INTERNATIONAL JOURNAL OF PHARMACEUTICAL SCIENCES
[ISSN: 0975-4725; CODEN(USA): IJPS00]
Journal Homepage: https://www.ijpsjournal.com

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Review Article

Chemical Approaches to Bioemulsifiers

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ARTICLE INFO

Published: 05 June 2025
Keywords:
Bioemulsifiers, Rhamnolipids, Poloxamers, Glycolipids, Lipopeptides
DOI:
10.5281/zenodo.15601700

ABSTRACT

Amphipathic compounds that are biodegradable and have a lower toxicity are known as bioemulsifiers. They can be produced using fermentative methods using agro-industrial waste products and oleaginous chemicals. In this respect, the current work details the synthesis and physical, chemical, and structural characterisation of the bioemulsifier produced by the yeast Scheffersomyces shehatae 16-BR6-2AI in a medium that contains soybean oil and hemicellulosic sugarcane bagasse hydrolysate. Following the bioemulsifier's production and isolation in Erlenmeyer flasks, the generated molecule's physicochemical and structural characterisation was completed. The fermentation parameters YX/S =0.45, YP/S =0.083, and productivity of 0.076g/L/h were attained. A polymer comprising 53% carbohydrates, 40.92% proteins, and 6.08% lipids was identified as the bioemulsifier. Amines, carbonyls, and amides were among the functional groups that the FTIR spectrum verified were present. The bioemulsifier was stable throughout a pH range of 2–12, salinity ranged from 1–15%, and temperature ranged from 20–120°C. The biomolecule was shown to have a superior emulsifying activity in non-polar organic solvents. Consequently, this biomolecule may be used in a variety of ways and has the potential to replace synthetic surfactants.

INTRODUCTION

The majority of our everyday, fundamental activities rely on the usage of some form of surfactant or emulsifier, such as toothpaste, personal hygiene products, cosmetics, and other pharmaceutical by-products, the majority of which have these chemicals. The market for these items is very large, and demand is always rising. But because certain petroleum-based chemical products are hazardous to the environment, non-biodegradable, and accumulable, there has been a broad push to replace chemically synthesised substances with biological products as emulsifiers[1]. Surface active substances known as bioemulsifiers lower the extent of interfacial

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Relevant conflicts of interest/financial disclosures: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

tension between solid-liquid or immiscible liquid interfaces, which leads to the production of more stable emulsions or bioemulsans. Molecular weights greater than 1 MDa are seen in high molecular weight bioemulsifiers. These primarily consist of the amphipathic polysaccharide, protein, lipopolysaccharide, and lipoprotein that aid in stabilising the oil-in-water emulsion composition[2].Mostof these substances have been investigatednutritionally, but a few of them bioemulsifiers have been approved by the World Health Organisation and the International Organisation for Animal Health. Additionally, the food, chemical, pharmaceutical, and oil sectors use a variety of biomolecules. The consistency of fat-soluble vitamins, fatty acids, and amino acids is enhanced by emulsifiers. Emulsions' chemical structure and function are closely related[3].

Characteristics

Synthetic bioemulsifiers are biologically derived emulsifying agents that are produced through biotechnological methods, often utilizing microorganisms such as bacteria, fungi, or yeast. They are synthetic in the sense that they are engineered or optimized for specific applications, unlike natural emulsifiers which are isolated from natural sources. The main characteristics of synthetic bioemulsifiers include:

1. **Bioavalibility:** Bioemulsifiers are appropriate for eco-conscious applications because, in contrast to synthetic chemical emulsifiers, they are typically biodegradable and do not harm the environment[4].

2. **Low Toxicity:** They tend to be less harmful since they are biologically manufactured, which makes them safer to employ in environmental, medicinal, cosmetic, and food applications[5].

3. **Surface-Active Properties:** Bioemulsifiers provide high-quality surfactant-like qualities that aid in emulsion stabilisation, surface tension reduction, and immiscible liquid dispersion[6].

4. **Adaptability:** They can be designed or altered to satisfy certain requirements, such increasing stability in a range of environments (temperature, pH, salinity), or increasing their efficacy in a variety of applications[7].

5. **Production Efficiency:** Economical biotechnological methods like fermentation, which use naturally occurring substances like sugars or oils as substrates, can be used to manufacture them[8].

6. **Compatibility:** Bioemulsifiers can be used in a variety of formulations because they frequently exhibit high compatibility with other components, including proteins, lipids, and polysaccharides[9].

7. **Antimicrobial Activity:** Additionally, certain bioemulsifiers have antibacterial qualities, which makes them helpful in formulations for cosmetics or food preservation since they stop microbes from growing.[10]

8. **Viscosity Modification:** Certain bioemulsifiers can modify the viscosity of formulations, adding a desirable texture or consistency to products like creams and lotions[11].

Classification and types

A variety of chemical classes are represented in synthetic bioemulsifiers. Typical varieties include sugar-based surfactants (alkyl polyglucosides, sucrose esters, sorbitan esters, polysorbates), polymeric surfactants (such as triblock copolymers like poloxamers/pluronics,

poloxamines), synthetic glycolipids (such as mono-rhamnolipid and sophorolipid analogues), and peptide-based amphiphiles[13]. Emulsifiers generated from sugar, such alkyl polyglucosides (APGs) and sucrose esters, are nonionic, plant-based surfactants that are completely biodegradable and have an eight to fourteen carbon tail connected to either glucose or sucrose.[12]. Analogues of synthetic glycolipids, such as ethers, carbamates, succinates, or rhamnolipid esters, resemble microbial biosurfactants. Additionally, lipopeptides and amphiphilic peptides (short tailored peptide sequences) have been created as designer emulsifiers with adjustable[14].

Chemical Structure and Synthesis: There are unique synthetic pathways for each class. Propylene oxide (which forms a PPO hydrophobic block) and ethylene oxide (which forms PEO hydrophilic blocks) are sequentially anionic polymerised to produce polxamers. Sugar surfactants are created when carbohydrates condense with fatty alcohols or acyl chlorides under the action of an acid or an enzyme. For instance, glucose and a fatty alcohol are combined in an acidic environment at a high temperature to create APGs[15]. Polysorbates, like Tween 20, are made by partially ethoxylating sorbitan, or dehydrated sorbitol, and then esterifying it with a fatty acid (in the case of Tween 20, lauric acid)[16]. By glycosylating and acylating rhamnose in vitro, synthetic mono-rhamnolipids have been created. One research found that mono-rhamnose may be esterified with C12-acyl chloride, etherified with a C12 alcohol, or reacted with C12 isocyanate to generate carbamate, ester, or ether links, respectively[17]. Additionally, ring-opening of a dodecenyl succinic anhydride by rhamnose produced a succinate-linked rhamnolipid[18]. Using these techniques, pure mono-rhamnolipid analogues that form themselves into nanoemulsions were produced (see figure below)[19][20]. By using recombinant techniques or solid-phase peptide synthesis, peptide emulsifiers may be created with exact sequence design and the addition of charged and hydrophobic residues[21].

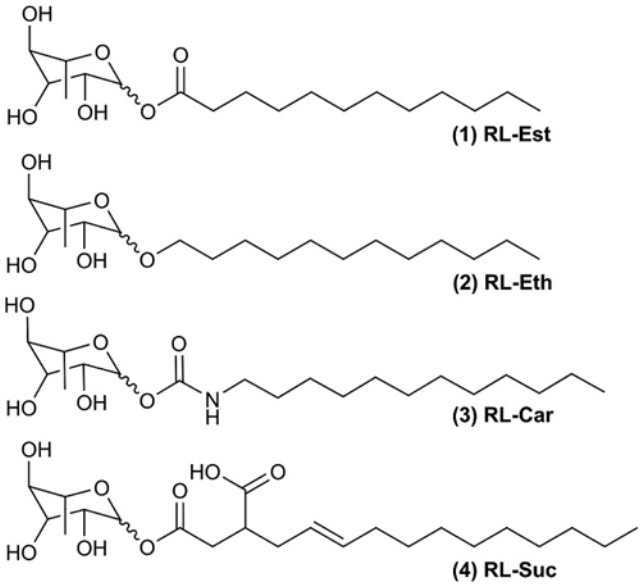

Figure 1: Chemical structures of synthetic rhamnolipids: (1) Rhamnose laurate (RL-Est); (2) Dodecyl rhamnoside (RL-Eth); (3) Rhamnose dodecylcarbamate (RL-Car) and (4) Mono-1-*O*-rhamnosyl (3-dodecenyl) succinate (RL-Suc).

Functional and Physicochemical Properties: Synthetic bioemulsifiers are designed to be very stable, biocompatible, and have great interfacial action. By steric stabilisation, several of them form strong O/W emulsions and are nonionic (neutral headgroups). For instance, poloxamers create highly hydrated micellar layers that dissolve hydrophobic medications and dramatically reduce interfacial tension[22]. APGs and sugar esters are moderate (low irritant) surfactants that have strong foaming and wetting properties. They are stable at room temperature and neutral pH and usually have high hydrophilic–lipophilic balance (HLB) values[23]. Amphiphilic peptides are capable of tight interfacial adsorption and extremely low interfacial tensions. According to research, certain synthetic peptides or short lipopeptides have more emulsifying activity than traditional biopolymers like gum Arabic and caseinate, and they even surpass standard detergents like SDS or Triton X[24]. Synthetic emulsifiers may generally be tuned to the required architecture, headgroups, and chain lengths, as well as qualities including oil-binding capacity, salt/pH tolerance, heat stability, and critical micelle concentration (CMC). One protein emulsifier that was designed, for instance, stayed active at high salinity, at 85°C, and between pH 3 and pH 11[25].

Biocompatibility: A lot of "bio"-designed surfactants stay away from harsh petrochemicals and switch to renewable ingredients. FDA-approved and non-toxic in medication compositions are polxamers[26]. By design, sugar-based emulsifiers are harmless for skin and food. Amino acids break down peptide emulsifiers. These characteristics frequently result in quick biodegradation and minimal toxicity. Conversely, surfactants originating from petroleum (such as SDS and LAS) are frequently irritating and long-lasting[27]. Thus synthetic bioemulsifiers aim to combine labile or natural-based structures with the functionality of classic surfactants.

Comparison with Natural Emulsifiers: Protein isolates (casein, whey), polysaccharides (gum Arabic, acacia), lecithin (phosphatidylcholine), and genuine microbial bioemulsifiers (high-MW glycolipoproteins) are examples of natural emulsifiers. Higher purity and more consistent composition are frequently provided by synthetic emulsifiers. In contrast to natural extracts, which differ depending on the source and necessitate biological creation, they may be optimised for consistency and scalable manufacturing. On the other hand, natural emulsifiers usually offer inherent health advantages and biodegradability. For example, numerous polysaccharides give viscosity, whereas lecithin is a nutritious phospholipid. Although they are expensive to make, microbial bioemulsifiers (such as surfactin and emulsan) have exceptional stability and biocompatibility[28]. These characteristics can be imitated by synthetic analogues: For instance, sugar esters are just as biodegradable as polysaccharides[29]. and protein emulsification patterns may be replicated by engineered peptides[30]. Generally speaking, bio-derived synthetic emulsifiers aim to close the gap; they are constructed from "green" building blocks (sugars, amino acids, and fatty acids) but are customised (structure–function) like petrochemicals. A table comparing natural and synthetic surfactants can mention that while synthetic surfactants are more consistent and tunable, they might not have the micronutrients or signalling effects of natural biopolymers.

Recent Literature Examples: These ideas are demonstrated by recent research. In 2023, synthetic mono-rhamnolipids (Figure) were described; they createds table nano-emulsions for controlling plant diseases and were innocuous to

soil microorganisms[31]. An amphiphilic 55-residue peptide from apomyoglobin, for instance, had more emulsifying ability than gum Arabic and sodium caseinate, demonstrating the logical design underlying the development of designer peptide emulsifiers[32]. A study published in 2022 emphasises the adjustable PEO/PPO ratios of triblock copolymer Pluronics (such as poloxamer 188 and F68) for solubility, thermal gelation, and membrane transport, which are still being optimised for drug carriers[33]. Novel alkyl glycoside and glucamide surfactants with different chain lengths and branching to balance biodegradability and performance (e.g.monoesters versus diesters of sucrose 58) are described. Sugar based surfactants are also an active research topic.Chemical experts can adjust the physicochemical
characteristics of "designer" biobased ionic surfac tants, such as fatty amino acid betaines from coconut oil, and polymeric emulsifiers such as PE grafted fatty chains and poly (glycerol) esters. According to these investigations, synthetic emulsifiers are adjustable and effective as conventionalones, and occasionally even more so, while yet being biodegradable[34].

Applications in Various Industries: Synthetic bioemulsifiers are used widely wherever emulsions are needed.

- **Pharmaceuticals:** PEGylated lipids and pluronic block copolymers stabilise liposomes and nanoemulsions for drug delivery. They can penetrate biological barriers and improve the solubility of hydrophobic medications. Excipients known as polysorbates, or Tweens, are widely used; one example is Tween 80 in injectable formulations. Emulsifiers based on sugar or peptides are being investigated.

- **Cosmetics & Personal Care:** For creams and lotions, mild sugar esters (such sucrose stearate), APGs, sorbitan esters (Spans), and silicone/surfactant hybrids are used. Stable skin sensation is provided by synthetic biocompatible copolymers. Bio-derived synthetic surfactants, such as co-emulsifiers from vegetable oils and polyglycerol esters, are promoted as environmentally beneficial substitutes.

- **Food Processing:** Glycerol and fatty acids are chemically synthesised to create common food emulsifiers, such as lecithin analogues, polyglycerol esters, and mono- and diglycerides of fatty acids (E471). Chocolate uses polyglycerol polyricinoleate (PGPR, E476), a synthetic fat-based emulsifier. Dairy and bakery emulsions are stabilised by polyoxyethylene derivatives and non-ionic sugar esters.

- **Bioremediation & Agriculture:** Both synthetic and biosurfactants are used in surfactant-enhanced cleanup. Synthetic emulsifiers, such as Triton X or Tween 80, have previously been used to solubilise pesticides or oil spills, however biosurfactants are favoured for their low toxicity. Peptide surfactants and synthetic glycolipid equivalents, such as rhamnolipid esters, are being tested recently to enhance h ydrocarbon biodegradation by providing a balance between high activity and regulated synthesis[35].

- **Other Industrial Uses:** Lubricants, paints, agrochemicals, and textiles employ synthetic emulsifiers (e.g. ethoxylated nonylphenols – though now being phased out) or greener replacements (e.g. polyethylene glycol ethers of castor oil, lignin-based surfactants).

Advantages and Limitations:

Synthetic bioemulsifiers provide the benefits of repeatability, design freedom, and frequently improved performance. Chemists can tailor HLB, CMC, and stability to meet particular formulation requirements by manipulating molecular structure (e.g. thermo-responsive poloxamer gels, salt-tolerant glycosides). Many are designed to be non-toxic and biodegradable from the start and are derived from renewable raw resources (plant oils, sugars). They eliminate the batch variability of biological extracts and may be manufactured at scale with consistent quality. But there are restrictions. Complex chemistry, catalysts, and purification procedures may be needed for synthetic pathways, increasing their expense and energy consumption. Some synthetic surfactants remain hazardous or non-biodegradable without careful design, which is a major factor driving the demand for green alternatives[36].

Synthesis Methods

Sugar-Based Emulsifiers: Alkyl polyglucosides (APGs) and sucrose esters (SEs) are two important sugar-derived emulsifiers. Usually, acid-catalyzed glycosidation of glucose with fatty alcohols produces APGs[37][38]. APG is synthesised industrially using either a direct Fischer acetalization or an indirect two-step process (Fig. 1). In the indirect approach (A), n-butanol and anhydrous glucose or glucose syrup first react at about 105°C with an acid catalyst (such as p-toluenesulfonic acid, or PTSA). Butyl glucoside is produced using azeotropic distillation, which removes water. Then, under vacuum (about 300 mmHg), excess fatty alcohol (such as C_{12}–C_{14} alcohol) and PTSA are added gradually while heating to ~115–120 °C. In these circumstances, the long-chain alcohol transacetalizes (displaces) butanol to liberate butanol and produce the alkyl glucoside. The surplus alcohol is then eliminated by vacuum distillation or solvent extraction after the mixture has been neutralised with a base (NaOH)[39]. In order to remove unreacted glucose, the crude APG is finally refined by dissolving it in water and extracting the result (for example, using diethyl ether)[38].

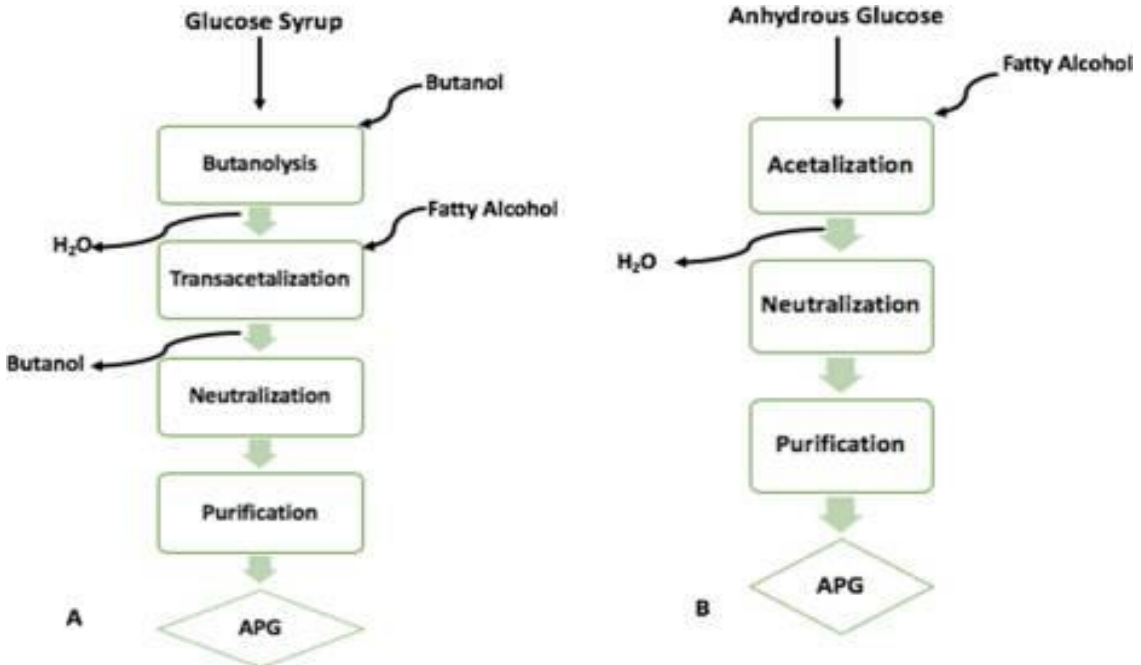

Figure 2: Industrial APG synthesis routes. (A) Indirect butanolysis / trans acetalization: glucose + n-butanol → butyl glucoside, then + fatty alcohol → APG. (B) Direct Fischer acetalization of glucose with fatty alcohol.

APG Stepwise Procedure:

1. Butanolysis: Anhydrous glucose (or concentrated glucose syrup) should be combined with PTSA (≈0.5–1 mol%) and excess n-butanol. Butyl glucoside is formed by heating to around 105°C for about one hour; water is then extracted by distillation[40].

2. Transacetalization: Anhydrous glucose (or concentrated glucose syrup) should be combined with PTSA (≈0.5–1 mol%) and excess n-butanol. Butyl glucoside is formed by heating to around 105°C for about one hour; water is then extracted by distillation[41]. This swaps the butyl group for the fatty chain, forming the APG; butanol distills off.

3. Neutralization: Cool and add aqueous NaOH to neutralize acid. Remove excess fatty alcohol (<1%) by vacuum distillation or by extraction with hexane/acetone[37].

4. Purification: Extract the APG into an organic solvent (such as diethyl ether) after dissolving the residue in water and washing to get rid of salts and sugars. To produce pure APG, dry and concentrate[37].

In the **direct Fischer acetalization route** (B), finely dried glucose is combined directly with a large excess of the fatty alcohol and an acid catalyst (e.g. PTSA) at ~115–130 °C[42]. Anhydrous conditions are required to suppress side reactions. The acid catalyzes formation of the glucoside linkage in one step. Excess alcohol is removed by special distillation, the product is neutralized with base, then washed or bleached to obtain the APG[39].

Scalability and Safety: Both APG techniques produce primarily water and alcohols as byproducts and use renewable feedstocks. Although the indirect method (using glucose syrup) is more cost-effective, it necessitates meticulous alcohol and water cleanup procedures. Corrosion and flammability must be controlled since high temperatures, vacuum, and strong acids and bases are necessary. To reduce waste, surplus alcohol and neutralising agents must be recycled[36]. APGs are biodegradable, but downstream purification (e.g. removal of catalyst residue) is necessary for safety in consumer products.

Sucrose Esters: The sucrose ($C_{12}H_{22}O_{11}$) headgroup of sucrose esters (SEs) is esterified with fatty acyl chains. The most common method for creating industrial SEs is to transesterify fatty acid methyl esters (FAMEs) with sucrose[43]. The typical process is: dissolve sucrose in a polar aprotic solvent (DMF or DMSO) and heat to 90–95 °C. Once dissolved, add FAME (e.g. methyl laurate or methyl palmitate) and a mild base catalyst (commonly K_2CO_3)[44]. Until the reaction is completed, stir or reflux (monitored by TLC). Methanol is produced together with sucrose mono- and di-esters by the base-catalyzed reaction.[42]. After cooling, the mixture is diluted with water and neutralised with a diluted acid, such as lactic or oxalic acid. The crude solid is cleaned (for example, with brine) and filtered after the solvent and methanol have evaporated. Typically, yields consist of around 70% sucrose monoester and 30% higher esters[46].

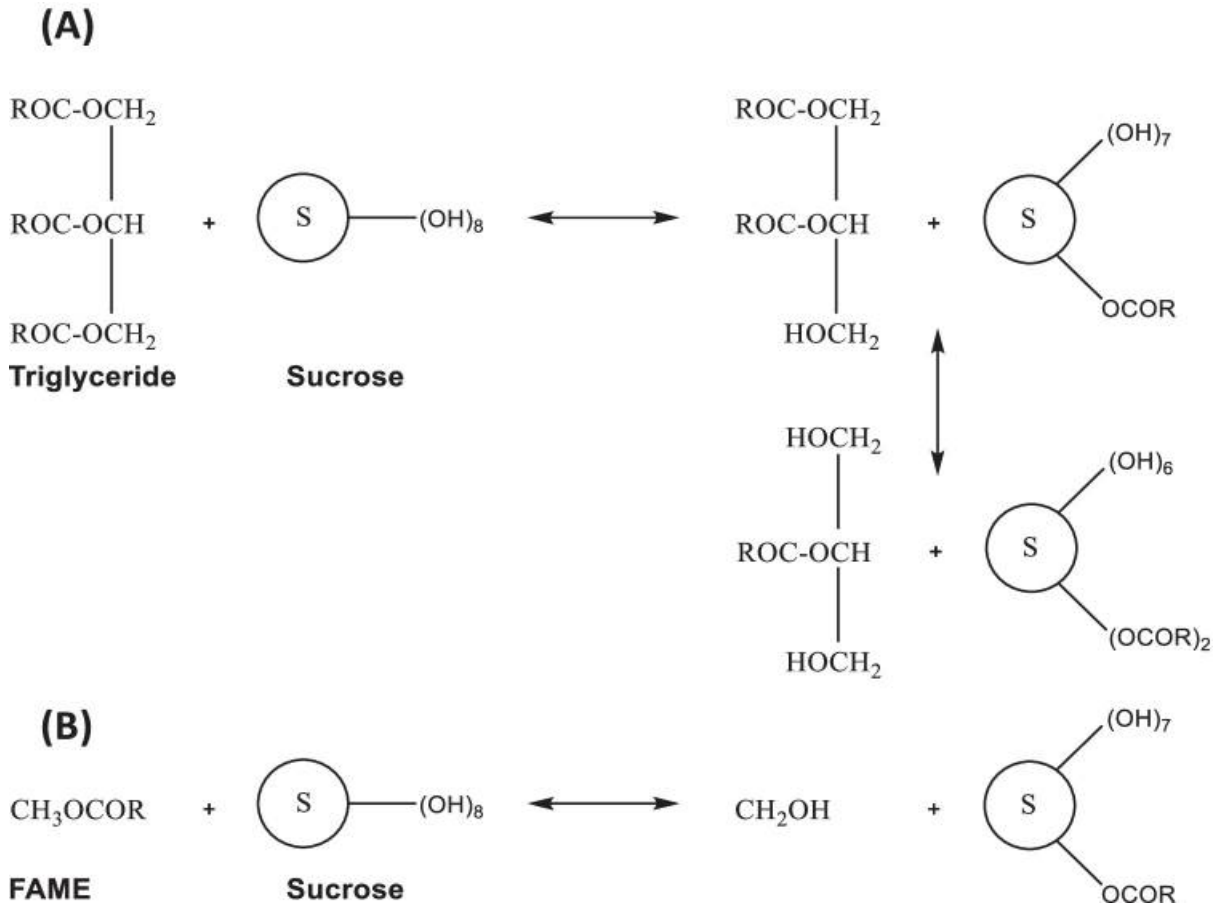

Figure 3: Sucrose ester synthesis routes. (A) Direct esterification of triglyceride vs. sucrose (makes mixture of esters). (B) Transesterification of FAME with sucrose (preferred industrial route, yielding mostly monoesters)

SE Stepwise Procedure:

1. Sucrose solution: Dissolve sucrose in dry DMF or DMSO and heat to ~90–95 °C

2. Transesterification: Add fatty acid methyl ester (molar excess) and K_2CO_3 catalyst. Continue reflux; methanol byproduct is removed (or can be distilled). Reaction progress is checked by TLC.

3. Workup: Cool and acidify (e.g. with oxalic or lactic acid) to quench K_2CO_3. Dilute with water; the sucrose esters precipitate or remain in solution.

4. Purification: Evaporate solvent, wash residue with brine to remove salts and residual methanol, then dry. The crude SE product is a mixture (mono-, di-, tri-esters) that may be further fractionated if a specific HLB is needed[43].

Consideration: Temperatures are restricted because sucrose is heat-sensitive. By using FAME instead of free fatty acids, saponification and water production are prevented. It is necessary to recycle or dispose of the inorganic salts and polar solvent with caution. The volatile byproduct of methanol needs to be burnt or condensed. To separate the desired monoester from the final product mixture, further separation (such as chromatography or distillation) is frequently necessary. Methanol is the primary byproduct of SE syntheses, which generally generate very little hazardous waste[46].

Synthetic Glycolipid Analogues (Mono-Rhamnolipids)

Synthetic glycolipids mimic bacterial rhamnolipids by linking sugars to fatty acids. A representative example is *mono-rhamnolipid esters/ethers*: α-L-rhamnose linked to a 3-hydroxy fatty acid. Chemical routes often first prepare the lipid tail (3-hydroxy acid) and then couple it to the sugar. One strategy is Fischer glycosylation: reacting L-rhamnose with a long-chain alcohol in acid to form a rhamnoside (ether linkage)[46]. Amonklam et al. used catalytic PTSA to show that L-rhamnose may be glycosylated with unsaturated alkenols. The reaction at about 80°C for 48 hours produced mostly α-rhamnosides in THF with PTSA (0.6 equiv). Solvent-free (alcohol as solvent) execution of the same reaction reduced the time to about 5 hours and produced yields of about 80–95%[48].

Rhamnolipid Analog Synthesis:

1. Lipid tail synthesis: Prepare the 3-hydroxy fatty acid chain. For example, use a Reformatsky condensation or enzymatic resolution to obtain (R)-3-hydroxydecanoic acid. Protect the acid as a methyl ester[49].

2. Sugar activation: Protect L-rhamnose (e.g. as its per-O-acetate) and convert to a glycosyl donor (e.g. rhamnosyl bromide or trichloroacetimidate) in situ[4].

3. Glycosylation: React the protected sugar donor with the fatty alcohol or fatty acid derivative under Lewis acid ($BF_3 \cdot Et_2O$ or TMSOTf) or in acid catalysis (Fischer method) For ether-type analogs, Fischer glycosylation (rhamnose + $C_nH_{2n+1}OH$, PTSA, 80–100 °C) yields rhamnosides. For ester linkage, a direct Koenigs–Knorr route can couple peracylated rhamnose halide to the 3-hydroxy acid (as its sodium salt), then deprotect acetates[50].

4. Deprotection: Remove protecting groups (e.g. alkaline methanolysis for acetates) to yield the free glycolipid. Purify by column chromatography or crystallization.

Environment/Safety: Protective groups, strong acids and bases, and frequently heavy metal catalysts (Ag_2CO_3, BF_3, etc.) are used in these multistep syntheses. There is a significant amount of solvent waste from various organic and aqueous extractions. The yield is modest generally. The product's biodegradability is a bonus. Impact can be reduced by creating more environmentally friendly processes (such as solvent-free glycosylation and enzymatic tail synthesis)[51].

Peptide-Based (Lipopeptide) Emulsifiers

The most common method for assembling peptide or lipopeptide surfactants is peptide synthesis with hydrophobic tails. Fmoc solid-phase peptide synthesis (SPPS) followed by lipid conjugation is a popular method. The cyclic lipoheptapeptide biosurfactant surfacting, for instance, was created using SPPS on acid-labile resin. In Thevissen et al.'s approach, Fmoc-SPPS on SASRIN resin was employed to create the heptapeptide backbone. The N-terminus (or an amino side chain) was then acylated with a (R)-3-hydroxy fatty acid utilising a carbodiimide (EDC) coupling to generate a depsipeptide bond. Following linear peptide construction, the peptide was separated from the resin and cyclized in solution. The lactone ring was formed via head-to-tail cyclisation, which was accomplished by HATU/DIEA coupling. Ultimately, chromatography was used to purify the cyclic lipopeptide[52].

Lipopeptide Synthesis Steps:

1. Peptide assembly: Perform Fmoc-SPPS on resin (e.g. Rink or SASRIN) to build the desired peptide sequence. Use standard coupling reagents (HBTU, DIC, etc.).

2. Lipid attachment: Couple a fatty acyl group to the N-terminus or a lysine side chain. For example, react (R)-3-hydroxydecanoic acid (activated with EDC/HOBt) with the resin-bound peptide N-terminus.

3. Cleavage and cyclization: Cleave the linear lipopeptide from resin. Then cyclize in dilute solution: activate the C-terminus (with HATU/DIEA) and allow it to react with the peptide N-terminus (or hydroxyl) to form a macrocyclic lactone.

4. Purification: Separate cyclic products by reverse-phase HPLC or silica chromatography. Verify the structure by NMR/MS.

Scale/Safety: Peptide syntheses generate a lot of waste (coupling byproducts, cleavage cocktails) and consume a lot of organic reagents (DMF, DCM, NMP). Protecting group solvents and coupling reagents (HATU, EDC) are dangerous. Automation is possible with solid-phase techniques, although they are still costly. Lipopeptides are powerful surfactants, but because of their high cost, they are usually only produced on a lab or pilot scale. Although efficiency may be increased with innovations like microwave SPPS or greener coupling reagents, the E-factor is high overall (a lot of solvent per kilogramme peptide)[53].

CONCLUSION

The synthesis of bioemulsifiers through chemical methods provides a promising alternative to microbial production, offering greater control over structure, scalability, and functional diversity. Synthetic bioemulsifiers- such as sugar based surfactants (alkyl polyglucosides, sucrose esters), polymeric emulsifiers (poloxamers, PEG copolymers), synthetic glycolipid analogues, and peptide based emulsifiers have been successfully engineered using a variety of well established chemical routes. Each class presents unique advantages:

- **Sugar-derived surfactants** (e.g., APGs and SEs) are renewable, biodegradable, and relatively non-toxic, with scalable synthesis and good emulsifying properties.

- **Polymeric emulsifiers** (e.g., PEO–PPO block copolymers) offer tunable amphiphilicity and thermal stability but require strict control over synthesis conditions.

- **Synthetic glycolipid analogues** mimic microbial biosurfactants and offer high surface activity, although their multistep synthesis can be complex and environmentally demanding.

- **Peptide-based emulsifiers** provide high biocompatibility and functional specificity but are costly and less feasible for large-scale production due to synthetic complexity.

Despite their advantages, synthetic routes often involve harsh reaction conditions, toxic reagents, or high-energy processes, raising concerns about environmental impact and cost. To address this, future research should prioritize **greener synthetic methods**, such as enzymatic catalysis, solvent-free reactions, and use of renewable feedstocks. Additionally, **structure-function studies** and **biocompatibility assessments** are critical to optimize performance for specific applications such as pharmaceuticals, cosmetics, and food. Overall, synthetically prepared bioemulsifiers represent a significant advancement in sustainable surfactant technology,

balancing performance with eco-friendly design. Their continued development will be pivotal in meeting the growing demand for effective and environmentally conscious emulsification agents.

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HOW TO CITE: Srushti Aoundhakar*, Muskan Mujawar, Rajnanda Patil, Priyanka Mohite, Dr. D. R Jadge, Chemical Approaches to Bioemulsifiers, Int. J. of Pharm. Sci., 2025, Vol 3, Issue 6, 969-984. https://doi.org/10.5281/zenodo.15601700