AMERICAN JOURNAL OF BIOCHEMISTRY AND BIOTECHNOLOGY

REVIEW ARTICLE

Biosurfactants in the Halal Economy: Sustainable Solutions for Food, Pharma, and Beyond

Kanokphorn Sangkharak[1], Suppasil Maneerat[2], Aem Nuylert[2], Abbas Labduang[3], Naeem Madsari[4], Atipan Saimmai[4]*

[1]Faculty of Agricultural Technology, Phuket Rajabhat University, Phuket, 83000, Thailand
[2]Center of Excellence in Food Safety and Management, Faculty of Agro-Industry, Prince of Songkla University, Hat Yai, Songkhla, 90110, Thailand
[3]Faculty of Management Science, Yala Rajabhat University, Yala 95000, Thailand
[4]Halal Institute, Prince of Songkla University, Hat Yai, Songkhla, 90110, Thailand

*Corresponding Author: S4680108@gmail.com

Abstract: Leaves from forage crops and vegetables such as water spinach, sweet potato, cassava, and especially taro, can be incorporated into pig diets as partially replace commonly used protein sources including fish meal or/and soybean meal. However, their use remains limited among farmers and livestock producers. This study aimed to compare feed intake, determine apparent digestibility coefficients, and analyze nitrogen retention in pigs fed various forms of taro-based diets. The experiment was conducted from September 9 to November 30, 2025, at Svay Rieng University, located along National Road 1, Chambak Village, Chek Commune, Svay Rieng City, Svay Rieng Province, Cambodia. Four castrated male crossbred pigs (average body weight: 15 kg; approximately 50 days old) were used in a 4×4 Latin square design. The study included four dietary treatments: fresh taro, boiled taro, dried taro, and ensiled taro, each applied across four experimental units. The trial was conducted over four periods, with each period comprising 5 days for diet adaptation followed by 5 days for the collection of feces and urine. Findings from the study demonstrated that crossbred pigs consumed higher amount of DM intakes in T2 (748g/day) and T4 (784 g/day), highly coefficient digestibility of DM in T1 (87.1%) or T2 (88.9%), and greatly nitrogen retention in T2 (9.27%). In conclusion, fresh or ensiled taro may be used at a 10% inclusion rate in pig diets, as long as it is thoroughly mixed with other ingredients. The crossbred pigs consumed high amount of DM intakes, exhibited highly in coefficient digestibility of DM, and indicated a greater nitrogen retention. Biosurfactants, microbial surface-active compounds, are gaining attention as sustainable, biocompatible alternatives to synthetic surfactants. Their properties, including emulsification, foaming, and antimicrobial activities, enable diverse applications in food, pharmaceutical, and cosmetic industries. With increasing demand for halal-certified products, biosurfactants offer potential as halal ingredients, provided they are produced using compliant strains, substrates, and processing methods. This review examines the production of halal-compatible biosurfactants, their key functional properties, and their applications in halal product development. Emphasis is placed on food, drug delivery, and personal care sectors, alongside certification standards. Biosurfactants are positioned as novel, ethical ingredients supporting the global expansion of halal-compliant biotechnology.

Keywords: Biosurfactants, Halal, Biotechnology, Applications, Natural Product

Received: 27-12-2025 | **Revised:** 22-06-2025 | **Accepted:** 24-06-2026 | **DOI:** 10.3844/ajbbsp.2026.22.03.032

Introduction

The global demand for halal-certified products has grown rapidly in recent years, driven by a rising Muslim population and increasing awareness of religious dietary and ethical standards .The term halal, meaning "permissible "in Arabic, extends beyond food and beverages to include pharmaceuticals, cosmetics, and other consumer goods .For a product to be considered halal, all components and production processes must comply with Islamic law, which prohibits substances such as pork derivatives and alcohol, and emphasizes cleanliness, safety, and ethical sourcing [1]. As a result, industries targeting the expanding halal market are increasingly focused on identifying and developing novel halal-compliant ingredients.

Biosurfactants, surface-active compounds produced by microorganisms such as bacteria, yeasts, and fungi, have emerged as promising candidates for halal-certified formulations .These amphiphilic molecules reduce surface and interfacial tension, stabilize emulsions, and exhibit antimicrobial and anti-adhesive properties [2]. Compared to synthetic surfactants, biosurfactants are biodegradable, less toxic, and can be derived from renewable resources, making them attractive for use in food, pharmaceutical, and personal care products [3]. When they are produced using halal-certified microbial strains and substrates that are free from animal-derived or non-compliant compounds, biosurfactants can align with halal requirements [4].

However, halal compliance is not inherently assured. Critical factors such as the origin of fermentation media, use of processing aids, and risk of contamination during production must be rigorously evaluated [5]. Bridging biotechnology and halal certification presents both new opportunities and unique regulatory challenges .This review explores the potential of biosurfactants as emerging halal ingredients by examining their microbial production, functional properties, and industry-specific applications .It also outlines key halal compliance criteria, regulatory frameworks, and market trends, aiming to bridge scientific innovation with religious principles and support future development of halal-certified biosurfactant technologies.

Overview of Biosurfactants

Definition and Classification

Biosurfactants are amphiphilic compounds produced by microorganisms such as bacteria, yeasts, and fungi .Comprising both hydrophilic and hydrophobic moieties, these molecules effectively reduce surface and interfacial tensions between liquids, solids, and gases .Unlike synthetic surfactants, biosurfactants are biodegradable, environmentally friendly, and exhibit low toxicity, making them attractive for industrial and biomedical applications [6]. They are broadly classified based on chemical structure and microbial origin, with five major categories:

Glycolipids

Glycolipids are among the most extensively studied biosurfactants due to their diverse structures and wide-ranging applications [7, 8]. They consist of a sugar moiety-typically glucose, rhamnose, or sophorose-linked to long-chain fatty acids or hydroxy fatty acids .This configuration imparts strong surface activity, enabling emulsification and wetting functions .Key examples include rhamnolipids (produced by Pseudomonas aeruginosa(and sophorolipids (Candida bombicola(, which also exhibit antimicrobial, anti-adhesive, and antibiofilm properties. Their production from renewable substrates enhances their appeal for sustainable and halal-compliant formulations [2]. Current research focuses on strain engineering and process optimization to improve yield and purity at commercial scale.

Lipopeptides and Lipoproteins

These biosurfactants are composed of a fatty acid tail covalently linked to a short peptide chain-either linear or cyclic-enabling interaction with biological membranes .Notable lipopeptides include surfactin, iturin, and fengycin, primarily produced by Bacillus subtilis .They possess strong antimicrobial, antiviral, antifungal, and hemolytic activities by disrupting cellular membranes [2]. Their surface activity and emulsifying ability make them valuable in pharmaceuticals, agriculture, food safety, and cosmetics .Halal-compliant production requires attention to fermentation substrates and purification methods.

Phospholipids

Produced under stress or nutrient-limited conditions, microbial phospholipids consist of glycerol backbones with fatty acid chains and phosphate-containing head groups .Found in genera such as Corynebacterium and Acinetobacter, they contribute to membrane stabilization, emulsification, and solubilization of hydrophobic substances [6]. Although less studied than

DOI: 10.3844/ajbbsp.2026.22.03.032

glycolipids or lipopeptides, phospholipids are biocompatible and potentially useful in halal-certified emulsions, drug delivery, and biodegradable detergents-pending further research into scalable production and halal validation.

Polymeric Biosurfactants

These high-molecular-weight biosurfactants are composed of complex polymers such as polysaccharides, proteins, lipids, or conjugates .Unlike low-molecular-weight surfactants, they stabilize emulsions over longer periods and under harsh conditions .Examples include emulsan (Acinetobacter calcoaceticus), liposan (Candida lipolytica), and alasan (Acinetobacter). Their emulsifying strength, stability across pH and temperature ranges, and compatibility with halal substrates make them suitable for enhanced oil recovery, wastewater treatment, food-grade emulsions, and eco-friendly detergents [9].

Particulate Biosurfactants

These cell-associated biosurfactants remain embedded in microbial structures such as outer membranes, vesicles, or cell wall fragments .Rather than being secreted into the medium, they act through direct surface contact, facilitating microbial adhesion, biofilm formation, and hydrophobic substrate colonization .Although understudied, their emulsifying capabilities and local activity make them promising for immobilized biocatalysis, soil remediation, and probiotic formulations [10]. Their relevance is growing in halal-compliant applications where localized action and structural integrity are critical.

Comparative Analysis of Biosurfactants and Synthetic Surfactants

A comparative evaluation of biosurfactants and synthetic surfactants is provided in Table 1. Biosurfactants offer several advantages, particularly biodegradability, low toxicity, renewable production routes, and potential compatibility with halal-certified supply chains [11]. In contrast, many synthetic surfactants are derived from petrochemical sources and may persist in the environment, contributing to ecological contamination and aquatic toxicity [12]. These differences are especially important for halal and sustainable product development, where both ingredient origin and environmental responsibility are key considerations.

Table 1: Comparative features of biosurfactants and synthetic surfactants in halal and sustainable applications

Property	Biosurfactants	Synthetic Surfactants	References
Source	Produced by microorganisms, plants, and biological renewable sources	Mainly synthesized from petrochemical sources	[13,14]
Biodegradability	Highly biodegradable and easily broken down by microorganisms	Moderate to low biodegradation rate with some resistant compounds	[11]
Toxicity	Low toxicity and high biocompatibility	Higher toxicity to aquatic life and the ecosystem	[3]
Environmental impact	Environmentally friendly and causes minimal ecological damage	Possible contribution to environmental pollution and bioaccumulation	[15]
Renewability of raw materials	Made using renewable sources such as agricultural waste and vegetable oil	Mainly rely on non-renewable petroleum sources	[13]
Surface tension reduction	They have the capability to reduce surface tension of water to 25-35 mN/m from 72 mN/m	Efficacious surface tension reduction though comparable or slightly less effective	[9]
Critical micelle concentration (CMC)	Lower CMC, suggesting efficiency at low concentrations	Usually have high CMC compared to some biosurfactants	[11]
Emulsification activity	Good emulsifying and emulsion stabilizing characteristics	Efficacious emulsification though they may need higher concentrations	[16]
Stability at extreme conditions	High stability under broad conditions of pH, salt concentration, and temperature	They are stable based on the surfactant category and formulation	[6, 17]
Antimicrobial activity	Have innate antimicrobial, anti-fungal, anti-viral, and antibiofilm qualities	Lack antimicrobial properties	[18, 19]
Foaming properties	Good foaming power and foam stability	Foam ability is good but depends on the surfactant used	[20]
Biocompatibility	High biocompatibility and therefore useful in foods, drugs, and cosmetics	Possibility of irritation or toxicity depending on application	[3]

Halal compliance potential	Halal in nature if microorganisms and substrates used are halal	It depends on raw material sourcing and production process	[4, 21]
Production cost	Relatively expensive as a result of fermentation and purification stages	Low because the processes are well-established and industrialized	[17, 22]
Commercial availability	Commercial production is not yet common	They are easily accessible with well-established markets	[17, 23]

Functionally, biosurfactants can provide effective surface tension reduction, low Critical Micelle Concentration (CMC), strong emulsifying activity, and good stability under broad ranges of pH, salinity, and temperature. Some biosurfactant classes also possess intrinsic antimicrobial, antifungal, and antibiofilm activities, which may add value in food preservation, pharmaceutical formulations, cosmetic products, and sanitation systems [19]. However, these functional advantages must be interpreted together with practical constraints, including lower commercial availability, product variability, and the need for application-specific safety and halal validation.

From an industrial perspective, biosurfactants hold substantial promise because they can be produced through fermentation using renewable and potentially halal-certified substrates. Nevertheless, broader adoption remains limited by relatively high production costs, yield variability, scale-up constraints, and expensive downstream processing compared with established synthetic surfactants [13]. Whereas Table 1 gives an overview of the physicochemical and functional differences between biosurfactants and synthetic surfactants, a more comprehensive comparison of their industrial feasibility, economic viability, and difficulties in practical application is provided in Table 2. There are certain advantages that biosurfactants possess in regard to sustainability, biodegradability, environmental friendliness, and compatibility with halal requirements. Nevertheless, conventional surfactants still dominate in world markets owing to their relatively inexpensive production, well-developed technology, supply chain, and scalability. The economic viability of biosurfactants is limited by low production capacity, expensive post-production processing, and poor commercial availability. Thus, although biosurfactants have many environmental and halal advantages, they are used mainly for special applications due to their relatively high cost.

Table 2: Comparison of biosurfactants and surfactants in relation to their use in industry

Aspect	Biosurfactants	Conventional Surfactants	Implications for Industry	References
Source of raw materials	Renewable resources from biomass, plant oils and agro-industrial residues	Petrochemical derivatives	Biosurfactants promote sustainability, however, depend upon substrate supply	[24]
Process of production	Fermentation and downstream processing	Chemical synthesis	The process of biosurfactant production is more complicated	[25]
Production cost	High	Low	Huge limitation for commercializing biosurfactants	[26]
Production yield	Sometimes low and strain-dependent	High and consistent	Biosurfactants have economic drawbacks	[27]
Scalability	Studied in many products but not yet achieved for most of them	Well-developed and industrialized	Conventional surfactants have an edge over biosurfactants in industrialization	[28]
Downstream process	Expensive and complicated process	Simple and well-optimized process	Contributes greatly to the overall cost of biosurfactants	[29]
Consistency of product	May vary from batch to batch	High consistency	Requires more quality control measures	[30]
Development of the supply chain	Maturing market	Well-established supply chains	Conventional surfactants are easily accessible	[15]
Market penetration	Limited, but growing	Dominant global market	Biosurfactants have a niche presence, with valuable applications	[31]
Regulatory acceptance	The regulatory framework is developing slowly	Established regulations	Can hamper commercialization of new biosurfactants	[27]
Environmental sustainability	High biodegradability and non-toxic	Variable biodegradability and toxicity	Biosurfactants provide strong environmental benefits	[32]

Halal certification prospects	High when substrates and processes are halal certified	Dependent on feedstock source and manufacturing process	Biosurfactants offer possibilities for halal certification	[33]
Industrial application	Largely specialty purposes (foods, cosmetics, pharmaceutics)	Widely applicable in detergents, oil, agriculture, manufacturing	Conventional surfactants are prevalent in industrial sectors	[34]
Economic viability	Presently hindered by high costs	Highly economical by virtue of economies of scale	Necessity for cost reduction cannot be overstated	[31]
Limitations of technologies	Poor production efficiency, foam formation problems, scaling problems, high purification costs	Environmental impacts and reliance on non-renewable raw materials	Limitations vary from one technology to another	[27]
Prospects for future development	Good growth prospects due to sustainability and halal trends	Slow growth, sustainability challenges	May increase market shares with improvements in technology	[31]

Table 3: Overview of biosurfactants in the halal economy: definition, applications, challenges, and future opportunities

Aspect	Details
Definition	Biosurfactants are surface-active compounds produced by microorganisms (e.g., bacteria, yeast, fungi) that reduce surface and interfacial tension. They are biodegradable, less toxic, and eco-friendly alternatives to synthetic surfactants [10, 17, 37]
Relevance to halal economy	Ensuring that production processes, microbial strains, raw materials, and downstream processing comply with halal principles (e.g., free from porcine-derived ingredients, alcohol, or cross-contamination). This compliance allows biosurfactants to be used in Muslim-majority markets and in global industries seeking halal certification [35, 38, 39]
Sustainability dimension	Biosurfactants align with green chemistry and circular economy goals by using renewable resources (e.g., agricultural by-products, plant oils, waste biomass). Their biodegradability supports environmental sustainability and reduces chemical pollution [40]
Applications in food industry	- Emulsifiers: Stabilize food products such as sauces, dressings, and bakery items [41] - Antimicrobial agents: Inhibit spoilage and pathogenic microbes [18] - Cleaning agents: Safe for food-contact surfaces [18] - Texture enhancers: Improve quality and shelf-life of halal-certified products [42]
Applications in pharmaceuticals	- Drug delivery systems: Enhance solubility and bioavailability of poorly soluble drugs [3] - Antimicrobial and antiviral properties: Support halal-certified medicines [3] - Wound healing and tissue engineering: Biosurfactants promote cell adhesion and regeneration [43]
Applications beyond food and pharma	- Cosmetics & Personal Care: Natural, skin-friendly emulsifiers and cleansers [44] - Agriculture: Biopesticides, biofertilizers, and soil remediation agents [45, 46] - Environmental: Oil spill management, wastewater treatment, bioremediation of pollutants [47] - Energy Sector: Enhanced oil recovery and biodiesel production [9]
Halal certification benefits	- Builds trust among Muslim consumers [1, 48] - Expands access to rapidly growing global halal markets [43, 48, 49] - Encourages innovation in sustainable, ethical biotechnology [48, 50]
Market opportunities	Rising global demand for halal-certified, eco-friendly products in food, pharmaceuticals, and cosmetics. Biosurfactants serve as a competitive advantage in meeting both halal and sustainability standards [19]
Challenges	- High production costs compared to synthetic surfactants [48] - Scale-up limitations in industrial production [51] - Need for regulatory harmonization across halal-certifying bodies [21] Limited consumer awareness of biosurfactant benefits [52]
Future directions	- Use of low-cost renewable substrates (e.g., agricultural waste to reduce costs) [53, 54] - Genetic and metabolic engineering for higher yield and productivity [53] - Development of standardized halal biosurfactant production guidelines [55] - Strengthening collaborations between scientists, halal authorities, and industry [19]

Halal Considerations

As global demand for halal-certified products continues to grow across the food, pharmaceutical, cosmetic, and personal care sectors, ensuring full compliance with Islamic law (Shariah (has become both a religious obligation and a strategic priority for industries targeting Muslim-majority markets [35]. In this context, biosurfactants, biodegradable and low-toxicity surface-active agents derived from microorganisms, have emerged as promising alternatives to conventional synthetic surfactants (Table 3) .However, the use of biosurfactants in halal-certified formulations is not automatically permissible .Their halal status depends on a comprehensive evaluation of multiple factors, including the microbial strains employed, the composition of

DOI: 10.3844/ajbbsp.2026.22.03.032

fermentation media, the use of processing aids, and the risk of cross-contamination with non-halal substances during production, purification, packaging, and distribution [36]. Ensuring halal integrity also requires adherence to established certification standards, supported by rigorous documentation and traceability systems .This section outlines the critical technical and regulatory considerations required to ensure the halal-compliant development and application of biosurfactants, forming the foundation for their ethical and lawful integration into halal-focused product innovation (Fig. 1).

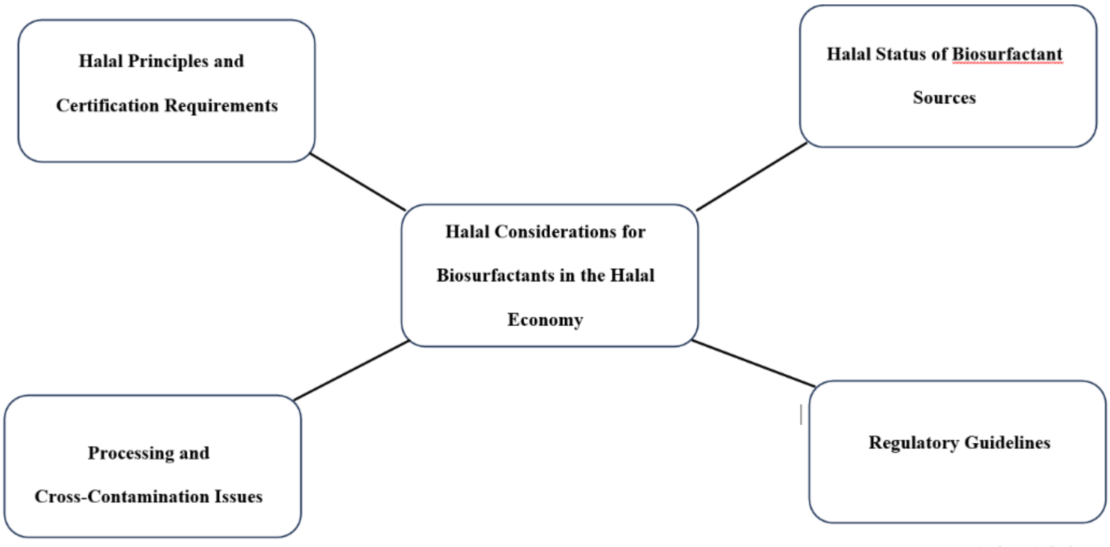

Fig. 1: Halal Considerations for Biosurfactants in the Halal Economy

Halal Principles and Certification Requirements

The Arabic term halal means "permissible "under Islamic law, encompassing both the ingredients used and the processes involved in the manufacturing, handling, and distribution of products .In sectors such as food, pharmaceuticals, and cosmetics, halal compliance extends beyond excluding haram (prohibited (substances-such as pork derivatives, blood, carrion, and intoxicants like alcohol -to include principles of ethical sourcing, hygienic preparation, and lawful processing [49]. To be eligible for halal certification, products must meet strict criteria:

1. Use of plant-based, synthetic, or animal-derived materials from properly slaughtered sources
2. Exclusion of intoxicants beyond allowable limits
3. Prevention of contamination with haram materials throughout manufacturing, storage, and transport
4. Implementation of sanitation and quality control protocols that satisfy both religious and scientific standards

In addition, a robust system of traceability and documentation is essential to maintain halal assurance throughout the supply chain Halal certification is granted by internationally recognized bodies such as JAKIM (Malaysia), MUI (Indonesia), IFANCA (USA), and (GSO) Gulf countries [56]. These authorities apply standardized guidelines and conduct on-site inspections to verify compliance .Third-party halal certification plays an increasingly vital role in building consumer trust, enhancing brand credibility, facilitating international trade, and ensuring access to the rapidly expanding global halal economy.

Halal Status of Biosurfactant Sources

Microorganisms

Selecting appropriate microbial strains is a fundamental step in halal-compliant biosurfactant production .Common strains such as Bacillus spp., Pseudomonas spp., and Candida spp .are generally acceptable, provided they are non-pathogenic and have not been genetically modified using haram materials) e.g., porcine genes or non-halal animal vectors. (Strains granted GRAS) Generally Recognized as Safe status are preferred for halal-certified products [36].

However, strains like Pseudomonas aeruginosa, despite their efficiency in producing rhamnolipids, pose safety concerns due to their pathogenic potential .Alternatives such as Pseudomonas putida or engineered GRAS organisms are increasingly explored .Any genetic modifications must avoid haram-derived elements to maintain halal integrity [43]. Therefore, the safety and permissibility of microbial strains must be carefully evaluated to align biosurfactant production with both scientific and Islamic ethical standards.

Culture Media

The composition of culture media plays a critical role in determining the halal status of biosurfactants .Many microorganisms require complex nutrients, such as peptones, tryptones, or yeast extract, which may be derived from non-halal animal sources and therefore may be unacceptable under halal guidelines .Halal compliance requires plant-based, synthetic, or halal-certified alternatives, such as soy peptone, halal-certified yeast extract, ammonium salts, or chemically defined media [19]. Common halal-compatible carbon sources include glucose, molasses, vegetable oils, and glycerol from halal biodiesel .Agro-industrial by-products such as molasses, whey, or used cooking oil are acceptable when their origins are halal contamination-free [4]. Rigorous sourcing and verification are therefore essential to ensure the halal integrity of fermentation systems.

Processing and Cross-Contamination Issues

Even when halal-compliant inputs are used, biosurfactants can lose their halal status due to cross-contamination during processing. Shared facilities that also handle non-halal materials pose risks. In such cases, Islamic purification) tahir) must be applied to cleanse equipment in accordance with Shariah law [57]. Downstream processes often involve organic solvents like ethanol or methanol, which must be halal-certified or used in trace amounts) typically <0.5 %v/v (as accepted by Islamic scholars and fatwas [58]. Packaging must also avoid contact with haram substances such as gelatin-based coatings or animal-derived polymers .To ensure consistent compliance, manufacturers must implement detailed Standard Operating Procedures (SOPs) covering the entire production process .These SOPs should be routinely audited by recognized halal certification bodies [38]. Thus, even with halal inputs, robust process control and risk mitigation are essential to preserve halal status.

Regulatory Guidelines

Halal biosurfactant production is governed by both national and international standards that regulate ingredient sourcing, processing, and certification. Key authorities include JAKIM (Malaysia), which provides the Manual Procedure for Malaysia Halal Certification (MPPHM) outlining requirements for ingredients, processing aids, sanitation, and documentation [[58. MUI/BPJPH (Indonesia), which enforces halal product assurance requirements with strict scrutiny of microbial and enzyme components; and GSO (Gulf region), which issues harmonized halal standards such as GSO 2055-1 and GSO 993 across Gulf Cooperation Council (GCC) countries .In addition, organizations such as the Organization of Islamic Cooperation/Standards and Metrology Institute for Islamic Countries (OIC/SMIIC (and the Indonesian National Standard (SNI (contribute to international standardization and mutual recognition of halal certifications] 38 .[Across these frameworks, core regulatory principles include traceability of raw materials, certification of upstream suppliers, prevention of cross-contamination, and compliance with Good Manufacturing Practices (GMP) and Halal Assurance Systems (HA)] .57 For [biosurfactant producers, engagement with accredited halal authorities and adherence to these protocols, from strain selection to final packaging, are essential to ensure both religious compliance and successful market entry.

Regulatory and Halal Certification Considerations

The expanding global halal market creates substantial opportunities for biosurfactant applications in food, pharmaceuticals, cosmetics, agriculture, and environmental technologies. Although biosurfactants are microbially derived and environmentally favorable, they must satisfy both religious and regulatory requirements throughout the production chain. In halal certification, evaluation extends beyond the microorganism itself to include strain origin, culture-media components, processing aids, fermentation additives, and materials or reagents used during downstream recovery and purification [4]. Therefore, biosurfactants cannot be assumed to be halal solely because they are bio-based; they may lose halal status if produced from non-compliant inputs or exposed to cross-contamination during manufacturing [36].

Several authorities provide halal certification guidance for biotechnology-related products, including JAKIM in Malaysia, BPJPH and MUI in Indonesia, the Gulf Cooperation Council’s Standardization Organization, and SMIIC under the OIC [39, 56]. However, the absence of a universally harmonized standard for microbial and biotechnological ingredients creates challenges for manufacturers seeking access to multiple markets [1, 49]. A biosurfactant certified as halal in one jurisdiction may require additional documentation, testing, or facility audits in another because of differences in national rules. Regulatory harmonization would therefore facilitate international trade, strengthen consumer confidence, and support the growth of halal-certified biosurfactant industries [21]. Advances in synthetic biology and precision fermentation may further improve production efficiency, but these technologies must be accompanied by transparent traceability systems and halal assurance throughout the supply chain.

Economic Feasibility Considerations in Halal Biosurfactant Production

Despite the increasing demand for sustainable and halal-approved biosurfactants, economic feasibility remains one of the major barriers to commercial-scale production. Reported biosurfactant yields vary substantially depending on the microbial producer, biosurfactant class, feedstock, and fermentation strategy. As shown in Table 4, some lipopeptide-producing strains generate less than 1 g/L, whereas sophorolipid-producing yeast such as Starmerella bombicola can produce more than 300 g/L. Such differences directly influence production economics because higher productivity can reduce unit production costs and improve industrial competitiveness [6, 17].

Table 4: Recent biosurfactant characteristics, production yields and applications by various microorganisms and substrates

Microorganism	Substrate	Biosurfactant Type	Yield (g/L)	Main Application	Reference
Bacillus subtilis	Pineapple peels	Surfactin	24.3	Bioremediation	[59]
Pseudomonas aeruginosa PTCC 1074	Soybean meal	rhamnolipid	19.68 g/kg dry substrate	Bioremediation	[27]
Kocuria marina DAGII	waste cooking oil	Polymeric	3.16	Cosmetics	[40]
Starmerella bombicola	Glucose + vegetable oil	Sophorolipid	200	Cosmetics and personal care	[60]
Pseudomonas aeruginosa 6K-11	residual frying oil	Rhamnolipid	52.2	Bioremediation processes	[61]
Pseudomonas aeruginosa 15GR	sugarcane bagasse + sunflower seed meal	Rhamnolipids	45	Bioremediation, Agriculture, Medicine	[62]
Streptomyces sp. 60s	waste vegetable frying oil + whey	Surfactin	1.64	Recovery heavy metals	[63]
Pseudomonas aeruginosa RS6	Waste glycerol	Rhamnolipid	11.32	Environmental remediation	[64]
Bacillus subtilis ATCC 21332	Glucose	Surfactin	14.1	Environmental remediation	[65]
Pseudomonas aeruginosa IITR110	Water chestnut shell hydrolysate	Lipopeptide	0.99	Soil remediation	[66]
Bacillus velezensis IITR111	Water chestnut shell hydrolysate	Rhamnolipid	1.18	Soil remediation	[66]

Substrate cost is another critical component of production expenditure. Consequently, considerable attention has been given to low-cost alternatives such as molasses, crude glycerol, waste frying oil, rice bran hydrolysate, and other agro-industrial residues. These feedstocks can reduce production costs while converting waste streams into value-added products, supporting both circular economy principles and sustainable goals [52]. For halal applications, however, the origin and handling of these substrates must be verified to ensure that they are halal-compliant and free from contamination.

Downstream processing is also a major economic constraint and may account for a substantial proportion of total production cost [17]. Recovery, purification, and concentration steps often require specialized equipment, solvents, and energy-intensive operations, especially when high-purity products are required for food, pharmaceutical, or cosmetic applications [19]. Future work should therefore focus on optimizing fermentation, improving in situ or low-solvent recovery methods, and using halal-compatible renewable resources to enhance economic viability and sustainability [40]. These strategies are essential for positioning biosurfactants as commercially realistic alternatives to conventional synthetic surfactants.

Applications of Halal-Compliant Biosurfactants

The multifunctional nature of biosurfactants, combined with their potential for halal compliance, makes them valuable across diverse industrial sectors .These compounds serve as ethical, sustainable alternatives to synthetic or animal-derived surfactants, particularly in industries where halal certification is essential [67]. This section outlines their application in food, pharmaceutical, cosmetic, and industrial contexts, emphasizing functionality, sustainability, and religious permissibility (Fig. 2).

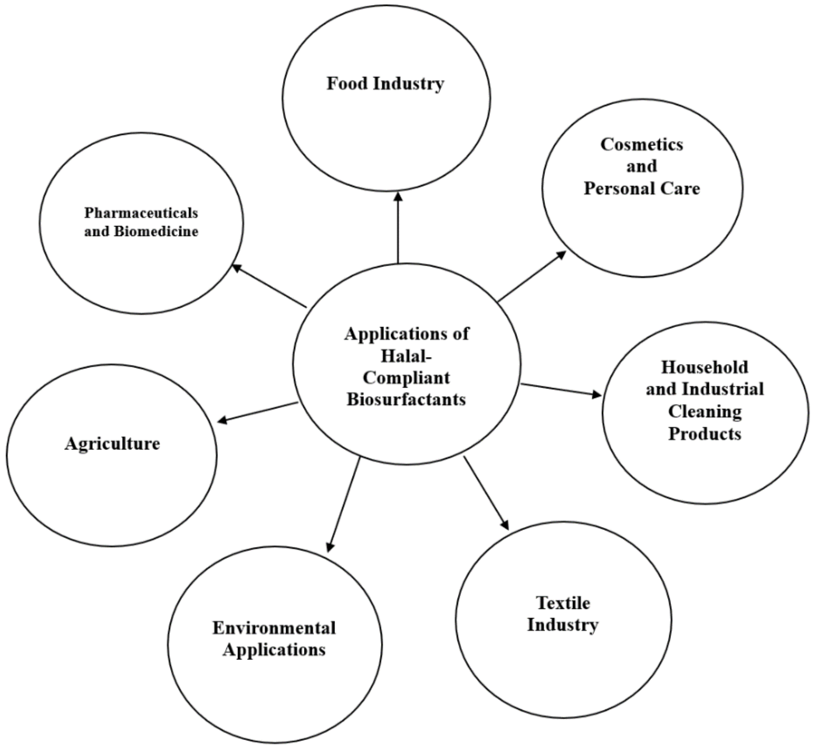

Fig. 2: Diverse Sectors of Biosurfactants Application in the Halal Economy

Food Industry

Biosurfactants are increasingly recognized in the food industry for their roles as natural emulsifiers, preservatives, and biofilm inhibitors [41]. Glycolipids such as rhamnolipids and sophorolipids have shown excellent performance in stabilizing oil-in-water emulsions, making them suitable for use in products such as salad dressings, baked goods, and dairy analogs [50]. These biosurfactants offer a halal-friendly alternative to conventional emulsifiers (e.g., mono -and diglycerides), which may originate from non-halal animal fats [67]. Beyond emulsification, biosurfactants exhibit antimicrobial activity against common foodborne pathogens such as Listeria monocytogenes, Salmonella spp., and Escherichia coli, thereby enhancing food safety and shelf life [2]. They also possess anti-biofilm properties, helping prevent microbial buildup on food-contact surfaces such as stainless steel and plastic, which is critical for maintaining hygiene in halal-certified production facilities [6]. Together, these attributes position biosurfactants as clean-label, sustainable, and halal-compatible ingredients that support modern food manufacturing while aligning with Islamic dietary laws and consumer preferences.

Pharmaceuticals and Biomedicine

Biosurfactants offer significant potential in halal pharmaceutical and biomedical applications, particularly where alcohol, porcine gelatin, or non-zabiha animal-based excipients are prohibited. Their amphiphilic structure enhances drug solubilization and permeability, making them valuable for improving the bioavailability of poorly water-soluble drugs. For example, rhamnolipids and surfactin have been incorporated into micelles and nanoparticle systems for oral and transdermal delivery, showing improved therapeutic outcomes [67]. Certain lipopeptides, such as surfactin and iturin, also possess anti-inflammatory and antimicrobial properties, supporting their use in wound care formulations without alcohol-based antiseptics.

Additionally, some biosurfactants exhibit anti-cancer activity by inducing apoptosis in tumor cells [18]. These multifunctional properties make biosurfactants promising candidates for halal-compliant therapeutic systems, where efficacy, safety, and religious compliance must align. As global demand for halal pharmaceuticals grows, biosurfactants represent a convergence of performance, ethical sourcing, and faith-based acceptability.

Cosmetics and Personal Care

In halal-certified cosmetics and personal care products, biosurfactants offer a skin-friendly, sustainable alternative to conventional surfactants like Sodium Lauryl Sulfate (SLS), which is known for causing skin irritation]23[. Biodegradable and non-toxic, biosurfactants such as rhamnolipids and sophorolipids provide effective cleansing, foaming, and emulsifying properties for use in shampoos, facial cleansers, body washes, lotions, and creams .Many also demonstrate antioxidant and antimicrobial activity, contributing to anti-aging and acne-fighting effects by reducing oxidative stress and inhibiting skin pathogens such as Propionibacterium acnes [18]. Their natural origin and compatibility with Islamic principles of cleanliness)taharah (and purity further reinforce their suitability for halal-compliant, clean-label personal care formulations.

Household and Industrial Cleaning Products

Biosurfactants are gaining attention as sustainable alternatives in household and industrial cleaning products .They excel in removing oils, greases, and hydrophobic residues, making them suitable for dishwashing liquids, laundry detergents, floor cleaners, and multipurpose surface cleaners .Unlike petroleum-based surfactants, biosurfactants are biodegradable and break down into harmless by-products, minimizing environmental impact, especially in aquatic systems [68]. For halal-conscious consumers, biosurfactants offer assurance against ingredients such as alcohol, porcine enzymes, and non-halal solvents that may be found in conventional cleaning agents .Their production from halal-certified microbes and substrates, together with low irritancy and favorable safety profiles, makes them attractive for eco-conscious and religiously observant households [23]. As demand for halal and green products rises globally, biosurfactants stand out as ethical, effective, and environmentally responsible cleaning agents.

Agriculture

Biosurfactants have shown strong potential in agriculture as multifunctional agents that enhance plant health and environmental sustainability, making them ideal for halal-compliant and eco-conscious farming .These microbial compounds can act as biopesticides, plant growth promotors, and soil conditioners, offering natural alternatives to synthetic agrochemicals that may raise health, ecological, or religious concerns. Lipopeptides like fengycin and iturin, produced by Bacillus spp., display potent antifungal activity against phytopathogens such as Fusarium and Rhizoctonia, reducing reliance on conventional fungicides [46]. Additionally, biosurfactants can enhance nutrient availability, seed germination, and beneficial microbial colonization (e.g., Rhizobium and Pseudomonas), contributing to better crop yields under low-input conditions [45]. Their ability to mobilize hydrocarbons and heavy metals also supports soil remediation without introducing potentially non-halal additivesT .hese characteristics align with Islamic values of environmental stewardship (khalifah) and purity in food production, positioning biosurfactants as strategic innovations in halal-certified agriculture.

Environmental Applications

In environmental biotechnology, biosurfactants are increasingly used for pollution remediation and ecosystem restoration. They are particularly effective in treating oil-contaminated soils and marine environments .Compounds such as rhamnolipids and sophorolipids emulsify petroleum hydrocarbons, enhancing their bioavailability to native microbes and accelerating biodegradation in both land and water systems [52]. Compared to conventional chemical dispersants, biosurfactants are biodegradable, less toxic, and derivable from renewable sources, making them suitable for green interventions .Moreover, their ability to chelate heavy metals such as cadmium, lead, and zinc enables effective removal from industrial effluents and contaminated soils [13]. These applications support global sustainability goals and reflect Islamic principles such as khalifah (earth stewardship) and (amanah) responsibility, which emphasize environmental protection and resource purification. As halal-conscious industries and governments pursue eco-friendly solutions, biosurfactants offer a powerful blend of scientific utility and ethical integrity.

Textile Industry

Biosurfactants provide a sustainable and ethically sound alternative to chemical surfactants in textile manufacturing, particularly for halal-compliant processing .They are used in bioscouring, dyeing, finishing, and softening, improving process

DOI: 10.3844/ajbbsp.2026.22.03.032

efficiency and reducing environmental load .In bioscouring, biosurfactants act as natural wetting and emulsifying agents, effectively removing oils and waxes from cotton without harsh alkaline treatments. This lowers environmental impact and enhances fabric quality [69]. During dyeing and finishing, biosurfactants improve dye penetration and fixation while eliminating the need for petrochemical or animal-derived emulsifiers that may be incompatible with halal standards .Their ability to soften fabrics without harmful substances is especially relevant in emerging halal fashion markets such as Indonesia and Malaysia, where regulatory efforts are expanding to cover textiles [70]. The adoption of biosurfactants supports both sustainability and religious compliance, contributing to the broader goals of ethical, clean-label manufacturing in the global textile sector.

Challenges and Future Perspectives

While biosurfactants offer great promise as multifunctional, halal-compliant ingredients, several technical, economic, and regulatory challenges hinder their broader adoption. Overcoming these barriers will require collaboration among researchers, industry stakeholders, and halal certification authorities to ensure sustainable and ethical development.

Technical and Economic Barriers

Despite their benefits, including biodegradability, low toxicity, and multifunctionality, biosurfactants remain cost-prohibitive, with production expenses often 3-10 times higher than those of synthetic surfactants .Contributing factors include low microbial yields, high-cost substrates, and complex downstream processing, which alone can account for over 50% of total cost [11]. Halal production imposes additional constraints, such as the need for halal-certified media and solvents (e.g., plant-based peptones, ethanol-free processes), which restrict purity and traceability requirements, and extensive documentation for halal certification, all of which may increase costs and time to market [19] .To address these issues, innovative strategies are needed, such as using low-cost halal substrates (e.g., agro-industrial waste) and developing scalable, cost-efficient purification technologies to improve economic viability and expand access to halal-certified biosurfactants.

Scale-up and Commercialization

Scaling up biosurfactant production from laboratory to industrial scale presents numerous challenges. Technical issues such as inefficient oxygen transfer, excessive foaming, and uneven mixing can disrupt fermentation performance, while contamination risks increase with scale and require rigorous quality control [17]. For halal production, halal integrity must be preserved throughout manufacturing by preventing cross-contamination, using halal-certified inputs and validated purification procedures (e.g., tahirah protocols), and maintaining strict traceability. Halal certification itself adds complexity through facility audits, ingredient traceability, and regulatory classification challenges, especially when determining whether biosurfactants should be treated as food additives, processing aids, or pharmaceutical actives [19]. In addition, consumer awareness of halal biosurfactants remains low, limiting market demand. Addressing these barriers requires collaboration among scientists, engineers, regulators, and certification bodies to streamline processes and support commercialization.

Research Gaps and Innovations Needed

Future Progress Depends on Filling Several Critical Research Gaps

(1) Strain development: Engineering high-yield, halal-compliant, non-pathogenic strains using tools like clustered regularly interspaced short palindromic repeats (CRISPR) provided no haram genetic material is used [71]

(2) Substrate optimization: Utilizing halal-certified, low-cost feedstocks such as cassava peels or date palm residues to improve sustainability and reduce costs [22]

(3) Process intensification: Integrating in situ product recovery and membrane bioreactors can enhance yield and efficiency.

(4) Functional validation: Further studies are needed to understand biosurfactants' bioactivities (e.g., anti-inflammatory, anti-aging, and antibiofilm effects) in real-world food, pharmaceutical, and cosmetic applications

(5) Halal traceability tools: Advanced analytical methods like LC-MS and DNA-based detection could help identify non-halal contaminants in media or process downstreams, ensuring compliance and transparency

Collaboration among scientists, engineers, halal scholars, and regulators is essential to ensure that future innovations are not only technologically advanced but also aligned with Islamic ethical values and market expectations.

DOI: 10.3844/ajbbsp.2026.22.03.032

Future Trends in Halal Biosurfactant Development

The outlook for halal biosurfactants is highly promising, driven by technological innovation and growing demand for ethically aligned products among Muslim and eco-conscious consumers. One major trend is the use of synthetic biology to develop microbial platforms capable of producing biosurfactants via halal-compliant metabolic pathways. These engineered systems use microbial chassis that exclude haram genetic materials and enable full traceability, ensuring both ethical and regulatory compliance [72]. Another emerging approach is the integration of halal biosurfactant production into circular economy frameworks, where agro-industrial waste (e.g., fruit peels, molasses, or plant oils) is repurposed as feedstock within halal-certified supply chains. This model aligns with Islamic values of environmental stewardship and the principle of maslahah (public benefit). Artificial Intelligence (AI) and data-driven technologies are also being used to optimize fermentation parameters, predict biosurfactant yields, and enhance process efficiency while ensuring compliance with halal input requirements [19]. Market demand for halal-certified biosurfactants is expected to grow across pharmaceutical, personal care, and green chemistry sectors. To support this expansion, regulatory harmonization efforts by bodies such as the Organization of Islamic Cooperation (OIC) and Standards and Metrology Institute for Islamic Countries (SMIIC) are working to establish unified guidelines for halal microbial and biotechnological products. As halal science advances in tandem with sustainability goals, biosurfactants are poised to become key clean-label ingredients in ethically responsible, cross-sector innovation [39].

Current Limitations and Challenges

Although biosurfactants have shown considerable promise as green chemistry solutions that are potentially compatible with halal requirements, several challenges still limit their large-scale application. First, biosurfactants produced via fermentation are relatively expensive because they require controlled operating conditions, specialized equipment, and energy input [6, 17]. Other cost-driving factors include culture-media components, carbon sources, and downstream recovery. Nevertheless, inexpensive substrates such as molasses, crude glycerol, waste frying oils, and agricultural residues can improve economic feasibility when their halal status and supply-chain integrity are verified [52]. Another challenge is downstream processing, including extraction, purification, and product recovery, which can be technically complex and costly [17]. Moreover, transferring lab-scale biosurfactant production to an industrial scale requires solutions for oxygen transfer, foaming, mixing, sterility, and process stability [73]. Variability in microbial strains, substrates, and fermentation conditions may also cause batch-to-batch inconsistency [6]. Therefore, standardization of production protocols, quality specifications, halal documentation, and analytical validation is essential before biosurfactants can be widely adopted in halal-certified industrial applications.

Conclusion

Biosurfactants represent a promising class of bio-based compounds that align with the growing global demand for halal-certified, sustainable, and multifunctional ingredients. Their ability to serve as natural emulsifiers, antimicrobials, and surface-active agents makes them valuable across food, pharmaceutical, cosmetic, environmental, and industrial sectors. Unlike conventional surfactants, biosurfactants are biodegradable, less toxic, and can be produced from renewable resources using halal-compliant microbial strains and substrates. However, their halal status depends on strict adherence to Islamic principles throughout the production process. This includes the use of non-pathogenic and GRAS-approved microorganisms, halal-certified culture media, halal-compatible processing aids, and careful control to avoid contamination during processing, packaging, and distribution. Halal certification also requires robust documentation, traceability, and compliance with standards set by recognized authorities such as JAKIM, MUI/BPJPH, GSO, and SMIIC/OIC. Despite their potential, challenges such as high production costs, limited industrial-scale adoption, downstream-processing complexity, batch-to-batch variability, and regulatory fragmentation remain. Addressing these barriers requires innovative strategies, including the use of agro-industrial waste as halal feedstocks, advanced bioreactors, improved recovery methods, standardized quality systems, and AI-driven optimization. Collaboration among scientists, engineers, industry stakeholders, and halal certifiers is essential to ensure both technical and religious compliance. Looking ahead, halal biosurfactants are well positioned to support ethical, sustainable, and cross-sector innovation. With the integration of synthetic biology, green chemistry, circular economy principles, and regulatory harmonization, these ingredients can help drive inclusive growth in the halal market. As awareness and technological readiness increase, biosurfactants have the potential to become key enablers of a global halal-certified bioeconomy.

Acknowledgment

The authors gratefully acknowledge Prince of Songkla University for resources, facilities, and a supportive academic environment, which were instrumental in completing this work.

Funding Information

The authors have not received any financial support or funding to report.

Author's Contributions

All authors equally contributed in this work.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

References

1. Noviyanti, R., & Hakim, R. (2025). Halal Industry Growth: Economic Opportunities and Challenges in Global Markets. *Jurnal Ilmu Ekonomi Dan Bisnis Islam*, *7*(1), 18–42. https://doi.org/10.24239/jiebi.v7i1.353.18-42
2. Essghaier, B., Naccache, C., Ben-Miled, H., Mottola, F., Ben-Mahrez, K., Khemakhem, M. M., & Rocco, L. (2024). Discovery and characterization of novel lipopeptides produced by Virgibacillus massiliensis with biosurfactant and antimicrobial activities. *3 Biotech*, *14*(11), 258. https://doi.org/10.1007/s13205-024-04100-9
3. Pala, M., Castelein, M. G., Dewaele, C., Roelants, S. L. K. W., Soetaert, W. K., & Stevens, C. V. (2024). Tuning the antimicrobial activity of microbial glycolipid biosurfactants through chemical modification. *Frontiers in Bioengineering and Biotechnology*, *12*, 1347185. https://doi.org/10.3389/fbioe.2024.1347185
4. Karahalil, E. (2020). Principles of halal-compliant fermentations: Microbial alternatives for the halal food industry. *Trends in Food Science & Technology*, *98*, 1–9. https://doi.org/10.1016/j.tifs.2020.01.031
5. Ren, X., He, Z., Peng, H., Zhang, J., Wang, S., Zhao, Y., Li, X., Song, Y., Zhao, X., & Ma, C. (2021). Bioconversion of Corn Steep Liquor to Biofertilizer by Symbiotic Fermentation. *American Journal of Biochemistry and Biotechnology*, *17*(4), 478–489. https://doi.org/10.3844/ajbbsp.2021.478.489
6. Dini, S., Bekhit, A. E.-D. A., Roohinejad, S., Vale, J. M., & Agyei, D. (2024). The Physicochemical and Functional Properties of Biosurfactants: A Review. In *Molecules* (Vol. 29, Issue 11, p. 2544). https://doi.org/10.3390/molecules29112544
7. Sari, M., Kanti, A., Artika, M., & Kusharyoto, W. (2013). Identification of Pseudozyma hubeiensis Y10BS025 as a Potent Producer of Glycolipid Biosurfactant Mannosylerythritol lipids. *American Journal of Biochemistry and Biotechnology*, *9*(4), 430–437. https://doi.org/10.3844/ajbbsp.2013.430.437
8. Subsanguan, T., Khondee, N., Rongsayamanont, W., & Luepromchai, E. (2022). Formulation of a glycolipid:lipopeptide mixture as biosurfactant-based dispersant and development of a low-cost glycolipid production process. *Scientific Reports*, *12*(1), 16353. https://doi.org/10.1038/s41598-022-20795-3
9. Purwasena, I. B., Amaniyah, M., Astuti, D. I., Firmansyah, Y., & Sugai, Y. (2024). Production, characterization, and application of Pseudoxanthomonas taiwanensis biosurfactant: a green chemical for microbial enhanced oil recovery (MEOR. *Scientific Reports*, *14*(1), 10270. https://doi.org/https://doi.org/10.1038/s41598-024-61096-1
10. Ganger, S., Sonawane, D., Mhatre, N., Saiger, F., & Pratap, A. (2024). Biosurfactant Production: Limitations and New Approaches. *Microbial Surfactants in Pharmaceuticals and Cosmetics*, 26–57. https://doi.org/10.1201/9781003424864-2
11. Sultana, S., Sultana, R., Al-Mansur, Md. A., Akbor, Md. A., Bhuiyan, N. A., Ahmed, S., Yasmin, S., & Shofiul Islam Molla Jamal, A. H. M. (2024). An industrially potent rhamnolipid-like biosurfactant produced from a novel oil-degrading bacterium, Bacillus velezensis S2. *RSC Advances*, *14*(34), 24516–24533. https://doi.org/10.1039/d4ra02572e
12. Chen, S., Chen, S., Yu, X., Wan, C., Wang, Y., Peng, L., & Li, Q. (2025). Sources of Lipopeptides and Their Applications in Food and Human Health: A Review. In *Foods* (Vol. 14, Issue 2, p. 207). https://doi.org/10.3390/foods14020207
13. Marchut-Mikołajczyk, O., Drożdżyński, P., Polewczyk, A., Smułek, W., & Antczak, T. (2021). Biosurfactant from endophytic Bacillus pumilus 2A: physicochemical characterization, production and optimization and potential for plant growth promotion. *Microbial Cell Factories*, *20*(1), 40. https://doi.org/https://doi.org/10.1186/s12934-021-01533-2
14. Mahmoud, Y. A.-G., El-Halmouch, Y. H., Nasr, E. E., Al-Sodany, Y. M., El-Nogoumy, B. A., & Ali, S. S. (2024). Exploring the potential of biosurfactants produced by fungi found in soil contaminated with petrochemical wastes. *Scientific Reports*, *14*(1), 25733. https://doi.org/10.1038/s41598-024-75865-5
15. Johnson, P., Trybala, A., Starov, V., & Pinfield, V. J. (2021). Effect of synthetic surfactants on the environment and the potential for substitution by biosurfactants. *Advances in Colloid and Interface Science*, *288*, 102340. https://doi.org/10.1016/j.cis.2020.102340

16. Nikolova, C. N., Ijaz, U. Z., Magill, C., Kleindienst, S., Joye, S. B., & Gutierrez, T. (2021). Response and oil degradation activities of a northeast Atlantic bacterial community to biogenic and synthetic surfactants. *Microbiome*, *9*(1), 191. https://doi.org/10.1186/s40168-021-01143-5
17. Kugaji, M., Ray, S. K., Parvatikar, P., & Anjanapura, V. R. (2025). Biosurfactants: A review of different strategies for economical production, their applications and recent advancements. *Advances in Colloid and Interface Science*, *333*, 103389. https://doi.org/https://doi.org/10.1016/j.cis.2024.103389
18. Kadiri, F.-Z., Ezaouine, A., Blaghen, M., Bennis, F., & Chegdani, F. (2024). Antibiofilm potential of biosurfactant produced by Bacillus aerius against pathogen bacteria. *Biocatalysis and Agricultural Biotechnology*, *56*, 102995. https://doi.org/10.1016/j.bcab.2023.102995
19. Thakur, B., Kaur, S., Dwibedi, V., Albadrani, G. M., Al-Ghadi, M. Q., & Abdel-Daim, M. M. (2024). Unveiling the antimicrobial and antibiofilm potential of biosurfactant produced by newly isolated Lactiplantibacillus plantarum strain 1625. *Frontiers in Microbiology*, *15*, 1459388. https://doi.org/10.3389/fmicb.2024.1459388
20. Jeong, G.-J., Kim, D.-K., Cho, K.-J., Choi, E.-J., Jung, W.-K., Khan, F., & Kim, Y.-M. (2025). Surface and Functional Properties of Biosurfactant Produced by Bacillus rugosus HH2 Derived from Jeotgal. *Journal of Microbiology and Biotechnology*, *35*, e2505029. https://doi.org/10.4014/jmb.2505.05029
21. Bakar, Marina Abu, Noor, A. M., Ismail, S., & Yusoff, M. (2025). Halal Meets Biotech: Exploring Integration Opportunities and Challenges in Malaysian Universities. *Sains Insani*, *10*(1), 62–74. https://doi.org/10.33102/sainsinsani.vol10no1.721
22. Elegbede, I. O., Salisu, M. A., Saba, A. O., Akanmu, R. T., Badmos, L., Olaleye-Haroun, S., & Adewale, R. (2025). Halal Harvesting: Exploring Aquatic Seafood and By-products as Ethical and Sustainable Alternatives for Fisheries. *Green and Blue Economy Frameworks for Halal Industry Sustainability*, 369–399. https://doi.org/10.1007/978-981-96-1729-6_19
23. Nasser, M., Sharma, M., & Kaur, G. (2024). Advances in the production of biosurfactants as green ingredients in home and personal care products. *Frontiers in Chemistry*, *12*, 1382547. https://doi.org/10.3389/fchem.2024.1382547
24. Abdelraof, M., Nooman, M. U., Hashem, A. H., & Al-kashef, A. S. (2024). Production and optimization of surfactin produced from locally isolated Bacillus halotolerans grown on agro-industrial wastes and its antimicrobial efficiency. *BMC Microbiology*, *24*(1), 193. https://doi.org/10.1186/s12866-024-03338-w
25. Faria, N. T., Nascimento, M. F., Ferreira, F. A., Esteves, T., Santos, Marisa Viegas, & Ferreira, Frederico Castelo. (2023). Substrates of opposite polarities and downstream processing for efficient production of the biosurfactant mannosylerythritol lipids from Moesziomyces spp. *Applied Biochemistry and Biotechnology*, *195*(10), 6132–6149. https://doi.org/https://doi.org/10.1007/s12010-023-04317-z
26. Schonhoff, A., Stöckigt, G., Wulf, C., Zapp, P., & Kuckshinrichs, W. (2023). Biosurfactants' production with substrates from the sugar industry – environmental, cost, market, and social aspects. *RSC Sustainability*, *1*(7), 1798–1813. https://doi.org/10.1039/d3su00122a
27. Dabaghi, S., Ataei, S. A., & Taheri, A. (2023). Production of rhamnolipid biosurfactants in solid-state fermentation: process optimization and characterization studies. In *BMC Biotechnology* (Vol. 23, Issue 1, p. 2). https://doi.org/10.1186/s12896-022-00772-4
28. Zhang, Y., Liu, J., Fan, S., Qin, Y., Xiao, Z., Chen, C., Yang, M., & Liu, W. (2023). Enhanced Fermentation for Rhamnolipid Production in a Membrane Bioreactor with a New Strain Pseudomonas aeruginosa BC1. *Industrial & Engineering Chemistry Research*, *62*(31), 12269–12276. https://doi.org/10.1021/acs.iecr.3c01475
29. Zhang, D., Luo, L., Jin, M., Zhao, M., Niu, J., Deng, S., & Long, X. (2022). Efficient isolation of biosurfactant rhamnolipids from fermentation broth via aqueous two-phase extraction with 2-propanol/ammonium sulfate system. *Biochemical Engineering Journal*, *188*, 108676. https://doi.org/10.1016/j.bej.2022.108676
30. Kubicki, S., Bator, I., Jankowski, S., Schipper, K., Tiso, T., Feldbrügge, M., Blank, L. M., Thies, S., & Jaeger, K.-E. (2020). A straightforward assay for screening and quantification of biosurfactants in microbial culture supernatants. *Frontiers in Bioengineering and Biotechnology*, *8*, 958. https://doi.org/10.3389/fbioe.2020.00958
31. Poveda-Giraldo, J. A., Solarte-Toro, J. C., Treinen, C., Noll, P., Henkel, M., Hausmann, R., & Cardona Alzate, C. A. (2025). Assessing the feasibility and sustainability of a surfactin production process: a techno-economic and environmental analysis. *Environmental Science and Pollution Research*, *32*(48), 27699–27714. https://doi.org/10.1007/s11356-024-32217-0
32. Rocha, M. de F. F., Júnior, P. S. S., Leite, M. S., Malpiedi, L. P., Pereira, M. M., Soares, C. M. F., & Lima, Á. S. (2023). Integrated Process of Biosurfactant Production by Bacillus atrophaeus ATCC-9372 Using an Air-Lift Bioreactor Coupled to a Foam Fraction Column. *Fermentation*, *9*(11), 959. https://doi.org/10.3390/fermentation9110959
33. Safari, P., Hosseini, M., Lashkarbolooki, M., Ghorbani, M., & Darzi, G. N. (2023). Evaluation of surface activity of rhamnolipid biosurfactants produced from rice bran oil through dynamic surface tension. *Journal of Petroleum Exploration and Production Technology*, *13*(10), 2139–2153. https://doi.org/10.1007/s13202-023-01660-z
34. Hegazy, G. E., Abu-Serie, M. M., Abou-elela, G. M., Ghozlan, H., Sabry, S. A., Soliman, N. A., Teleb, M., & Abdel-Fattah, Y. R. (2022). Bioprocess development for biosurfactant production by Natrialba sp. M6 with effective direct virucidal and anti-replicative potential against HCV and HSV. *Scientific Reports*, *12*(1), 16577. https://doi.org/10.1038/s41598-022-20091-0
35. Zafar, M. B., Abu-Hussin, M. F., & Ali, H. (2025). Mapping the research on halal industry: a retrospective analysis. *Journal of Islamic Marketing*, *16*(6), 1770–1806. https://doi.org/10.1108/jima-08-2024-0348
36. Basuki, N., Yulianti, R., Fathurrohman SW, O., & Salamah, N. (2025). A review of the halal status of ceramide in cosmetics: a strategic approach to halal policy and consumer awareness in Indonesia. In *Journal of Halal Product and Research* (Vol. 8, Issue 1, pp. 90–100). https://doi.org/10.20473/jhpr.vol.8-issue.1.90-100
37. Bahrini, I., Siddiqui, A. J., Awadelkareem, A. M., Patel, M., Gupta, A., Albulaihed, Y., Ashraf, M. S., Shamsuddeen, S. B., & Adnan, M. (2026). Biosurfactants as next-generation antimicrobials: mechanistic insights and applications in antibiofilm strategies for combatting antimicrobial resistance. *Naunyn-Schmiedeberg's Archives of Pharmacology*, *399*(2), 1769–1791. https://doi.org/10.1007/s00210-025-04546-5

38. Fathima, A. M., Rahmawati, L., Windarsih, A., & Suratno. (2024). Advanced Halal Authentication Methods and Technology for Addressing Non-Compliance Concerns in Halal Meat and Meat Products Supply Chain: A Review. *Food Science of Animal Resources*, *44*(6), 1195–1212. https://doi.org/10.5851/kosfa.2024.e75
39. Fauzi, M. A., Mohd Ali, N. S., Mat Russ, N., Mohamad, F., Battour, M., & Mohd Zaki, N. N. (2024). Halal certification in food products: science mapping of present and future trends. *Journal of Islamic Marketing*, *15*(12), 3564–3580. https://doi.org/10.1108/jima-12-2023-0407
40. Brahma, D., Sarker, A., Kulavi, S., & Dutta, D. (2024). Valorization and kinetic modeling of biosurfactant produced by Kocuria marina DAGII using waste cooking oil as a substrate. In *Biocatalysis and Agricultural Biotechnology* (Vol. 58, p. 103214). https://doi.org/10.1016/j.bcab.2024.103214
41. Ribeiro, B. G., Guerra, J. M. C., & Sarubbo, L. A. (2022). Production of a biosurfactant from S. cerevisiae and its application in salad dressing. *Biocatalysis and Agricultural Biotechnology*, *42*, 102358. https://doi.org/10.1016/j.bcab.2022.102358
42. Ribeiro, B. G., de Souza Leão, V. L. X., Guerra, J. M. C., & Sarubbo, L. A. (2023). Cookies and muffins containing biosurfactant: textural, physicochemical and sensory analyses. *Journal of Food Science and Technology*, *60*(8), 2180–2192. https://doi.org/10.1007/s13197-023-05745-9
43. Wahab, Z. H. A., & Al-Sahlany, S. T. G. (2025). Bacterial Biosurfactants as Bioactive Ingredients: Surfactin’s Role in Food Preservation, Functional Foods, and Human Health. *Bacteria*, *4*(4), 49. https://doi.org/10.3390/bacteria4040049
44. Sayeed, S. Y., & Goyal, A. (2025). Eco-friendly biosurfactants in shampoo: Green chemistry innovations for sustainable personal care. *Journal of Dermatologic Science and Cosmetic Technology*, *2*(3), 100105. https://doi.org/10.1016/j.jdsct.2025.100105
45. Rizqia, H. D., Asranudin, Tangahu, B. V., Warmadewanthi, I. D. A. A., Shimizu, K., Purnomo, A. S., Putra, S. R., Putro, H. S., Hamzah, A., Rohma, N. A., & Rohmah, A. A. (2023). The application of biosurfactant-producing bacteria immobilized in PVA/SA/bentonite bio-composite for hydrocarbon-contaminated soil bioremediation. *RSC Advances*, *13*(31), 21163–21170.
46. Narenkumar, J., Das, B., Abilaji, S., Sathishkumar, K., AlSalhi, M. S., Devanesan, S., Rajasekar, A., & Malik, T. (2024). Biosurfactant-assisted bio-electrokinetic enhanced remediation of heavy metal-contaminated soil. *Frontiers in Microbiology*, *15*, 1458369. https://doi.org/10.3389/fmicb.2024.1458369
47. Chen, W.-T., Ou, J.-H., Lin, W.-Z., Surampalli, R. Y., Chen, Ssu-Ching, & Kao, C.-M. (2026). Application of a novel complex surfactant to enhance the bioremediation of weathered-diesel oil contaminated soils: mechanism and mesocosm-scale study. *Journal of Soils and Sediments*, *26*(6), 196. https://doi.org/https://doi.org/10.1007/s11368-026-04391-w
48. Pandit, N. K., & Meena, S. S. (2026). Exploring Sustainable Biosurfactant Production Through Waste Valorization: Emerging Research Trends and Industrial Applications. *Waste and Biomass Valorization*, *17*(2), 585–619. https://doi.org/10.1007/s12649-025-03169-4
49. Aufi, I., Julian, F. A., Maulidizen, A., Ariaputra, R. F., & Fauzan, M. (2024). The role of certification standards in shaping halal supply chain practices: a qualitative literature review. *Journal of Islamic Law and Legal Studies*, *1*(2), 78–91.
50. Kobayashi, Y., & Fukuoka, T. (2025). Sophorolipids, commercialized glycolipid biosurfactants: Derivatives, component analysis, and applications. *Journal of the American Oil Chemists’ Society*, *102*(2), 251–260. https://doi.org/10.1002/aocs.12883
51. Leal, E., Teixeira, J. A., & Gudiña, E. J. (2024). Development of Foam-Free Biosurfactant Production Processes Using Bacillus licheniformis. *Fermentation*, *10*(7), 340. https://doi.org/10.3390/fermentation10070340
52. Aqif, M., Shah, M. U. H., Khan, R., Umar, M., Sajjad, H., Razak, S. I. A., Wahit, M. U., Khan, S. U.-D., Sivapragasam, M., Ullah, S., & Nawaz, R. (2024). Glycolipid biosurfactants production using low-cost substrates for environmental remediation: progress, challenges, and future prospects. *Environmental Science and Pollution Research*, *31*(35), 47475–47504. https://doi.org/10.1007/s11356-024-34248-z
53. Paul, S., Nayak, J., Paul, I., Kumar, R., & 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*(18), 1430–1454. https://doi.org/10.1080/10643389.2025.2543795
54. Grewal, J., & Gulati, J. S. (2026). Production of biosurfactants. *Sustainable Technologies for Value Addition to Biomass Waste*, 539–564. https://doi.org/10.1016/b978-0-443-36318-4.00026-1
55. Deliaz, M. F., Kurniawan, A. R., Sari, F. M., & Setiadi, F. (2025). Halal alternative raw materials for pharmaceutical and cosmetic applications: a systematic review. In *Journal of Halal Product and Research* (Vol. 8, Issue 2, pp. 171–179). https://doi.org/10.20473/jhpr.vol.8-issue.2.171-179
56. Akbar, J., Gul, M., Jahangir, M., Adnan, M., Saud, S., Hassan, S., Nawaz, T., & Fahad, S. (2023). Global Trends in Halal Food Standards: A Review. *Foods*, *12*(23), 4200. https://doi.org/10.3390/foods12234200
57. Hidayati, L., Cheumar, M., Sucipto, S., & Juliana, J. (2024). Integrating Halal Assurance and Quality Management: A Strategic Framework for Sustainable Growth in the Food Industry. *Industria: Jurnal Teknologi Dan Manajemen Agroindustri*, *13*(2), 239–254. https://doi.org/10.21776/ub.industria.2024.013.02.8
58. Ikhiwan, M., Hanisah, N., & Tukiran, N. A. (2024). Halal authentication of alcohol in food and beverages products: a review. *Science Letters*, *18*(1), 50–60. https://doi.org/10.24191/scl.v18i1.6527
59. Jeevanandam, J., Adetunji, C. O., Inobeme, A., Michael, O. S., Selvam, J. D., Thangadurai, D., Islam, S., Ubi, B. E., & Olaniyan, O. T. (2022). Cultivation of biosurfactants on cheap energy sources using agricultural wastes. *Applications of Biosurfactant in Agriculture*, 109–126. https://doi.org/10.1016/b978-0-12-822921-7.00004-0
60. De Maeseneire, S. L., Soetaert, W. K., & Vandamme, E. J. (2024). Bubbling insights: unveiling the true sophorolipid biosynthetic pathway by Starmerella bombicola. In *Biotechnology for Biofuels and Bioproducts* (Vol. 17, Issue 1, p. 125).
61. Alarcon-Ancajima, I., Merino, F., & Gutierrez-Moreno, S. (2025). Influence of Dissolved Oxygen on the Pseudomonas aeruginosa 6K-11 Rhamnolipid Production. *Applied Microbiology*, *5*(4), 147. https://doi.org/10.3390/applmicrobiol5040147
62. Chauhan, S., Mohanty, A., & Meena, S. S. (2025). Unlocking the potential of rhamnolipids: production via agro-industrial waste valorization, market insights, recent advances, and applications. In *Biomass Conversion and Biorefinery* (Vol. 15, Issue 22, pp. 28847–28876). https://doi.org/10.1007/s13399-025-06671-w

DOI: 10.3844/ajbbsp.2026.22.03.032

63. Hesham, N., Ibrahim, S., Abdulla, H., & Taher, H. (2025). Biosurfactant production from actinomycetes using agro-industrial wastes and applications in heavy metal removal and precious metal recovery. *Environmental Sustainability*, *8*(3), 499–512. https://doi.org/10.1007/s42398-025-00367-7
64. Mahamad, S. S., Mohamed, M. S., Radzuan, M. N., Winterburn, J., & Zakaria, M. R. (2025). Optimizing rhamnolipid bio-surfactant production in a bioreactor using waste glycerol. *Bioprocess and Biosystems Engineering*, *48*(12), 1999–2016. https://doi.org/10.1007/s00449-025-03224-3
65. Martins, T. B., Debon, J., Schmidell, W., & Soares, H. M. (2025). Effect of oxygen mass transfer coefficient (kLa) on surfactin production by Bacillus subtilis ATCC 21332. *Brazilian Journal of Chemical Engineering*, *42*, 1315–1326. https://doi.org/10.1007/s43153-024-00528-x
66. Tripathi, V., Gaur, V. K., & Manickam, N. (2025). Water chestnut shell as a novel substrate for biosurfactant production: Enhanced oil recovery and soil decontamination. *Process Biochemistry*, *157*, 65–74. https://doi.org/10.1016/j.procbio.2025.07.001
67. Noor, N. M., Azmi, N. A. N., Hanifah, N. A., & Zamarudin, Z. (2025). Advances in Lipid Processing and Utilization: Mechanisms, Applications, and Halalan Toyyiban Concept. *Halalan Toyyiban Lipids Processing and Utilization: Concepts, Technologies, and Applications*, 89–106. https://doi.org/10.21467/books.181.8
68. Johnson, P., Trybala, A., Starov, V., & Pinfield, V. J. (2021). Effect of synthetic surfactants on the environment and the potential for substitution by biosurfactants. *Advances in Colloid and Interface Science*, *288*, 102340. https://doi.org/10.1016/j.cis.2020.102340
69. Mustafa, G., Islam, M., Rehman, A., Ahmad, W., Djohan, A. C., Layly, I. R., Franco, M., & Irfan, M. (2025). Innovative applications of microbial biosurfactants for textile cleaning and finishing. *Microbial Biotechnology in Textile Innovation*, 79–102.
70. Paraska, O., Synyuk, O., Radek, N., Zolotenko, E., & Mykhaylovskiy, Y. (2023). Usage of biosurfactants as environmental friendly detergents for textile products cleaning. *Fibres and Textiles*, *30*(5), 42–51. https://doi.org/10.15240/tul/008/2023-5-005
71. Alsomali, N., & Hussein, G. (2021). CRISPR-Cas9 and He Jiankui's Case: an Islamic Bioethics Review using Maqasid al-Shari'a and Qawaid Fighiyyah. *Asian Bioethics Review*, *13*(2), 149–165. https://doi.org/10.1007/s41649-021-00167-1
72. Herdiana, Y. (2025). Halal challenges and health risks in genetically modified organisms (GMOs): a critical approach. *Cogent Food & Agriculture*, *11*(1), 2565716. https://doi.org/10.1080/23311932.2025.2565716
73. Wang, Y., Li, H., Mao, Y., Li, P., Wu, H., Ye, J., & Zhang, H. (2026). Metabolic engineering of Bacillus subtilis for high-yield surfactin production. *Biotechnology for Biofuels and Bioproducts*, *19*(1), 43. https://doi.org/10.1186/s13068-026-02762-6