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BEYOND SURFACE ACTIVITY: THE EXPANDING ROLE OF MICROBIAL BIOSURFACTANTS IN SUSTAINABLE AGRICULTURE

ALÉM DA ATIVIDADE TENSOATIVA: O PAPEL DOS BIOSSURFACTANTES MICROBIANOS NA AGRICULTURA SUSTENTÁVEL

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ABSTRACT

The search for more sustainable agricultural alternatives has intensified in response to growing concerns about food security, climate change, and the environmental impacts associated with the intensive use of chemical inputs. In this context, biosurfactants have attracted increasing attention as microbial-derived compounds that combine biodegradability, low toxicity, and a wide range of properties relevant to agriculture. This review brings together recent advances in microbial biosurfactant production and discusses their potential applications in plant pathogen management, agricultural formulations, soil quality improvement, plant growth promotion, and the bioremediation of contaminated soils. It also examines the main barriers to large-scale adoption, including production costs, process optimization, formulation standardization, and the need for field validation under commercial farming conditions. Overall, the available evidence suggests that biosurfactants are a promising alternative for supporting more sustainable agricultural systems. However, their broader commercial use will depend on advances that integrate microbial biotechnology, formulation development, and consistent agronomic validation across different production systems.

Keywords: biosurfactants; sustainable agriculture; bioinputs; plant growth promotion; bioremediation.

RESUMO

O interesse por alternativas mais sustentáveis para a agricultura tem aumentado diante dos desafios relacionados à segurança alimentar, às mudanças climáticas e aos impactos causados pelo uso intensivo de insumos químicos. Nesse cenário, os biossurfactantes vêm se destacando por serem moléculas produzidas por microrganismos que combinam baixa toxicidade, biodegradabilidade e diferentes

propriedades de interesse agrícola. Esta revisão reúne estudos recentes sobre a produção microbiana desses compostos e discute seu potencial em diferentes aplicações, incluindo o controle de fitopatógenos, o uso como adjuvantes em formulações agrícolas, a melhoria da qualidade do solo, a promoção do crescimento vegetal e a biorremediação de áreas contaminadas. Também são abordados os principais entraves para sua utilização em larga escala, como os elevados custos de produção, a necessidade de processos mais eficientes, a padronização das formulações e a validação em condições reais de campo. De modo geral, os estudos indicam que os biossurfactantes representam uma alternativa promissora para o desenvolvimento de sistemas agrícolas mais sustentáveis. Entretanto, sua adoção comercial ainda depende de avanços que permitam integrar a produção biotecnológica, o desenvolvimento de formulações e a comprovação de sua eficiência em diferentes condições de cultivo.
Palavras-chave: biossurfactantes; agricultura sustentável; bioinsumos; promoção do crescimento vegetal; biorremediação.

1. INTRODUCTION

Global food production is under increasing pressure to meet the demands of a growing population while responding to rapid urbanization and changing consumption patterns. At the same time, agricultural systems must cope with climate change, soil degradation, water scarcity, and the continuous loss of arable land, all of which threaten long-term productivity (Deng *et al.,* 2025; Li *et al.,* 2026). Addressing these interconnected challenges requires production systems capable of sustaining crop yields while conserving natural resources and improving the resilience of agroecosystems (Gawdiya *et al.,* 2025; Menia *et al.,* 2026; Panda, 2025).

Over the past decades, higher agricultural productivity has largely depended on mineral fertilizers, pesticides, and other synthetic inputs. Although these technologies have played a fundamental role in increasing crop yields, their intensive use has also been associated with soil and water contamination, biodiversity loss, the emergence of resistant pests and phytopathogens, and the progressive degradation of agricultural ecosystems (Alom *et al.,* 2025; Nwankwo *et al.,* 2025; Olamiti, 2026; Xiao *et al.,* 2026). These concerns have encouraged the development of alternative production strategies that reduce dependence on conventional agrochemicals without compromising agricultural productivity. Within this context, bio-based agricultural inputs have gained increasing importance because of their potential to improve resource-use efficiency while reducing environmental impacts (Da Silva *et al.,* 2025; Förster, 2025; Gomide *et al.,* 2026).

Among these biological alternatives, biosurfactants have attracted considerable attention because their amphiphilic structure combines physicochemical and biological properties that are relevant to agriculture (Abdoli *et al.,* 2025; Garg *et al.,* 2025; Marks, Nogueira, & Hungria, 2025). Produced primarily by microorganisms and frequently obtained from renewable substrates, these molecules are biodegradable, generally exhibit low toxicity, and can perform multiple functions within agricultural systems. Rather than serving a single purpose, biosurfactants can act as complementary components in sustainable crop management by supporting different biological and physicochemical processes (Pandit & Meena, 2026; Sharma *et al.,* 2025).

This review examines recent advances in microbial biosurfactant production and discusses how these compounds are being incorporated into different areas of agriculture. Particular attention is given to plant pathogen management, agricultural formulations, soil quality, plant growth promotion, and the bioremediation of contaminated soils. Instead of considering these applications in isolation, we discuss biosurfactants as multifunctional molecules whose combined properties enable diverse roles within agricultural production systems. The review also examines the technological and agronomic barriers that continue to limit large-scale adoption and discusses research directions that may facilitate their broader implementation.

2. BIOSURFACTANTS

Biosurfactants are microbial surface-active molecules characterized by remarkable structural diversity and a broad range of physicochemical and biological properties. Their composition varies according to the producing microorganism and cultivation conditions, resulting in compounds with distinct surface activities, biological functions, and application potential (Athira & Abdulla, 2026; Maji *et al.,* 2026; Wahab & Al-Sahlany, 2025). These characteristics have supported the growing use of biosurfactants in several industrial sectors, particularly as sustainable alternatives to synthetic surfactants (Paul *et al.,* 2025; Silva *et al.,* 2026).

Recent research has expanded beyond the discovery of new biosurfactant-producing microorganisms to improving production efficiency, exploring renewable feedstocks, and developing processes suitable for large-scale applications (Dhiman *et al.,* 2025; Kapoor *et al.,* 2026; Singh & Kumar, 2025). As a result, current studies increasingly combine microbial prospecting, bioprocess optimization, and application-driven research to overcome technical and economic barriers that still limit commercial adoption. Understanding the characteristics, classification, and production strategies of biosurfactants is therefore essential for evaluating their potential in sustainable agricultural systems (Handa, Kaur, & Chatterjee, 2025).

2.1. Characteristics And Classification

Biosurfactants are classified according to their molecular weight, functional properties, or chemical composition, although classification based on chemical structure is the most widely used (Hsu *et al.,* 2025; Luong, Moorthy, & Luong, 2026). This approach divides biosurfactants into glycolipids, lipopeptides and lipoproteins, phospholipids, fatty acids, polymeric biosurfactants, and particulate biosurfactants. Because these groups differ in molecular structure, they also differ in surface activity, emulsifying ability, and biological functions (Satpute *et al.,* 2026; Uddin *et al.,* 2025). Low-molecular-weight biosurfactants, especially glycolipids and lipopeptides, are generally more efficient at reducing surface and interfacial tension, whereas high-molecular-weight compounds are better emulsifiers and produce more stable emulsions (Lourenço, Duarte, & Ribeiro, 2024; Matosinhos *et al.,* 2026; Sałek, Euston, & Janek, 2022). These differences largely explain why distinct biosurfactant classes are suited to different biotechnological applications.

Glycolipids and lipopeptides are the most extensively studied biosurfactants. Their prominence is associated with their high surface activity, diverse biological functions, and the availability of well-characterized microbial producers. As a result, rhamnolipids, sophorolipids, mannosylerythritol lipids (MELs), trehalolipids, surfactin, iturin, and fengycin have become the compounds most frequently investigated in studies of biosurfactant production and application (Chaudhary *et al.,* 2026; Indoria *et al.,* 2026). Other classes, including phospholipids, fatty acids, polymeric biosurfactants, and particulate biosurfactants, have received less attention but also exhibit properties of biotechnological interest (Meng *et al.,* 2026). This uneven distribution of research appears to reflect the current stage of knowledge and technological development rather than intrinsic differences in application potential. The major biosurfactant classes, representative compounds, and their general characteristics are summarized in Table 1.

Table 1. Classification of the major biosurfactant classes based on their chemical structure and general characteristics

Class	Representative compounds	General characteristics	References
Glycolipids	Rhamnolipids, sophorolipids, mannosylerythritol lipids (MELs), trehalolipids	Efficient reduction of surface and interfacial tension; good emulsifying capacity and formation of stable emulsions.	Panicker (2025).
Lipopeptides and lipoproteins	Surfactin, iturin, fengycin	High surface activity combined with antimicrobial, membrane-active, and surface-modifying properties.	Jain, Bhagat, & Reddy (2025).

Phospholipids	Phosphatidylethanolamine	Reduce interfacial tension and contribute to emulsion stabilization.	Wang *et al.* (2025).
Fatty acids and neutral lipids	Hydroxylated fatty acids and lipid derivatives	Facilitate emulsification and interactions with hydrophobic compounds.	Hsu *et al.* (2025).
Polymeric biosurfactants	Emulsan, alasan, liposan	High emulsifying capacity and long-term emulsion stability.	Gaur *et al.* (2026).
Particulate biosurfactants	Cell surface-associated vesicles and whole microbial cells	Promote cell adhesion, biofilm formation, and interactions with hydrophobic surfaces.	Sharma, Sunder, & Srivastava (2021).

Source: Prepared by the authors.

2.2. Microbial Production

Biosurfactants are synthesized by a wide variety of microorganisms, reflecting their metabolic diversity and ability to produce compounds with distinct structural and functional properties (Chegini & Zare, 2025; Ullah, Selvarajan, & Lau Vetter, 2026). Their synthesis is frequently associated with the metabolism of hydrophobic substrates but also occurs in cultures grown on hydrophilic carbon sources. Product yield and composition are influenced by nutrient availability, culture medium composition, pH, temperature, aeration, and fermentation time (Bustos-Vázquez *et al.*, 2025; Matosinhos *et al.*, 2026). This variability highlights the importance of selecting appropriate microbial strains and cultivation conditions to obtain consistent production and product quality (Maji *et al.,* 2026; Sharma & Lamsal, 2025).

Bacteria dominate biosurfactant production because they combine rapid growth with high productivity and well-characterized metabolic pathways (Saranraj *et al.,* 2022). Species of *Pseudomonas* and *Bacillus* remain the best-known producers of rhamnolipids and lipopeptides, respectively, and continue to underpin research on biosurfactant production and industrial applications (Kabeil *et al.,* 2025; Satpute *et al.,* 2026). Yeasts represent another important production platform, particularly for glycolipids such as sophorolipids and mannosylerythritol lipids (MELs). Their efficient use of renewable feedstocks and agro-industrial residues has strengthened interest in yeast-based production systems as a means of reducing manufacturing costs while improving process sustainability (Morita *et al.,* 2009; Shokri *et al.,* 2025).

Filamentous fungi have broadened the spectrum of microorganisms available for biosurfactant production. Their capacity to grow on lignocellulosic materials and other agro-industrial by-products, combined with extensive metabolic diversity, has encouraged the exploration of these organisms as alternative production platforms (Hilmy *et al.,* 2026). Biosurfactant-producing species have been reported within the genera *Absidia* (Mendonça *et al.,* 2026), *Aspergillus* (Rita *et al.,* 2025), *Penicillium* (Costa *et al.,* 2025), and *Trichoderma* (Valerio-Aguilar *et al.,* 2026). The number of reports remains considerably lower than that for bacteria and yeasts, indicating that fungal biosurfactants remain comparatively underexplored despite their potential for expanding the diversity of available molecules.

Carbon source selection is equally important for the economic viability of biosurfactant production (Rasheed *et al.,* 2025). Waste cooking oils, crude glycerol, molasses, whey, cereal brans, and lignocellulosic residues have been widely investigated because they lower raw material costs while promoting the recovery of agricultural and industrial wastes within circular economy strategies (Hilmy *et al.,* 2026; Tornuk & Akman, 2026). Current research therefore seeks production systems that combine efficient microbial platforms with inexpensive renewable substrates, reducing production costs without compromising biosurfactant performance. The principal microbial producers, the biosurfactants they synthesize, and their main characteristics are summarized in Table 2.

Table 2. Major microbial platforms used for biosurfactant production.

Microbial group	**Representative genera**	**Major biosurfactants**	**General characteristics**	**References**
Bacteria	*Pseudomonas*, *Bacillus*	Rhamnolipids, surfactin, iturin, fengycin	High productivity and the largest number of reported biosurfactants.	Lavanya e Agarwala (2026).
Yeasts	*Starmerella*, *Candida*	Sophorolipids, mannosylerythritol lipids (MELs), liposan	Efficient glycolipid producers with good adaptation to renewable feedstocks.	Holguín-Salas *et al.* (2025).
Filamentous fungi	*Aspergillus*, *Penicillium*,	Diverse biosurfactan	Emerging production	Subramanian et al.

	Trichoderma, Fusarium	ts and surface-active compounds	platform with high metabolic diversity and efficient utilization of agro-industrial residues.	(2025).

Source: Prepared by the authors.

2.3. Challenges For Production And Application

The commercial adoption of biosurfactants remains constrained by technical and economic factors that limit their large-scale production (Jui *et al.,* 2026). Laboratory studies have consistently demonstrated their potential, yet transferring these results to industrial production requires efficient fermentation processes, reproducible product quality, and competitive manufacturing costs (Raheja *et al.,* 2025). These challenges are closely connected, since improvements in production efficiency directly affect downstream processing requirements and the overall cost of the final product. Consequently, biosurfactants often remain more expensive than conventional surfactants, particularly when high product purity is required (Kim *et al.,* 2026).

Process performance is influenced by several variables, including the producing microorganism, culture medium composition, and carbon source (Laribi *et al.,* 2025). Small changes in these parameters can affect both biosurfactant yield and composition, making process optimization essential for consistent production. For this reason, agro-industrial residues have become attractive alternatives to conventional substrates because they reduce raw material costs while adding value to agricultural by-products, supporting circular economy and bioeconomy initiatives (Gupta, Gaur, & Singh, 2026). Even so, variations in the chemical composition of these feedstocks may influence process reproducibility and require careful optimization before industrial implementation.

Downstream processing remains another major barrier to commercial production (Grewal & Gulati, 2026). Recovery, concentration, and purification generally involve multiple processing steps that increase manufacturing costs and may reduce overall product recovery, especially when highly purified biosurfactants are required (Corrales *et al.,* 2026). Comparisons among studies are further complicated by differences in cultivation conditions, analytical methods, and purification procedures, which can produce biosurfactants with distinct compositions and functional properties even when the same microorganism is employed (Garg *et al.,* 2025). This lack of methodological standardization also limits direct comparisons of production efficiency and makes it more difficult to identify robust processes for industrial application.

Advances in metabolic engineering, fermentation technology, renewable feedstocks, and downstream processing continue to improve the prospects for commercial biosurfactant production (Carmona Marques *et al.,* 2025). The main obstacle, however, is no longer the identification of new biosurfactant-producing microorganisms but the development of production systems that combine technical reliability, economic competitiveness, and industrial scalability. For agricultural applications, these advances must also be accompanied by validation under practical field conditions before biosurfactants can be more widely incorporated into commercial products (Khoulati *et al.,* 2025).

3. APPLICATIONS OF BIOSURFACTANTS IN AGRICULTURE

The properties of biosurfactants have enabled their use in several areas of agriculture, extending beyond their traditional role as surface-active molecules. Their reported applications include plant pathogen management, soil quality improvement, agricultural formulations, and the remediation of contaminated environments (Sheth *et al.,* 2026). These functions are often interconnected, since the same biosurfactant may simultaneously influence microbial populations, improve the performance of agricultural inputs, and modify physicochemical processes in the soil. This functional diversity has supported the investigation of biosurfactants as components of integrated strategies for more sustainable agricultural production. The following sections examine these applications in relation to some of the main challenges facing modern agriculture.

3.1. Sustainable Management Of Plant Pathogens

Plant diseases caused by fungi, bacteria, viruses, and other phytopathogens remain a major constraint on agricultural productivity. Disease control still relies predominantly on chemical pesticides, which have contributed substantially to crop protection but have also favored the emergence of resistant pathogen populations and raised environmental concerns associated with their intensive use (Bakr *et al.,* 2025; Cucu *et al.,* 2025; Rather *et al.,* 2025). These limitations have stimulated the search for complementary disease management strategies based on biological products, including biosurfactants (Bender *et al.,* 2026).

Unlike conventional pesticides, biosurfactants may combine direct antimicrobial activity with the ability to stimulate plant defense responses. Depending on their chemical structure, they can disrupt microbial membranes, interfere with cell adhesion and biofilm formation, alter membrane permeability, or activate signaling pathways associated with systemic resistance, reducing pathogen establishment through multiple mechanisms rather than a single biological target (Khan *et al.,* 2025; Sultana *et al.,* 2025; Wahab & Al-Sahlany, 2025). This combination of direct and indirect effects has contributed to their growing use in integrated plant disease management.

Most studies have focused on lipopeptides and glycolipids because these classes include the biosurfactants with the most consistent evidence of antifungal and antibacterial activity (Awadelkareem *et al.,* 2025). By contrast, considerably less information is available for other biosurfactant classes, indicating that their potential for plant pathogen management remains less thoroughly explored. The principal biosurfactants investigated for disease control, their reported mechanisms of action, and representative target phytopathogens are summarized in Table 3.

Table 3. Major biosurfactants investigated for plant pathogen management, their mechanisms of action, and representative target phytopathogens.

Class	**Biosurfactant**	**Main mechanisms of action**	**Representative target phytopathogens**	**References**
Lipopeptide	Surfactin	Membrane disruption;	*Fusarium* spp., *Botrytis*	Jemil *et al.* (2024).

		induction of systemic resistance; inhibition of biofilm formation	*cinerea*, *Rhizoctonia solani*	
Lipopeptide	Iturin	Pore formation in the plasma membrane; increased membrane permeability; antifungal activity	*Fusarium* spp., *Alternaria* spp., *Colletotrichum* spp.	Wang et al. (2024).
Lipopeptide	Fengycin	Membrane disruption; inhibition of spore germination; antifungal activity	*Botrytis cinerea*, *Fusarium* spp., *Magnaporthe oryzae*	Abdelmoteleb et al. (2023).
Glycolipid	Rhamnolipids	Membrane disruption; inhibition of microbial adhesion and biofilm formation; induction of plant defense responses	*Pseudomonas syringae*, *Xanthomonas* spp., *Botrytis cinerea*	Darwiche et al. (2026).
Glycolipid	Sophorolipids	Antimicrobial activity; altered membrane permeability; interference with microbial colonization	*Fusarium* spp., *Alternaria* spp., *Xanthomonas* spp.	Panicker (2025).

Glycolipid	Mannosylerythritol lipids (MELs)	Modification of cell–surface interactions; antimicrobial and anti-adhesive activities	Limited evidence for agricultural phytopathogens	Münßinger et al. (2024).

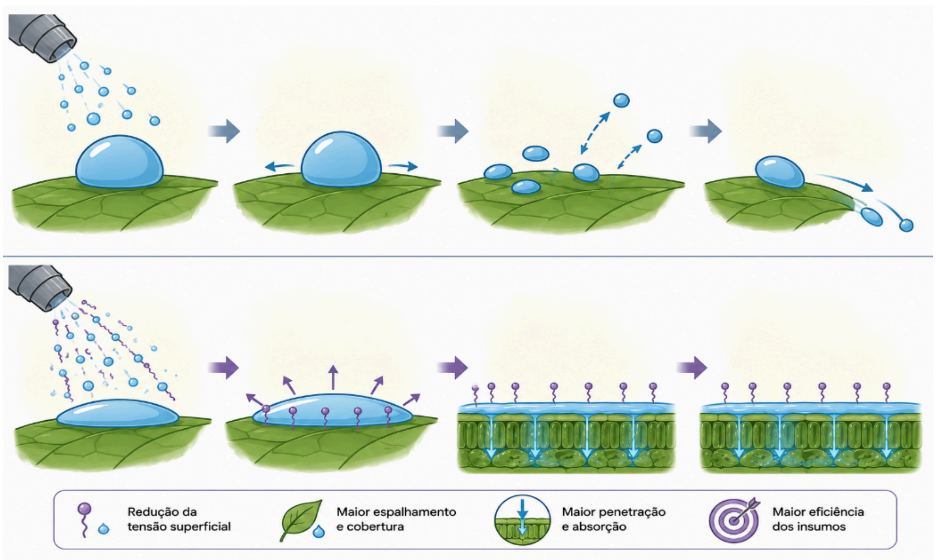
Source: Prepared by the authors.

3.2. Biosurfactants as Adjuvants For Improving Agrochemical Performance

Biosurfactants are increasingly incorporated into agricultural formulations as adjuvants because their amphiphilic structure modifies interfacial properties, improving the dispersion, emulsification, and stability of active ingredients (Sheth *et al.,* 2026; Begum, Mondal, & Mandal, 2026). By reducing the surface tension of spray solutions, they promote greater droplet spreading, increase retention on leaf surfaces, and facilitate the penetration of active compounds into plant tissues (De Carvalho, Weitz, & Conte-Junior, 2026; Awasthi *et al.,* 2026). These effects may improve the efficiency of agrochemical applications by increasing contact between the active ingredient and its biological target rather than simply increasing the amount of product applied.

Positive effects have been reported for formulations containing fertilizers, herbicides, fungicides, and insecticides (Pagano *et al.,* 2025; Verma *et al.,* 2025; Yasir, Hossain, & Pratap-Singh, 2025). Under appropriate conditions, improved spray coverage and retention may reduce application rates and minimize runoff losses, contributing to more efficient use of agricultural inputs. Most of the available evidence, however, has been generated under laboratory or greenhouse conditions. Field performance is often more variable because formulation efficiency depends on environmental conditions, crop architecture, application technology, and interactions with the active ingredient. These factors help explain why relatively few biosurfactant-based adjuvants have reached commercial use despite the promising experimental results. A schematic representation of these mechanisms is presented in Figure 1.

Figure 1. Mechanism of action of biosurfactants as adjuvants in agricultural formulations. (A) Conventional spraying, characterized by higher surface tension, limited leaf coverage, and increased runoff. (B) Spraying with biosurfactants, resulting in lower surface tension, greater droplet spreading, and enhanced penetration of active ingredients.



Source: Prepared by the authors using ChatGPT (GPT-5.5; OpenAI) for illustration development.

Beyond improving spray deposition, biosurfactants also function as emulsifiers, dispersants, wetting agents, and stabilizers in agricultural formulations (Abd-Elsalam *et al.*, 2025; Ansari *et al.*, 2025). These properties contribute to formulation stability and promote a more uniform distribution of active ingredients on the target surface. Their multifunctionality also creates opportunities to replace or reduce the use of conventional formulation additives, supporting the development of bio-based agricultural products with lower environmental impact (Da Silva *et al.,* 2025; De Souza *et al.,* 2026).

Commercial implementation still depends on overcoming several formulation challenges. Compatibility with different active ingredients, storage stability, process standardization, and consistent performance under field conditions remain important limitations (Macchia *et al.,* 2025). The effectiveness of a biosurfactant as an adjuvant is therefore determined not only by its surface activity but also by its behavior within the complete formulation and under practical application conditions. Demonstrating consistent performance across different crops, environments, and production systems remains one of the main steps required for broader commercial adoption (Chauhan, Mohanty, & Meena, 2025; Rafiq *et al.,* 2025).

3.3. Soil Quality And Nutrient Availability

Soil quality directly influences nutrient availability, microbial activity, water dynamics, and root development, making it a key determinant of agricultural productivity and the long-term sustainability of cropping systems (Țopa *et al.,* 2025; Kumar *et al.,* 2025). Intensive cultivation, repeated fertilizer application, and inadequate soil management can alter these processes, reducing nutrient use efficiency and accelerating soil degradation (Yimer & Tarnawa, 2025; Asante *et al.,* 2025). Because biosurfactants modify interactions among soil particles, water, and mineral compounds, they have been investigated as biological tools for improving nutrient dynamics and soil functioning (Sethi *et al.,* 2025).

Their effects are associated with changes in interfacial interactions within the soil matrix, influencing nutrient solubility, mobility, and availability (Gonzalo & González-Pérez, 2025; Hayes & Roulia, 2025). Biosurfactants may increase the availability of poorly soluble nutrients, promote the release of compounds retained on soil particles, and stimulate microbial processes involved in nutrient cycling (Shahabirokni *et al.,* 2025). The magnitude of these responses, however, depends on several factors, including soil texture, mineral composition, organic matter content, and the physicochemical characteristics of the biosurfactant itself. As a result, responses reported under controlled conditions are not always directly transferable to different agricultural systems.

The rhizosphere represents another important target for biosurfactant activity. By influencing microbial interactions, biosurfactants may favor the establishment of plant growth-promoting microorganisms and stimulate processes related to organic matter mineralization and nutrient cycling (Marks, Nogueira, & Hungria, 2025). These responses may improve nutrient use efficiency and support soil fertility management, although the relative contribution of biosurfactants within the complex soil microbiome remains difficult to isolate under field conditions. The principal soil processes affected by biosurfactants, their mechanisms of action, and their potential agronomic implications are summarized in Table 4.

Table 4. Soil processes affected by biosurfactants and their potential agronomic implications.

Soil process	Mechanism	Effect	Agronomic implication	References
Nutrient solubilization	Surface tension reduction and micelle formation	Increased availability of poorly soluble nutrients	Improved nutrient uptake	(Ahammad; Kim, 2025).
Desorption of adsorbed nutrients	Modification of interactions between soil particles and mineral compounds	Release of retained nutrients	Improved soil fertility	**(Hayat** et al., **2026).**
Microbial activity	Stimulation of beneficial rhizosphere microorganisms	Enhanced mineralization and nutrient cycling	Improved soil biological quality	Marks, Nogueira & Hungria (2025).
Soil–water interactions	Modification of interfacial properties	Improved water infiltration and distribution	More efficient water and nutrient use	**Shahabirokni *et al.* (2025).**
Metal complexation	Formation of metal complexes and increased ion mobility	Reduced metal toxicity and greater nutrient availability	Enhanced root growth and plant development	**Eras-Muñoz *et al.* (2022).**

Source: Prepared by the authors.

Most available evidence has been obtained from laboratory, greenhouse, or short-term experiments. Long-term field studies remain limited, particularly across contrasting soil types, cropping systems, and climatic conditions (Sheth *et al.,* 2026; Khoulati *et al.,* 2025; Jamilah *et al.,* 2025; Marks, Nogueira, & Hungria, 2025). Establishing consistent application protocols and identifying the environmental conditions under which biosurfactants provide reproducible agronomic benefits remain important challenges for their incorporation into soil fertility management.

3.4. Plant Growth Promotion

Plant growth promotion is one of the most widely investigated agricultural applications of biosurfactants, particularly when these compounds are associated with plant growth-promoting microorganisms (PGPM) (Ríos-Ruiz *et al.,* 2025; Gaurav *et al.,* 2026). Rather than supplying nutrients directly, biosurfactants influence soil physicochemical properties and rhizosphere processes that regulate plant development. Changes in nutrient availability, microbial activity, and root–soil interactions may create conditions that favor plant establishment and growth (Mohanty, Manyapu, & Mandpe, 2025; Abdoli *et al.,* 2025).

The reported responses arise from the interaction of multiple processes rather than from a single mechanism of action. Biosurfactants may increase nutrient availability, facilitate rhizosphere colonization by beneficial microorganisms, influence plant–microbe interactions, and contribute to organic matter mineralization and nutrient cycling (Panhwar *et al.,* 2025; Sun *et al.,* 2025). Some studies also describe improved tolerance to abiotic stresses such as drought and salinity, suggesting that biosurfactants can help maintain plant performance under environmental conditions that limit crop development (Rahim *et al.,* 2025; Di Sario *et al.,* 2025).

Interest has also grown in combining biosurfactants with microbial inoculants. In these systems, biosurfactants may improve the establishment of beneficial microorganisms in the rhizosphere, potentially increasing the effectiveness of microbial inoculants (Kampouris *et al.,* 2025). Positive responses have been reported for seed germination, root development, plant biomass, leaf area, and crop yield (Jamilah *et al.,* 2025; Mendonça *et al.,* 2026; Shahabirokni *et al.,* 2025; Abdoli *et al.,* 2025; Paul *et al.,* 2025). The magnitude of these responses, however, varies substantially among crop species, soil conditions, and management practices, indicating that plant growth promotion cannot be attributed solely to the presence of biosurfactants. The principal mechanisms involved in biosurfactant-mediated plant growth promotion are summarized in Table 5.

Table 5. Processes influenced by biosurfactants and their potential contributions to plant growth

Process influenced	Role of biosurfactants	Potential plant response	Potential agronomic benefit	References
Nutrient availability	Increased nutrient solubilization and mobility	Greater nutrient acquisition	Improved nutrient use efficiency	Panhwar *et al.* (2025); Mohanty, Manyapu, & Mandpe (2025)
Rhizosphere colonization	Facilitation of beneficial microbial establishment	Stronger plant–microbe interactions	Enhanced root development	Sun *et al.* (2025); Kampouris *et al.* (2025)

Root development	Modification of rhizosphere conditions	Root system expansion	Greater water and nutrient acquisition	Abdoli *et al.* (2025); Jamilah *et al.* (2025)
Abiotic stress tolerance	Mitigation of drought- and salinity-induced effects	Maintenance of plant physiological performance	More stable crop performance under stress	Rahim *et al.* (2025); Di Sario *et al.* (2025)

Source: Prepared by the authors.

Most available evidence has been obtained under controlled experimental conditions, whereas long-term field studies remain comparatively scarce (Sharma *et al.,* 2025; Albuquerque *et al.,* 2025). Plant responses are influenced by the interaction between biosurfactants, soil properties, native microbial communities, environmental conditions, and application strategy, making it difficult to establish broadly applicable recommendations. Defining the production systems in which biosurfactants consistently improve plant performance remains one of the main challenges for their wider adoption in agriculture.

3.5. Bioremediation Of Contaminated Soils

Agricultural intensification has contributed to the accumulation of contaminants in soil, including pesticide residues, fuel-derived hydrocarbons, fertilizers, and potentially toxic metals, compromising soil quality, ecosystem functioning, and crop productivity (Malla *et al.,* 2026; Kumar, Arora, & Shadangi, 2026). Bioremediation has become an important strategy for reducing contaminant levels through biological processes that promote their transformation, degradation, or immobilization (Vuković Domanovac *et al.,* 2025; Qattan, 2025). Within this context, biosurfactants have been investigated primarily because they modify the availability of contaminants to microorganisms rather than acting directly on the contaminants themselves (Handa, Kaur, & Chatterjee, 2025).

Their amphiphilic structure reduces surface and interfacial tension, promotes micelle formation, and increases the apparent solubility of hydrophobic compounds (Samant & Kaliappan, 2025; Satpute, Sati, & Pratap, 2026). These changes facilitate the desorption of contaminants retained in the soil matrix, increasing their accessibility to microbial degradation. Biosurfactants may also interact with potentially toxic metals through complexation processes that influence metal mobility and contribute to either contaminant removal or stabilization, depending on remediation objectives (Raheja *et al.,* 2025). The effectiveness of these mechanisms, however, depends on contaminant chemistry, soil properties, and environmental conditions, which may lead to substantial variation among remediation systems.

The combined use of biosurfactants with contaminant-degrading microorganisms has produced encouraging results for the remediation of hydrocarbons, pesticides, and other persistent contaminants (Elias *et al.,* 2025). Nevertheless, the positive effects reported under experimental conditions cannot be generalized to all contaminated environments because contaminant concentration, soil composition, microbial communities, and environmental conditions strongly influence remediation efficiency. The principal agricultural contaminants targeted by biosurfactant-assisted bioremediation, together with their mechanisms of action and potential environmental outcomes, are summarized in Table 6.

Table 6. Agricultural contaminants targeted by biosurfactant-assisted bioremediation and their potential environmental benefits.

Contaminant	Role of biosurfactants	Primary effect	Potential environmental benefit	References
Hydrocarbons	Increased solubilization and micelle formation	Greater bioavailability for microbial degradation	Recovery of contaminated soils	Handa, Kaur, & Chatterjee (2025).
Pesticides	Desorption and increased contaminant availability	Enhanced biodegradation	Reduced persistence and lower environmental toxicity	Qattan (2025).
Potentially toxic metals	Complexation and changes in metal mobility	Enhanced removal or immobilization	Reduced contamination and ecotoxicological risk	Raheja *et al.* (2025).
Persistent organic compounds	Increased accessibility to degrading microorganisms	Enhanced biodegradation	Improved soil environmental quality	Elias *et al.* (2025).
Mixed contaminants	Simultaneous interaction with organic and inorganic contaminants	Improved remediation efficiency	Recovery of degraded agricultural land	Vuković Domanovac *et al.* (2025).

Source: Prepared by the authors.

Most available studies have been conducted under laboratory or pilot-scale conditions, whereas field-scale validation remains comparatively limited (Aprilya *et al.,* 2026; De Oliveira *et al.,* 2026). In addition, increasing contaminant mobility does not necessarily translate into improved remediation if microbial degradation is insufficient or environmental conditions are unfavorable. Defining application strategies that balance contaminant availability with effective biodegradation remains one of the main challenges for the broader use of biosurfactants in the remediation of agricultural soils.

4. LIMITATIONS, CHALLENGES, AND FUTURE PERSPECTIVES

Research on agricultural applications of biosurfactants has expanded considerably in recent years, providing evidence of their potential for plant disease management, agricultural formulations, soil quality improvement, plant growth promotion, and bioremediation (Abdoli *et al.,* 2025; Ansari *et al.,* 2025; Marks, Nogueira, & Hungria, 2025; Sheth *et al.,* 2026; Satpute, Sati, & Pratap, 2026). Much of this progress has established the biological and physicochemical versatility of biosurfactants. Their broader adoption in agriculture, however, is no longer limited by the identification of new applications but by the ability to translate experimental evidence into commercially viable technologies. Technological, agronomic, economic, and regulatory barriers continue to limit large-scale implementation and remain the main focus of current research (Begum, Mondal, & Mandal, 2026; Lavanya & Agarwala, 2026; Abdoli *et al.,* 2025; Handa, Kaur, & Chatterjee, 2025).

4.1. Technological Challenges

The commercial competitiveness of biosurfactants remains closely associated with the efficiency of their production systems. Although numerous producing microorganisms and renewable substrates have been identified, manufacturing costs continue to exceed those of conventional surfactants because of limitations related to fermentation efficiency, industrial scale-up, downstream processing, and product recovery (Ahluwalia *et al.,* 2025; Ganger *et al.,* 2025; Garg *et al.,* 2025). These production stages are closely interconnected, meaning that improvements in one part of the process do not necessarily result in economically viable manufacturing if limitations persist elsewhere.

Technological development also extends beyond biosurfactant production itself. Product performance depends on the compatibility of biosurfactants with fertilizers, pesticides, microbial inoculants, and other formulation components rather than on the properties of the biosurfactant alone (Paul *et al.,* 2025). Consequently, overcoming technological barriers requires integrated production and formulation strategies capable of generating stable, reproducible, and economically competitive products. Even when these requirements are met, however, successful agricultural implementation ultimately depends on consistent performance under practical field conditions.

4.2. Agronomic Challenges

Addressing technological constraints alone is insufficient to ensure the successful adoption of biosurfactants in agriculture. Once production and formulation challenges have been overcome, biosurfactant-based products must also demonstrate consistent agronomic performance under the diverse environmental conditions encountered in commercial farming. Consequently, the transition from experimental studies to agricultural production systems remains one of the principal challenges for biosurfactant application (Adhikary *et al.,* 2026).

Although positive responses have frequently been reported under laboratory and greenhouse conditions, these results are not consistently reproduced in the field, where crop species, soil properties, climatic conditions, management practices, and native microbial communities interact simultaneously (Khoulati *et al.,* 2025). This environmental complexity contributes to considerable variation in reported responses and limits the development of recommendations that can be broadly applied across agricultural production systems.

Another challenge is the integration of biosurfactants into existing crop management practices. Synergistic effects have been reported when biosurfactants are combined with fertilizers, pesticides, and plant growth-promoting microorganisms, but evidence regarding formulation stability, compatibility, and agronomic performance under commercial conditions remains limited (Abitabile *et al.,* 2025; Shaikat, Rabbani, & Ahamad, 2026). Likewise, environmental persistence varies according to soil and climatic conditions, influencing application frequency, product performance, and management decisions (Beretta *et al.,* 2026).

A further limitation is the absence of standardized field evaluation protocols. Current studies differ substantially in biosurfactant type, formulation, crop species, soil characteristics, application methods, and environmental conditions, making direct comparisons difficult and limiting the identification of the factors that consistently determine agronomic performance. As evidence supporting agricultural applications continues to accumulate, research is increasingly focused on establishing standardized field evaluations that allow meaningful comparisons across agricultural production systems. Coordinated multi-location field trials and standardized evaluation protocols will therefore be essential to identify robust application strategies, generate comparable evidence, and support the commercial implementation of biosurfactants in agriculture (Da Silva *et al.,* 2026; Khoulati *et al.,* 2025; Barbosa *et al.,* 2025).

4.3. Future Perspectives

Current research increasingly emphasizes the translation of experimental findings into commercially viable agricultural technologies. As evidence supporting the principal applications of biosurfactants continues to accumulate, research has progressively shifted toward improving production efficiency, formulation performance, and field reproducibility (Lavanya & Agarwala, 2026; Zheng *et al.,* 2026; Maji *et al.,* 2026).

Meeting these objectives will require greater integration between microbial biotechnology, formulation science, and agronomic research. Advances in microbial engineering, fermentation strategies, and renewable feedstocks are expected to improve production efficiency, whereas innovations in formulation technologies may enhance product stability, compatibility with agricultural inputs, and application performance (Sharma *et al.,* 2025; Abitabile *et al.,* 2025). Rather than functioning as isolated biological products, biosurfactants are increasingly being incorporated into integrated agricultural technologies, including controlled-release systems, multifunctional bioformulations, and precision agriculture approaches that seek to optimize product delivery and input-use efficiency (Matos *et al.,* 2026; Valente *et al.,* 2025; Kruger *et al.,* 2025). At the same time, advances in omics technologies and systems biology continue to improve the understanding of microbial metabolism and biosynthetic pathways, supporting the identification of strains and production strategies better suited to agricultural applications (Shaikat, Rabbani, & Ahamad, 2026; Zheng *et al.,* 2026).

The successful incorporation of biosurfactants into agricultural production systems will ultimately depend on advances beyond product development. Standardized production methods, harmonized field evaluation protocols, and regulatory frameworks adapted to biological products remain essential for generating comparable evidence and reducing uncertainty regarding field performance (Adhikary *et al.,* 2026; Garg *et al.,* 2025; Ahluwalia *et al.,* 2025). Strengthening collaboration among researchers, industry, and regulatory agencies will also be important for accelerating technology transfer and establishing practical recommendations for commercial agriculture (Shaikat, Rabbani, & Ahamad, 2026). Overall, the literature indicates that the next stage of development will depend on transforming the current body of experimental evidence into reproducible agricultural technologies capable of delivering consistent technical, economic, and agronomic performance under commercial farming conditions.

5. CONCLUSION

The literature reviewed demonstrates that biosurfactants constitute a diverse group of microbial molecules whose physicochemical and biological properties support multiple agricultural applications. Their multifunctional nature enables simultaneous contributions to plant disease management, agricultural formulations, soil functioning, plant growth promotion, and the remediation of contaminated environments, highlighting their potential to support more sustainable agricultural production systems.

The current literature also indicates that the principal limitation is no longer demonstrating the versatility of biosurfactants but translating this knowledge into technologies that perform consistently under commercial agricultural conditions. Progress in production efficiency, formulation development, and field validation has expanded the feasibility of agricultural applications, yet variability in production systems, environmental conditions, and evaluation protocols continues to limit reproducibility and large-scale implementation.

Future advances will depend on integrating microbial biotechnology, process engineering, formulation science, and agronomic validation into coordinated development strategies. Equally important is the adoption of standardized production and field evaluation protocols capable of generating comparable evidence across crops, soils, and production systems. The broader contribution of biosurfactants to sustainable agriculture will therefore depend not on identifying additional applications, but on translating the existing body of knowledge into technologies that combine reproducible production, robust formulations, and consistent field performance under commercial farming conditions.

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