus* RAG-1	Smyth *et al*., 2010
PAH-contaminated soils	Desorbs polycyclic aromatic hydrocarbons (PAHs) from soil organic matter and clay mineral surfaces into the aqueous phase, thereby enhancing fungal and bacterial degradation	Rhamnolipids	*Pseudomonas aeruginosa* (metabolic mutant, non-pathogenic)	Yang *et al.*,2025
Microplastic surface modification	Alters the ζ-potential of polystyrene (PS) and polyethylene terephthalate (PET) particles, promotes homoaggregation with threefold faster settling, and modifies	Rhamnolipids, Sophorolipids	*Pseudomonas* spp., *Starmerella bombicola*	Bhatt P *et al.,* 2021

	the plastisphere microbiome			
Heavy metal contamination (mine drainage)	Complexes Ni2+, Zn2+, and Co2+ through phosphate headgroups and supports bioleaching consortia in acidic mine tailings	Phosphatidylethanolamine	*Thiobacillus thiooxidans*, *Acidithiobacillus* spp.	Sachdev and Cameotra, 2013
Carbon capture (biofilm bioreactor)	Stabilises biofilm architecture that supports carbonic anhydrase-active MICP communities and accelerates CaCO3 mineralisation	Sophorolipids	*Starmerella bombicola*, *Sporosarcina pasteurii*	Mujah *et al*.,2022
Petroleum-contaminated Arctic / cold soils	Maintains surfactant CMC function at 2–8°C and supports psychrophilic hydrocarbon-degrading communities	Cold-active glycolipids	*Halomonas* spp., deep-sea *Bacillus* isolates	Kubicki *et al*., 2019

Even when present in low abundance, biosurfactant-producing microbes are important in stimulating overall community activity suggesting that mixed microbial consortia are more likely to be efficacious for bioremediation strategies. Microplastic pollution poses similar challenges. Particles such as polystyrene and polyethylene terephthalate can remain suspended in water due to their surface charge. Rhamnolipids can lower this charge facilitating aggregation and sedimentation to aid removal from aquatic systems (Bhatt *et al.,* 2021). The plastisphere, a distinct microbial community associated with microplastics, is also impacted by biosurfactant-producing microorganisms which can alter surface properties influence pollutant adsorption and control biofilm formation. These systems may provide opportunities to find novel biosurfactants with unique environmental functions. Biosurfactants can enhance the bioremediation of marine oil pollution by emulsifying hydrocarbons and increasing their bioavailability for microbial degradation (Liu *et al.,* 2018; Prince, 2015). This process is illustrated in Figure 4.

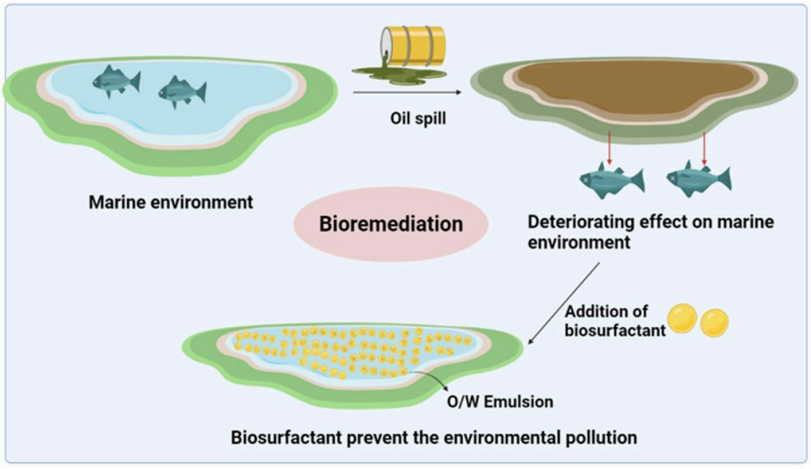


Figure 4. Bioremediation of hydrocarbons and microplastics

Carbon capture and waste valorisation strategies

Waste-based biorefineries for biosurfactant production are a sustainable approach to valorize waste streams and reduce production costs. Several substrates such as crude glycerol from biodiesel production, dairy whey, cassava wastewater, olive-mill waste, brewery residues, lignocellulosic biomass and used cooking oil have been successfully exploited for this purpose (De Almeida *et al.,* 2016). Of particular benefit is Bacillus subtilis which produces enzymes such as amylases, xylanases, proteases and pectinases that break down complicated organic materials, allowing for substrate utilization without extensive pretreatment. Tolerance to inhibitory compounds can be further improved by adaptive laboratory evolution and biosurfactant production enabled under harsh conditions (Gudiña *et al.,* 2021). Biosurfactants may further contribute to carbon capture through processes like microbially induced calcium carbonate precipitation, in which certain bacteria transform carbon dioxide into calcite. Biosurfactant-producing microbes can enhance calcium carbonate formation through stabilizing biofilms and increasing cell-mineral interactions (Mujah *et al.,* 2022*)*. This process has some useful applications, such as in the stabilisation of soils and in the treatment of industrial waste, but its overall contribution to the sequestration of carbon on a global scale is limited.

Role of marine and extremophilic microbes under changing environments

Marine and extremophilic microorganisms are a rich source of new biosurfactants adapted to extreme environmental conditions such as low temperature, high pressure, high salinity and extreme pH. Deep-sea microbes produce biosurfactants that are active under low temperature and high-pressure

conditions. These compounds often contain unsaturated fatty acids, which help maintain membrane fluidity, and structural features that increase their resistance to degradation, making them suitable for applications in cold environments (Kubicki *et al.,* 2019). Biosurfactants of halophilic microorganisms such as *Halomonas* are stable at salt concentrations greater than 10%, making them useful in saline environments and industrial processes. Biosurfactants produced by alkaliphilic Bacillus species are active in alkaline environments and hence have potential uses in the paper and textile industries. Increasing temperatures, thawing permafrost and changes in ocean chemistry caused by climate change are changing microbial ecosystems. Such changes are likely to affect the availability, function and diversity of biosurfactant producing microbes, presenting both opportunities and challenges for sustainable technology development and bioprospecting.

Industrial and economic perspectives

Current global market and trends

The global biosurfactant market was valued at approximately USD 2.3 billion in 2023 and is projected to grow at an annual rate of 5–7% through to 2030. This growth is being driven primarily by applications in personal care products, household cleaning, and agricultural biopesticides (Grand View Research, 2023). At present, production is dominated by a limited number of microorganisms, particularly *Starmerella bombicola* for sophorolipid production and *Bacillus amyloliquefaciens* for lipopeptide production. These organisms are favoured because of their technical maturity and relatively favourable regulatory status. Owing to limited process optimisation and regulatory constraints, however, many other potentially useful biosurfactant-producing microorganisms remain underexplored. Interest is increasingly turning towards less-studied microorganisms that may produce novel biosurfactants for high-value applications, including pharmaceuticals and environmental remediation in extreme environments. In such cases, higher production costs may be justified by the specialised functionality of the resulting products (Marchant and Banat*,* 2021*;* Satpute *et al.,* 2022). In recent years, there has been considerable progress in the widespread commercialization of biosurfactants. In May 2024, Evonik inaugurated the first industrial-scale rhamnolipid biosurfactant synthesis plant in Slovakia, an important step in the commercialization of microbial surfactants (Evonik, 2024). AGAE Technologies and Dispersa announced steps to increase production capacity in March 2025, which are estimated to deliver more than 1,000 metric tons per year in biosurfactant manufacturing (Bettenhausen,2025). The global biosurfactant market is projected to reach USD 4.44 billion by 2023,

with Europe contributing a major share, indicating the increasing industrial demand for environmentally friendly surfactants (Yanvarov and Havryliak, 2024). This increasing enthusiasm is driven by the European sustainability programs like European Green Deal and Chemicals Strategy for Sustainability advocating safer and sustainable chemical production and use (European Commission, 2020).

During the same period, glycolipids led the market, largely owing to rising demand for rhamnolipids and sophorolipids in environmental and industrial applications. Following pre-registration in 2024, the European Chemicals Agency (ECHA) accelerated rhamnolipid registration, and in March 2025, Japan's PMDA approved sophorolipids for over-the-counter skincare, opening further pathways for commercial expansion (Kabeil *et al.,* 2025).

Challenges in scale-up and cost reduction

Biosurfactant production scale-up has many technical hurdles and foaming during fermentation is one of the most important. Microorganisms that produce biosurfactants often require high aeration rates, which may lead to excessive foam formation. This increases contamination, obstructs oxygen transfer and decreases reactor efficiency. Chemical antifoaming agents are known to be detrimental to product quality and downstream processing. Some engineering approaches have been investigated to enable simultaneous product recovery, such as specialised mixing systems that reduce bubble formation, pressurised bioreactors and foam-fractionation techniques. However, these approaches are not yet widely implemented at industrial scale and are often too costly for broad application (Mukherjee *et al.,* 2021; Roelants *et al.,* 2019). Biosurfactant production involves substrate preparation, fermentation, and downstream recovery and purification Figure 5.

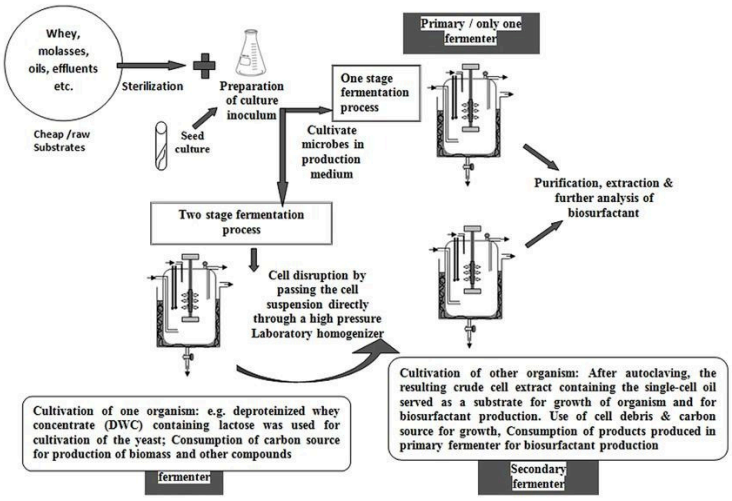


Figure 5. Challenges in scale-up and cost reduction

Downstream processing remains a major contributor to overall production costs, accounting for approximately 60–80% of total expenditure. For example, rhamnolipid purification typically involves multiple steps, including solvent extraction, acid precipitation, and membrane separation, all of which are both costly and environmentally intensive (Matosinhos *et al*., 2026). To reduce reliance on organic solvents, alternative approaches such as in situ foam fractionation and aqueous two-phase extraction have been proposed, although their large-scale implementation remains challenging (Maji *et al*., 2026). Further optimisation of these processes will require a deeper understanding of the physicochemical behaviour of biosurfactants. Recent advances in integrated fermentation engineering have begun to address some of these constraints. Solomon and Vishnu (2025) reported that, compared with conventional batch fermentation, machine-learning-guided process control in a continuous bioreactor reduced downstream processing energy requirements by 22% for surfactin production. Similarly, Wang *et al.* (2025) highlighted that integrating design-of-experiments frameworks with predictive models can rapidly identify optimal nutrient feed rates and dissolved oxygen set points, thereby narrowing the gap between laboratory-scale titres and industrial output. Paul *et al.* (2025) further showed that combining artificial neural network models with genetic algorithm optimisation improved prediction of biosurfactant concentration to within a 3% margin of error for *Bacillus subtilis* ATCC 6633 cultivated on sugarcane molasses. Collectively, these findings suggest that AI-assisted bioprocess control is emerging as a key enabler of cost-competitive industrial biosurfactant production (Solomon and Vishnu*,* 2025; Wang *et al.,* 2025; Paul *et al.,* 2025).

Waste-to-biosurfactant approaches: agro-industrial residues and food waste

The use of agro-industrial waste as a substrate for biosurfactant production is a promising approach for cost reduction and sustainability improvement. Successfully used substrates include crude glycerol (De Almeida *et al.,* 2016), dairy whey (Mohanty *et al.,* 2021), cassava wastewater, olive mill waste and lignocellulosic hydrolysates. However, these materials usually contain toxic compounds such as methanol, furfural and phenolics which can inhibit the microbial growth and introduce variability in the production process. Some microorganisms, like Starmerella bombicola, can survive these conditions under optimized parameters, while some Bacillus strains have been subject to adaptive evolution to maintain their production efficiency on inhibitory substrates. More and more future research is focused on naturally tolerant microbial strains from environments such as compost systems, forest soils and industrial waste sites. These organisms are already adapted to complex and inhibitory substrates and thus represent promising candidates for biosurfactant production on waste. Commercial feasibility of biosurfactants is shown by industrial case studies. The sophorolipid products are sold in Germany under the brand Rewoferm and are made from renewable glycerol and plant-derived oils for use in cleaning products and personal care. U.S.-based Jeneil Biosurfactant Company produces rhamnolipid-based formulations for industrial and agricultural uses through proprietary fermentation processes (Marchant and Banat, 2021). Similarly, several biopesticides based on biosurfactants from Bacillus subtilis, such as Serenade, Cease, and Rhapsody, have been registered in the United States and Europe. These are examples of effective translation of biosurfactants from laboratory research to commercial products with the support of proper regulatory approval, technological development and market demand.

Emerging frontiers

Synthetic biology and genetic engineering for enhanced yield

Biosurfactant production has been significantly transformed by advances in synthetic biology. Modern Strategies are focused on whole-pathway engineering, alteration of regulatory systems and re-design of host organisms, whereas earlier approaches were focused primarily on overexpression of single genes. One important development is the application of non-pathogenic hosts with GRAS status, e.g. Pseudomonas putida KT2440. Due to its metabolic versatility and its tolerance to a broad spectrum of substrates, this organism is particularly suitable for biosurfactant production. Metabolic flux towards biosurfactant synthesis can be re-directed by deletion of beta-oxidation genes

such as fadBA through genetic modification. High mono-rhamnolipid yields (~45 g/L) and reduced product heterogeneity were achieved by incorporation of rhamnolipid biosynthesis genes from Pseudomonas aeruginosa under strong promoters (Tiso *et al.,* 2017). Research in *Bacillus* species has focused on engineering non-ribosomal peptide synthetase (NRPS) systems. CRISPR-Cas9 technologies enable reprogramming of adenylation domains, modular swapping of NRPS components, and operon editing, leading to the production of novel surfactin analogues with improved properties, such as enhanced tolerance to metal ions. These advances demonstrate the feasibility of designing customised biosurfactants for specific industrial applications (Théatre *et al., 2021*). Recent efforts have also applied genome-scale metabolic modelling and multi-omic integration to identify metabolic targets systematically for improving biosurfactant yields. extensively reviewed CRISPR-Cas9 applications in biosurfactant-producing bacteria, showing that precise disruption of competing pathways and promoter engineering collectively enhanced production efficiency across multiple organisms, including *Pseudomonas fluorescens* and *Burkholderia thailandensis* (Nikolova *et al.,* 2021). (Yang *et al*., 2025) showed that engineering lipase regulation in *Pseudomonas aeruginosa* enabled the efficient use of waste frying oil as a carbon source for rhamnolipid production, directly linking synthetic biology strategies with circular economy principles (Yang *et al., 2025*). Similarly, (Gharsallah *et al*., 2025) reported that *Bacillus* strains producing novel lipopeptide variants with modified fatty acid chain lengths showed broad-spectrum antifungal activity against nine phytopathogenic fungi, underscoring the value of NRPS module diversity for generating structurally distinct biocontrol agents (Gharsallah *et al.,* 2025).

Ai and machine learning in biosurfactant discovery

To accelerate discovery and optimisation in biosurfactant research, artificial intelligence (AI) and machine learning are increasingly being applied. These approaches assist in predicting molecular properties, optimising fermentation processes, and identifying biosynthetic gene clusters. Graph neural networks, for example, can predict properties such as critical micelle concentration, emulsification efficiency, and biodegradability, thereby guiding the selection of promising biosurfactant molecules. Multiple fermentation parameters, including carbon-to-nitrogen ratio, dissolved oxygen, pH, temperature, and agitation speed, are being analysed using machine learning models such as neural networks and random forests. These models can outperform traditional one-factor-at-a-time optimisation approaches and enable substantial improvements in yield (Raza *et al.,* 2021). PRISM and antiSMASH are also widely used bioinformatics platforms for mining environmental

metagenomic data for polyketide synthase gene clusters and non-ribosomal peptide synthetases. This has led to the identification of hundreds of previously unknown biosynthetic pathways from marine and polar environments. However, converting these discoveries into commercially available products remains a major challenge and an important focus for future research (Navarro-Muñoz *et al.,* 2020). Beyond conventional machine learning, recent studies have begun incorporating large language models (LLMs) and deep learning architectures into biosurfactant research workflows. (Zhang *et al.,* 2026) described an innovative synergy between mechanistic biosurfactant research and LLM-based predictive modelling, particularly for interpreting biosurfactant interactions with polycyclic aromatic hydrocarbons (PAHs) during bioremediation, illustrating how AI can accelerate the rational design of biosurfactant systems for contaminant-specific applications (Zhang *et al*., 2026). (Paul *et al.,* 2025) extensively reviewed AI-assisted approaches in microbial biosurfactant bioprocesses, reporting that design-of-experiments methods combined with response surface methodology and neural network models yielded at least a twofold improvement in biosurfactant titres across most published studies. They also identified model interpretability and data availability as the principal challenges to wider adoption (Paul *et al.,* 2025). (Wang *et al.*, 2025) further highlighted that the AI-powered "Design–Build–Test–Learn" framework is shifting microbial biosurfactant production from reactive optimisation to predictive bioprocess management, enabling real-time adaptive control of bioreactors at pilot scale (Wang *et al.,* 2025).

Biosurfactants in nanotechnology and smart formulations

Under different environmental conditions, biosurfactants can self-assemble into a variety of nanostructures, including vesicles, nanotubes, liquid-crystalline phases, and micelles. This property makes them highly suitable for applications in nanotechnology and targeted drug delivery. Sophorolipids, for example, can form nanoscale ribbons and tubular structures, with their morphology controlled by factors such as temperature and pH. These systems are attractive as delivery platforms because they combine biodegradability and intrinsic bioactivity with antimicrobial effects (Baccile *et al.,* 2012). Rhamnolipid-stabilised silver nanoparticles have also shown enhanced control of microbial biofilms by combining the antimicrobial properties of silver ions with the membrane-disrupting action of biosurfactants (Santos *et al.,* 2021). Despite these promising developments, concerns remain regarding the long-term environmental impact of metal-based nanomaterials in soil and aquatic systems. Research is therefore moving towards responsive biosurfactant systems that can be activated by environmental triggers such as pH changes, microbial enzymes,

or oxidative stress. Although still at an early stage, this approach holds strong potential for advanced biomedical applications.

Recent publications have expanded this field further. Wang *et al.* (2024b) provided an extensive review of biosurfactant applications in medical science, highlighting the use of rhamnolipid-stabilised solid lipid nanoparticles for dermal drug delivery and showing that such formulations offer improved biocompatibility and skin permeation compared with systems based on synthetic surfactants (Wang *et al.,* 2024a). Asadpour Panbehchouleh *et al.* (2024) developed rhamnolipid-based solid lipid nanoparticles loaded with menadione sodium bisulfite as a skin-lightening formulation, demonstrating favourable in vitro and in vivo safety profiles and highlighting the potential of biosurfactant-based cosmeceutical nanosystems (Asadpour Panbehchouleh *et al.,* 2024). Azevedo *et al.* (2024) examined rhamnolipid-based nanosystems for food applications and reported that nanoemulsions and nanostructured lipid carriers stabilised with rhamnolipids provided superior oxidative stability and antimicrobial protection compared with traditional synthetic emulsifiers, while also meeting clean-label regulatory requirements (Azevedo *et al.,* 2024). In the context of anticancer applications (Singh *et al*., 2025) reviewed the progress of sophorolipids as anticancer agents, noting their capacity to induce apoptosis in drug-resistant breast cancer cells through downregulation of Bcl-2 and NF-κB expression when incorporated into targeted nanoparticle systems (Singh *et al.,* 2025). Taken together, these developments indicate that biosurfactant-based nanotechnology is moving beyond proof-of-concept studies towards application-ready advances across the pharmaceutical, food, and cosmetic sectors.

Challenges and future prospects

Regulatory hurdles and safety assessments

Regulatory approval for biosurfactant-based products is complex and depends on the region and application sector. This is a particularly difficult challenge for small and medium-sized businesses. In the EU, agricultural biosurfactants must comply with Regulation No. 1107/2009, which requires full ecotoxicological testing on soil organisms, aquatic species and beneficial insects in realistic environmental conditions. In pharmaceutical applications, biosurfactants are considered as biologics and require full clinical evaluation with detailed chemistry, manufacturing and control documentation in accordance with good manufacturing practice. Many academic institutions do not have the infrastructure to meet these regulatory demands (Satpute *et al.,* 2022). Unlike biofertilisers which often benefit from simplified regulatory routes, biosurfactants still lack dedicated frameworks in many jurisdictions, with

approval processes being costly and time-consuming. These processes need to be streamlined with more collaboration between researchers and regulatory agencies. There are important knowledge gaps on the long-term impacts of low-dose exposures on soil microbiota, earthworms and pollinators. Limited toxicity data for important species such as Apis mellifera continues to be a major hurdle for regulatory approval in some regions. Recent milestones, however, do signal substantive progress. Japan's Pharmaceuticals and Medical Devices Agency (PMDA) approved the use of sophorolipids in skin-care applications in March 2025. This approval is the first dedicated regulatory recognition of a glycolipid biosurfactant by a prominent Asian regulatory authority (Kabeil *et al.,* 2025). In 2024, rhamnolipids were fast-tracked for pre-registration by the European Chemicals Agency (ECHA) under REACH, a crucial step expected to reduce the time and cost of full commercial authorization in the European Union The United States Environmental Protection Agency (EPA) has also noted a growing trend toward the phase-out of synthetic surfactants under multiple regulatory structures, creating market space and regulatory momentum for biodegradable alternatives incorporating biosurfactants. In the Indian subcontinent, there has been increasing discussion around the development of a regulatory category for microbially produced surface-active agents under the Central Drugs Standard Control Organisation (CDSCO) and the Department for Promotion of Industry and Internal Trade (DPIIT) bioeconomy initiative, which underscores the growing awareness that the lack of a dedicated classification framework continues to be a major obstacle to commercialisation (Satpute *et al.,* 2022). Collectively, these developments seem to point to a gradually improving regulatory landscape for biosurfactants while the need for harmonisation across jurisdictions is still unmet (Miao *et al., 2024)).* The major emerging technological frontiers in biosurfactant biotechnology, including synthetic biology, metagenomic mining, artificial intelligence, extremophile bioprospecting, and nanotechnology, are summarized in Table 5.

Table 5. Emerging Frontiers in Biosurfactant Biotechnology

Frontier	Microbial / Biotechnological Application	Organism / Tool / Example	Ref.
Synthetic Biology — GRAS host engineering	CRISPR–Cas9-mediated deletion of β-oxidation genes (fadBA), chromosomal integration of rhlAB under a constitutive promoter, and quorum-sensing decoupling	*P. putida* KT2440 ΔfadBA:rhlAB — 45 g/L mono-rhamnolipid titre	Tiso *et al.*, 2017
Synthetic Biology — NRPS module engineering	Reprogramming of adenylation (A) domains, modular NRPS swapping, and CRISPR-guided srfA operon editing for the generation of novel surfactin analogues	*Bacillus subtilis* 168, srfA-edited — altered amino acid at position 7 and improved metal-ion tolerance	Théatre A *et al*., 2021
Metagenomic genome mining	Detection of NRPS/PKS biosynthetic gene clusters (BGCs) from uncultured environmental metagenomes using	Indian Ocean and Arctic deep-sea sediment metagenomes	Navarro-Muñoz

	antiSMASH 7.0 and PRISM 4, enabling BGC-to-product discovery pipelines	— hundreds of novel lipopeptide BGC clusters identified	*et al*., 2020
AI/ML — fermentation optimisation	Artificial neural network (ANN) and random forest models predict titre from multivariable fermentation data, including C:N ratio, dissolved oxygen, pH, temperature, and agitation	*Bacillus* spp. and *Candida* spp. — 15–30% titre improvement compared with OVAT optimisation	Raza *et al*., 2021
Extremophile bioprospecting	Isolation from deep-sea hydrothermal vents, hypersaline lakes, and Arctic permafrost, with characterisation of thermostable and halotolerant biosurfactants	*Halomonas* spp. (NaCl >10%); deep-sea *Bacillus* isolates (200 atm, 2–4°C)	Kubicki *et al.,* 2019 Shultz and rosado 2020
Nanotechnology / smart formulations	Self-assembly of sophorolipids into nanotubes and vesicles (50–500 nm), including stimuli-responsive, pH-switchable controlled-release formulations	Sophorolipid nanotubes with encapsulated essential oils against *Candida tropicalis* biofilm — 16-fold MBEC reduction	Santos *et al.,* 2021

Integration into sustainable development goals

Adopting the United Nations Sustainable Development Goals (SDGs) could help unlock funding opportunities, interdisciplinary collaboration, and broader social impact in biosurfactant research. Biosurfactants may contribute to food security through improving crop productivity, soil quality and plant stress tolerance. They may also benefit public health by contributing to the mitigation of antimicrobial resistance and to the development of safer therapeutic agents. Environmental benefits include improved water quality through pollutant removal, support to sustainable production systems through waste valorisation, and less dependence on petrochemicals. These contributions are particularly relevant to the goals on responsible consumption and production, climate action and innovation. But trade-offs have to be handled carefully. For example, the ability of biosurfactants to mobilise heavy metals in soil could lead to increased risk of groundwater contamination if applications are not properly controlled. Dealing with these challenges will be necessary for the responsible and sustainable use of biosurfactants.

Roadmap for future research and commercialisation

Future progress in biosurfactant research and application will require coordinated and multidisciplinary efforts. Exploration of under-investigated environments, such as marine ecosystems, polar regions, deep-sea habitats, and other extreme niches, is essential for the discovery of novel biosurfactant-

producing microorganisms. Metagenomic approaches, combined with traditional microbial isolation techniques, are likely to improve discovery efficiency. The development of publicly accessible databases cataloguing biosurfactant structures, functions, and biological activities would also support the application of artificial intelligence and reduce duplication of research efforts. In agriculture, long-term field studies are needed to evaluate the effects of biosurfactants on soil microbiomes, crop productivity, and environmental sustainability across multiple growing seasons. In biomedical applications, comprehensive in vivo studies on toxicity, pharmacokinetics, and efficacy will be required to meet regulatory standards. Clearer approval pathways and faster commercialisation will also depend on stronger collaboration between researchers and regulatory agencies such as the EPA, CDSCO, and ANVISA. Emerging evidence from 2024 to 2026 highlights several priorities that anchor this roadmap. First, the integration of biosurfactant production into circular bioeconomy frameworks is accelerating. For example, AmphiStar received EUR 12.5 million in July 2025 from the European Innovation Council to scale biosurfactant production entirely from bio-based waste, demonstrating the feasibility of economically viable closed-loop production *(*Vigil *et al.,* 2024; (Miao *et al.,* 2024). Second, bioremediation pipelines for emerging pollutants such as microplastics require further optimisation of biosurfactants. (Sony *et al.* 2025) showed that rhamnolipids isolated from the marine bacterium *Stutzerimonas stutzeri* MW15 enabled effective bioremediation of both heavy metals and crude oil in marine environments, highlighting the value of marine microbiome exploration as a source of multifunctional biosurfactants (Sony *et al.,* 2025) Third, recent work shows that sustainable production from secondary feedstocks, such as food-processing by-products and waste oils, is technically feasible at laboratory scale, with response surface methodology and fed-batch optimisation improving yields for sophorolipids. However, scale-up remains limited, and productivity for mannosylerythritol lipids is still low (Miao *et al.,* 2024).

Fourth, (Gan *et al.,* 2026) showed that the biocontrol pipeline for *Bacillus* lipopeptides is expanding. The tiered screening of Bacillus from rhizosphere soils has resulted in the isolation of B. velezensis strains with strong lipopeptide synthesis. The field studies revealed that crude lipopeptide extracts boost the growth and yield of maize, peanut and sunflower (Gan *et al*., 2026).

Taken together, these advances indicate that biosurfactant research is entering a more applied and translational phase. Future work should therefore focus not only on discovery and innovation, but also on standardisation of production protocols, long-term ecological safety assessment, and internationally coordinated regulatory structures.

Toxicity and safety in bioremediation

Biosurfactants employed in plant growth-promotion (PGP) and bioremediation are typically considered safer than synthetic ones, as lipopeptides (surfactin, iturin, fengycin, lichenysin) and glycolipids (rhamnolipids, sophorolipids, trehalose lipids) are more biodegradable and much less aquatic-toxic than conventional alkyl sulfate/sulfonate surfactants. (Romero Vega and Gallo Stampino, 2025) Biosurfactant-producing bacteria have been reported to be used in agriculture for heavy-metal and hydrocarbon bioremediation, which reduces environmental toxicity and makes them ideal for ecologically sensitive sites. They also enhance the solubility and bioavailability of pollutants for microbial degradation.(Sundaram *et al.,* 2024) However, a comprehensive review in 2025 cautions that large-scale agricultural use still requires careful safety evaluation: some biosurfactant-producing microbes (e.g., *Pseudomonas aeruginosa*, *Burkholderia* spp.) are themselves opportunistic pathogens, and antimicrobial lipopeptides may also inhibit beneficial soil microbes such as nitrogen fixers and mycorrhizal fungi in an unintentional manner. The persistence of biosurfactants in soil depends on soil texture, pH and moisture. Therefore, ecotoxicological risk assessment and regulatory screening are still needed before broad field application (Abdoli *et al.,* 2025).

Conclusion

This review has examined biosurfactants with a particular focus on the microorganisms that produce them, their genetic characteristics, ecological roles, biosynthetic pathways, and strategies for strain discovery. Key application areas discussed include the mitigation of antimicrobial resistance, sustainable agriculture, and environmental remediation in the context of climate change. Several applications are now supported by strong evidence, including agricultural biocontrol using *Bacillus* lipopeptides, hydrocarbon bioremediation using microbial consortia and *Pseudomonas* species, and the use of surfactin-based systems for disrupting biofilms associated with clinical pathogens. Although quorum-sensing-related mechanisms are being studied extensively, further validation in real biological systems is still needed before clinical implementation can be fully realised. Biosurfactants offer a promising route towards more sustainable solutions in the post-pandemic era. However, achieving this potential will require a transition from laboratory-scale research to real-world application, supported by long-term field trials, in vivo studies, scalable production technologies, and clear regulatory frameworks. The vast diversity of microbial life offers considerable potential for the discovery of new and more effective biosurfactants. A deeper understanding of microbial systems will be essential for developing technologies that are safe, scalable, and reliable. Ultimately, microorganisms possess the biochemical tools needed to address many global challenges, and the key task is to integrate scientific discovery,

technological advancement, and policy support in order to harness these capabilities effectively.

Acknowledgements

Authors would like to thank Sathyabama Institute of Science and Technology for providing the necessary facilities, resources and support to conduct this research.

Conflicts of interest

The authors declare no conflict of interest.

References

Abdoli, S., Asgari Lajayer, B., Bagheri Novair, S. and Price, G. W. (2025). Unlocking the potential of biosurfactants in agriculture: Novel applications and future directions. Sustainability, 17:2110.

Armstrong, D. G., Tan, T. W., Boulton, A. J. M. and Bus, S. A. (2020). Diabetic foot ulcers: a review. JAMA, 330:62.

Asadpour Panbehchouleh, F., Amani, H. and Saeedi, M. (2024). Menadione sodium bisulfite loaded rhamnolipid based solid lipid nanoparticle as skin lightener formulation: a green production beside in vitro/in vivo safety index evaluation. Advanced Pharmaceutical Bulletin, 14:047.

Azevedo, M. A., Teixeira, J. A., Pastrana, L. and Cerqueira, M. A. (2024). Rhamnolipids: A biosurfactant for the development of lipid-based nanosystems for food applications. Comprehensive Reviews in Food Science and Food Safety, 23:e13252.

Baccile, N., Babonneau, F., Jestin, J., Pehau-Arnaudet, G. and Van Bogaert, I. N. A. (2012). Unusual, pH-induced, self-assembly of sophorolipid biosurfactants. ACS Nano, 6:4763.

Bettenhausen, C. (2025). Two biosurfactant makers scale up

Bhatt, P., Bhatt, K., Sharma, A., Zhang, W., Mishra, S. and Chen, S. (2021). Biotechnological basis of microbial consortia for the removal of pollutants from the environment. Critical Reviews in Biotechnology, 41:359.

Borah, S. N., Goswami, D., Sarma, H. K., Cameotra, S. S. and Deka, S. (2016). Rhamnolipid biosurfactant against Fusarium verticillioides to control stalk and ear rot disease of maize. Frontiers in Microbiology, 7:1505.

Banat, I. M., Carboué, Q., Saucedo-Castañeda, G. and Cázares-Marinero, J. de J. (2021). Biosurfactants: The green generation of speciality chemicals and potential production using solid-state fermentation (SSF) technology. Bioresource Technology, 320(Part A), Article 124222. https://doi.org/10.1016/j.biortech.2020.124222

Cameotra, S. S. and Singh, P. (2009). Synthesis of rhamnolipid biosurfactant and mode of hexadecane uptake by Pseudomonas species. Microbial cell factories, 8:16.

Ceresa, C., Fracchia, L., Williams, M., Banat, I. M. and Díaz De Rienzo, M. A. (2020). The effect of sophorolipids against microbial biofilms on medical-grade silicone. Journal of Biotechnology, 309:34.

D'Aquila, P., De Rose, E., Sena, G., Scorza, A., Cretella, B., Passarino, G. and Bellizzi, D. (2024). Quorum quenching approaches against bacterial-biofilm-induced antibiotic resistance. Antibiotics, 13:619.

De Almeida, D. G., Soares da Silva, R. C. F., Luna, J. M., Rufino, R. D., Santos, V. A., Banat, I. M. and Sarubbo, L. A. (2026). Biosurfactants: Promising Molecules for Petroleum Biotechnology Advances. Frontiers in Microbiology. 7:1718. https://doi.org/10.3389/fmicb.2016.01718

Déziel, E. et al. (2026). Microbial Primer: Biosurfactants – the ABCs of Microbial Surface-Active Metabolites. Microbiology, 171:001604.

European Commission, Directorate-General for Research and Innovation. (2018). A sustainable bioeconomy for Europe: Strengthening the connection between economy, society and the environment: Updated bioeconomy strategy. Publications Office of the European Union. https://doi.org/10.2777/792130

Evonik Industries AG. (2024). Evonik drives sustainable biosurfactant revolution with inauguration of new facility in Slovakia. https://www.evonik.com/en/news/press-releases/2024/05/evonik-drives-sustainable-biosurfactant-revolution-with-inaugura.html

Fenibo, E. O., Ijoma, G. N., Selvarajan, R. and Chikere, C. B. (2019). Microbial surfactants: The next generation multifunctional biomolecules for applications in the petroleum industry and its associated environmental remediation. Microorganisms, 7:581. https://doi.org/10.3390/microorganisms7110581

Femina Carolin, C., Senthil Kumar, P. and Tsopbou Ngueagni, P. (2021). A review on new aspects of lipopeptide biosurfactant: Types, production, properties and its application in the bioremediation process. Journal of Hazardous Materials, 407:124827. https://doi.org/10.1016/j.jhazmat.2020.124827

Fracchia, L., Cavallo, M., Martinotti, M. G. and Banat, I. M. (2012). Biosurfactants and bioemulsifiers biomedical and related applications–present status and future potentials. Biomedical science, engineering and technology, 14:1-49.

Gan, T., Li, T., Yu, H., Yu, A., Zhao, M., Zhao, C., Xu, L., Cheng, J. and Ma, Y. (2026). From soil to crop: A tiered screening strategy for lipopeptide-producing *Bacillus* with antifungal, antibacterial and plant growth-promoting activities. Frontiers in Microbiology, 17:1798265. https://doi.org/10.3389/fmicb.2026.1798265

Grand View Research (2024). Biosurfactants market size, share & trends analysis report by product (rhamnolipids, sophorolipids, MES, APG, sorbitan esters, sucrose esters), by application (household detergents, personal care, …), by region, and segment forecasts, 2024-2030. https://www.grandviewresearch.com/press-release/global-biosurfactants-market.

Gdaniec, B. G., Bonini, F., Prodon, F., Braschler, T., Köhler, T. and van Delden, C. (2021). Pseudomonas aeruginosa rhamnolipid micelles deliver toxic metabolites and antibiotics into Staphylococcus aureus. iScience, 25:103669.

Gharsallah, H., Cheffi, M., Mallek, R., Omri, N., Triki, M. A., Öztop, M. H. and Zarai, Z. (2025). Antifungal potential of Bacillus strains: implications for biocontrol strategies in food safety and sustainable agriculture. Frontiers in Microbiology, 16:1615252.

Gudiña, E. J., Rocha, V., Teixeira, J. A. and Rodrigues, L. R. (2021). Antimicrobial and antiadhesive properties of a biosurfactant isolated from Lactobacillus paracasei ssp. paracasei A20. Letters in Applied Microbiology, 50:419.

Hamid, B., Zaman, M., Farooq, S., Fatima, S., Sayyed, R. Z., Baba, Z. A., Sheikh, T. A., Reddy, M. S., El Enshasy, H., Gafur, A. and Suriani, N. L. (2023). Bacterial plant biostimulants: a sustainable way towards improving growth, productivity, and health of crops. Sustainability, 13:2856.

Jahan, R. Bodratti A. M., Tsianou M. and Alexandridis P. (2020). Biosurfactants, natural alternatives to synthetic surfactants: Physicochemical properties and applications. Advances in Colloid and Interface Science, 275:102061. https://doi.org/10.1016/j.cis.2019.102061

Kabeil, S. S., Al-Zaban, M. I., Hassan, M. M. and Abd-Ellatif, S. (2025). Comprehensive review on factors affecting biosurfactant production by Pseudomonas aeruginosa. PeerJ, 13:e18981.

Kubicki, S., Bollinger, A., Katzke, N., Jaeger, K.-E., Loeschcke, A. and Thies, S. (2019). Marine biosurfactants: biosynthesis, structural diversity and biotechnological applications. Marine Drugs, 17:408.

Langford, B. J., So, M., Raybardhan, S., Leung, V., Westwood, D., Daneman, N. and MacFadden, D. R. (2021). Antibiotic prescribing in patients with COVID-19: rapid review and meta-analysis. Clinical Microbiology and Infection, 27:520.

Leistikow, K. R., May, D. S., Suh, W. S., Vargas Asensio, G., Schaenzer, A. J., Currie, C. R. and Hristova, K. R. (2024). Bacillus subtilis-derived peptides disrupt quorum sensing and biofilm assembly in multidrug-resistant Staphylococcus aureus. mSystems, 9:e00712-24.

Liu, G., Zhong, H., Yang, X., Liu, Y., Shao, B. and Liu, Z. (2018). Advances in applications of rhamnolipids biosurfactant in environmental remediation: A review. Biotechnology and Bioengineering, 115:796.

Maji, D., Ravichandran, D., Dalal, G. and Kumar, K. (2026). Fermentative routes of microbial biosurfactants production: emerging trends, innovations and multifaceted applications, Bioprocess and Biosystems Engineering, 1.

Marchant, R. and Banat, I. M. (2021). Biosurfactants: a sustainable replacement for chemical surfactants? Biotechnology Letters, 34:1597.

Markande, A. R., Patel, D. and Varjani, S. (2021). A review on biosurfactants: Properties, applications and current developments. Bioresource Technology, 330:124963. https://doi.org/10.1016/j.biortech.2021.124963

Matosinhos, R. D., Cascaes, J. M., Gerloff, D. K. B., de Oliveira, D., Monteiro, A. R., Calado, H. D. R. and Andrade, C. J. D. (2026). Integrated enzymatic and fermentative pathways for next-generation biosurfactants: advances in process design, functionalization, and industrial scale-up. Fermentation, 12:31.

Miao, Y., To, M. H., Siddiqui, M. A., Wang, H., Lodens, S., Chopra, S. S., Kaur, G., Roelants, S. L. K. W. and Lin, C. S. K. (2024). Sustainable biosurfactant production from secondary feedstock—recent advances, process optimization and perspectives. Frontiers in Chemistry, 12:1327113. https://doi.org/10.3389/fchem.2024.1327113

Mohanty, S. S., Koul, Y., Varjani, S., Pandey, A. and Ngo, H. H. (2021). Chang J. S. Wong J.W.C. and Bui X. T. A critical review on various feedstocks as sustainable substrates for biosurfactants production: A way towards cleaner production. Microbial Cell Factories, 20:120. https://doi.org/10.1186/s12934-021-01613-3

Mujah, D., Shahin, M. A. and Cheng, L. (2022). State-of-the-art review of biocementation by microbially induced calcite precipitation (MICP). Geomicrobiology Journal, 34:524.

Mukherjee, S., Das, P. and Sen, R. (2021). Towards commercial production of microbial surfactants. Trends in Biotechnology, 24:509.

Mulk, S., Wahab, A., Yasmin, H., Mumtaz, S., El-Serehy, H.A., Khan, N. and Hassan, M. N. (2022). Prevalence of wheat associated Bacillus spp. and their bio-control efficacy against fusarium root rot. Frontiers in Microbiology, 12:798619.

Murray, C. J., Ikuta, K. S., Sharara, F., Swetschinski, L., Aguilar, G. R., Gray A. et al. (2022). Global burden of bacterial antimicrobial resistance in 2019. The Lancet, 399:629.

Navarro-Muñoz, J. C., Selem-Mojica, N., Mullowney, M. W., Kautsar, S. A., Tryon, J. H., Parkinson, E. I. *et al.* (2020). A computational framework to explore large-scale biosynthetic diversity. Nature Chemical Biology, 16:60.

Nickzad, A. and Déziel, E. (2021). The involvement of rhamnolipids in microbial cell adhesion and biofilm development. Frontiers in Microbiology, 7:1265.

Nikolova, C. and Gutierrez T. (2021). Biosurfactants, Their Applications in the Oil, Gas Industry: Current State of Knowledge, Future Perspectives. Frontiers in Bioengineering and Biotechnology, 9:626639. https://doi.org/10.3389/fbioe.2021.626639

Ongena, M. and Jacques, P. (2021). Bacillus lipopeptides: versatile weapons for plant disease biocontrol. Trends in Microbiology, 16:115.

Passos, T. F. and Nitschke, M. (2024). The pH and sucrose influence rhamnolipid action toward planktonic and biofilms of Listeria monocytogenes. Microorganisms, 12:2078.

Prince, R. C. (2015). Oil spill dispersants: Boon or bane? Environmental Science & Technology, 49:6376.

Paul, S., Nayak, J., Paul, I., Kumar, R. and Jeon, B. H. (2025). Technological advancement in sustainable production of biosurfactant using agro-industrial wastes: A review of enhanced bioprocessing and computational optimization techniques. Critical Reviews in Environmental Science and Technology, 55:1430-1454.

Raza, Z. A., Khalid, Z. M., Khan, M. S., Banat, I. M., Rehman, A., Naeem, A. and Saddique, M. T. (2021). ANN-guided fermentation optimisation for rhamnolipid production. Biotechnology Letters, 31:1399.

Reis, R. S., Pereira, A. G., Neves, B. C. and Freire, D. M. G. (2022). Gene regulation of rhamnolipid production in Pseudomonas aeruginosa. Bioresource Technology, 102:6377.

Rivardo, F., Martinotti, M. G., Turner, R. J. and Ceri, H. (2011). Synergistic effect of lipopeptide biosurfactant with antibiotics against Escherichia coli CFT073 biofilm. International Journal of Antimicrobial Agents, 37:324.

Roelants, S. L. K. W., De Maeseneire, S. L., Ciesielska, K., Van Bogaert, I. N. A. and Soetaert, W. (2019). Biosurfactant gene clusters in eukaryotes. Applied Microbiology and Biotechnology, 98:3449.

Romero Vega, G. and Gallo Stampino, P. (2025). Bio-based surfactants and biosurfactants: An overview and main characteristics. Molecules, 30:863.

Sachdev, D. P. and Cameotra, S. S. (2013). Biosurfactants in agriculture. Applied Microbiology and Biotechnology, 97:1005.

Sana, S., Datta, S., Biswas, D. and Sengupta, D. (2023). Synergistic antibiofilm efficacy of sophorolipid–nisin combination. Microbial Pathogenesis, 176:106019.

Santos, D. K. F., Rufino, R. D., Luna, J. M., Santos, V. A. and Sarubbo, L. A. (2021). Biosurfactants: multifunctional biomolecules. International Journal of Molecular Sciences, 17:401.

Satpute, S. K., Banpurkar, A. G., Dhakephalkar, P. K., Banat, I. M. and Chopade, B. A. (2022). Methods for investigating biosurfactants. Critical Reviews in Biotechnology, 30:127.

Singh, S. B., Kuniyal, K., Rawat, A., Bisht, A., Shah, V. and Daverey, A. (2025). Sophorolipids as anticancer agents: progress and challenges. Discover Oncology, 16:507.

Smyth, T. J. P., Perfumo, A. and Marchant, R. (2010). Isolation and analysis of lipopeptides and high molecular weight biosurfactants, In: Timmis K.N. (Ed.), Handbook of Hydrocarbon and Lipid Microbiology, Springer, Berlin, Heidelberg, pp.3689-3704. https://doi.org/10.1007/978-3-540-77587-4_286

Solomon, A. A. and Vishnu, D. (2025). Integrated strategies for biosurfactant production and scale-up: advances in fermentation engineering and computational modelling, Results in Engineering, 106853.

Sony, J. B., Manjusha, W. A., Sangeetha, V. S., Vincent, S. G. T., Citarasu, T. and Anusha, J. R. (2025). Bioremediation of crude oil and heavy metal pollutants in marine environment by biosurfactant, rhamnolipid isolated from Stutzerimonas stutzeri MW15. Journal of Genetic Engineering and Biotechnology, 23:100507.

Sundaram, T., Govindarajan, R. K., Vinayagam, S., Krishnan, V., Nagarajan, S., Gnanasekaran, G., Baek, K. H. and Rajamani Sekar, S. (2024). Advancements in biosurfactant production using agro-industrial waste for industrial and environmental applications. Frontiers in Microbiology, 15:1357302.

Schultz, J. and Rosado, A. S. (2020). Extreme environments: A source of biosurfactants for biotechnological applications. Extremophiles, 24:189-206. https://doi.org/10.1007/s00792-019-01151-2

Théatre, A., Cano-Prieto, C., Bartolini, M., Laurin, Y., Deleu, M., Niehren, J., Fida, T., Gerbinet, S., Alanjary, M., Medema, M. H., Léonard, A., Lins, L., Jacquemyn, H., Raaijmakers, J. M. and Ongena, M. (2021). Surfactin-like lipopeptides from *Bacillus* spp.: Natural biodiversity and properties. Frontiers in Bioengineering and Biotechnology, 9:623701.

Thakur, P., Saini, N. K., Thakur, V. K., Gupta, V. K., Saini, R. V. and Saini, A. K. (2021). Rhamnolipid the glycolipid biosurfactant: Emerging trends and promising strategies in the field of biotechnology and biomedicine. Microbial Cell Factories, 20:1. https://doi.org/10.1186/s12934-020-01497-9

Tiso, T., Zauter, R., Tulke, H., Leuchtle, B., Li, W.-J., Behrens, B., Wittgens, A., Rosenau, F., Hayen, H., Blank, L. M. and Jaeger, K. E. (2017). Designer rhamnolipids by reduction of congener diversity: Production and characterization. Microbial Cell Factories, 16:225.

Ullah, H., Selvarajan, R. and Lau Vetter, M. C. (2026). Genome-mining revealed biosurfactant production capacity and gene co-occurrence patterns in diverse ecosystems. Microbial Cell Factories, 25:84.

Vigil, T. N., Felton, S. M., Fahy, W. E., Kinkeade, M. A. and Visek, A. M. (2024). Janiga A.R. et al., Biosurfactants as templates to inspire new environmental and health applications. Frontiers in Synthetic Biology, 2:1303423.

Wang, H., Roelants, S. L. K. W., To, M. H., Patria, R. D., Kaur, G., Lau, N. S., Lau, C. Y., Van Bogaert, I. N. A., Soetaert, W. and Lin, C. S. K. (2019). Starmerella bombicola: Recent advances on sophorolipid production and prospects of waste stream utilization. Journal of Chemical Technology & Biotechnology, 94:999.

Wang, S., Xu, M., Han, Y. and Zhou, Z. (2024a). Exploring mechanisms of antifungal lipopeptide iturin A from Bacillus against Aspergillus niger. Journal of Fungi, 10:172.

Wang, X., An, J., Cao, T., Guo, M. and Han, F. (2024b). Application of biosurfactants in medical sciences. Molecules, 29:2606.

Wang, Z. Z., Zeng, D. W., Zhu, Y. F., Zhou, M. H., Kondo, A., Hasunuma, T. and Zhao, X. Q. (2025). Fermentation design and process optimization strategy based on machine learning. Bioresource Technology Reports, 29:100002.

Wen, Y. *et al*. (2026). Bioengineering modification and application of bacterial outer membrane vesicles, International Journal of Medical Sciences.

WHO. (2022). Global Antimicrobial Resistance and Use Surveillance System (GLASS) Report 2022, World Health Organization.

Yang, R., Shi, Y., Bian, J., Sun, M., Ma, J., Ren, C., Feng, X., Wang, Y., Yang, Y., Zhou, J., Fu, J. and Li, R. (2025). Genetically engineered Pseudomonas aeruginosa with lipase regulation for production of rhamnolipids from waste frying oil. Frontiers in Microbiology, 16:1691217.

Yanvarov, Y. B. and Havryliak, V. V. (2024). Market analysis of microbial surfactants. Biotechnologia Acta, 17:5-13. https://doi.org/10.15407/biotech17.05.005

Zhang, J., Zhi, Y., Lu, Y. and Ma, F. (2026). Outer membrane vesicles as a versatile nanoplatform for advanced vaccine development and immunotherapy. Frontiers in Immunology, 17:1707391.

(Received: 6 September 2026, Revised: 9 November 2026, Accepted: 16 November 2026)