

Glycolipid Biosurfactants for Enhanced Oil Recovery in High-Wax Crude Oil Reservoirs: A Review

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Abstract

High-wax crude oil presents a major challenge to enhanced oil recovery (EOR) because wax precipitation increases oil viscosity and restricts hydrocarbon flow. Although glycolipid biosurfactants have emerged as sustainable alternatives to conventional chemical surfactants, their effectiveness and mechanisms in high-wax crude oil systems remain insufficiently synthesized. This study reviews the application of glycolipid biosurfactants, particularly rhamnolipids and sophorolipids, for EOR in high-wax crude oil reservoirs, emphasizing interfacial tension reduction, wettability alteration, hydrocarbon mobilization, wax degradation, and stability under reservoir conditions. A narrative literature review was conducted using ScienceDirect, PubMed, and SpringerLink, primarily covering publications from 2015 to 2025. Studies were screened for relevance to glycolipid biosurfactants and their reported effects on interfacial tension, critical micelle concentration, emulsification, wettability, viscosity, biodegradation, stability, and oil recovery. Fourteen relevant studies were included and comparatively analyzed using descriptive quantitative comparison and qualitative synthesis. The reviewed studies indicate that glycolipid biosurfactants enhance hydrocarbon mobilization by reducing interfacial tension, shifting wettability toward more water-wet conditions, promoting emulsification, and enabling hydrocarbon degradation or dispersion. Sophorolipids demonstrated strong interfacial activity and stability under elevated temperature and salinity, with reported additional oil recovery of up to 27.27% in sandstone core experiments, while rhamnolipid-based systems achieved a reported 15.4% increase in oil recovery. These findings support glycolipid biosurfactants as promising sustainable EOR agents for high-wax reservoirs, while highlighting the need for pilot-scale validation, long-term stability assessment, adsorption studies, and techno-economic evaluation.

Keywords *Biosurfactants, Rhamnolipid, High-Wax Crude Oil, Interfacial Tension, Wettability Alteration*

INTRODUCTION

Global industrialization remains heavily reliant on petroleum resources, yet mature reservoirs often reach a point where conventional recovery methods leave a substantial fraction of the oil initially in place (Elshafie et al., 2015; Ganji et al., 2020). This residual oil can be particularly difficult to mobilize in high-wax crude oil systems, where solid hydrocarbon components increase viscosity, restrict fluid flow, and create permeability barriers within porous media (Patowary et al., 2018). Conventional Enhanced Oil Recovery (EOR) strategies commonly employ synthetic chemical surfactants; however, concerns about their environmental toxicity and limited biodegradability have spurred interest in more sustainable alternatives (Ahuekwe et al., 2016; Mishra et al., 2021). Consequently, biosurfactants have attracted increasing attention for their biodegradability, low

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toxicity, and ability to maintain surface activity under challenging reservoir conditions (Nikolova & Gutierrez, 2021; Pal et al., 2023).

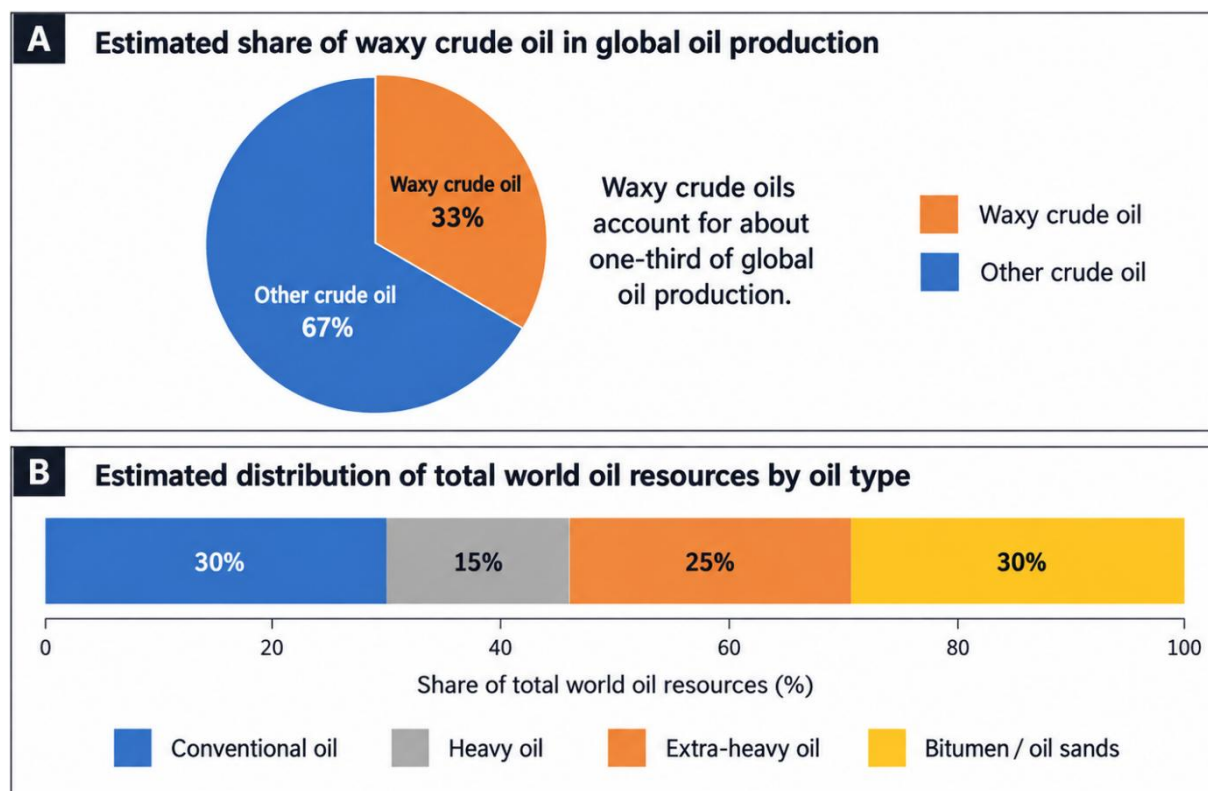


Figure 1. Global context of waxy and unconventional crude-oil resources. (A) Waxy crude oil accounts for approximately one-third of global oil production. (B) Estimated distribution of total world oil resources by oil type. Adapted from [Fakroun and Benkreira \(2020\)](#) and [Schlumberger \(2016\)](#)

Biosurfactants, particularly rhamnolipids synthesized by *Pseudomonas* spp., have emerged as promising agents for Enhanced Oil Recovery (EOR) because of their strong interfacial activity and ability to modify oil–brine–rock interactions ([Patowary et al., 2018](#); [Rehman et al., 2021](#); [Mishra et al., 2021](#)). Previous studies have demonstrated that rhamnolipids can reduce surface tension, stabilize oil–water dispersions, and improve the mobilization of trapped hydrocarbons. Rhamnolipid-producing microorganisms have also demonstrated substantial crude-oil biodegradation and emulsification capabilities, indicating their potential to improve hydrocarbon accessibility and fluid mobility ([Rehman et al., 2021](#)). For example, rhamnolipid-based treatment has been reported to achieve high total petroleum hydrocarbon degradation, exceeding that obtained with sodium dodecyl sulfate under comparable conditions ([Patowary et al., 2018](#)).

High-wax crude oil is particularly susceptible to temperature-induced flow restrictions. As illustrated in Figure 2, cooling toward the pipe wall can lower the local temperature below the wax appearance temperature (WAT), initiating paraffin crystallization and progressive wax deposition that reduces the effective flow area. This behavior highlights the need for recovery agents that can effectively interact with waxy hydrocarbon systems while improving oil mobility. Beyond rhamnolipids, yeast-derived sophorolipids produced by strains such as *Candida keroseneae* have demonstrated strong surface activity and stability under elevated temperature, salinity, and broad pH conditions ([Elshafie et al., 2015](#); [Ganji et al., 2020](#)). These glycolipid biosurfactants can reduce interfacial tension and alter rock wettability toward more water-wet conditions, thereby

facilitating the mobilization of residual hydrocarbons. Their performance may be further enhanced through synergistic approaches; for example, combining sophorolipids with silica nanofluids has been reported to increase structural disjoining pressure and promote the liberation of heavy hydrocarbons from mineral surfaces (Hou et al., 2022). In addition, biosurfactant-producing microorganisms have demonstrated the ability to degrade different petroleum hydrocarbon fractions, further supporting their potential application in challenging waxy petroleum systems (Pandey et al., 2021).

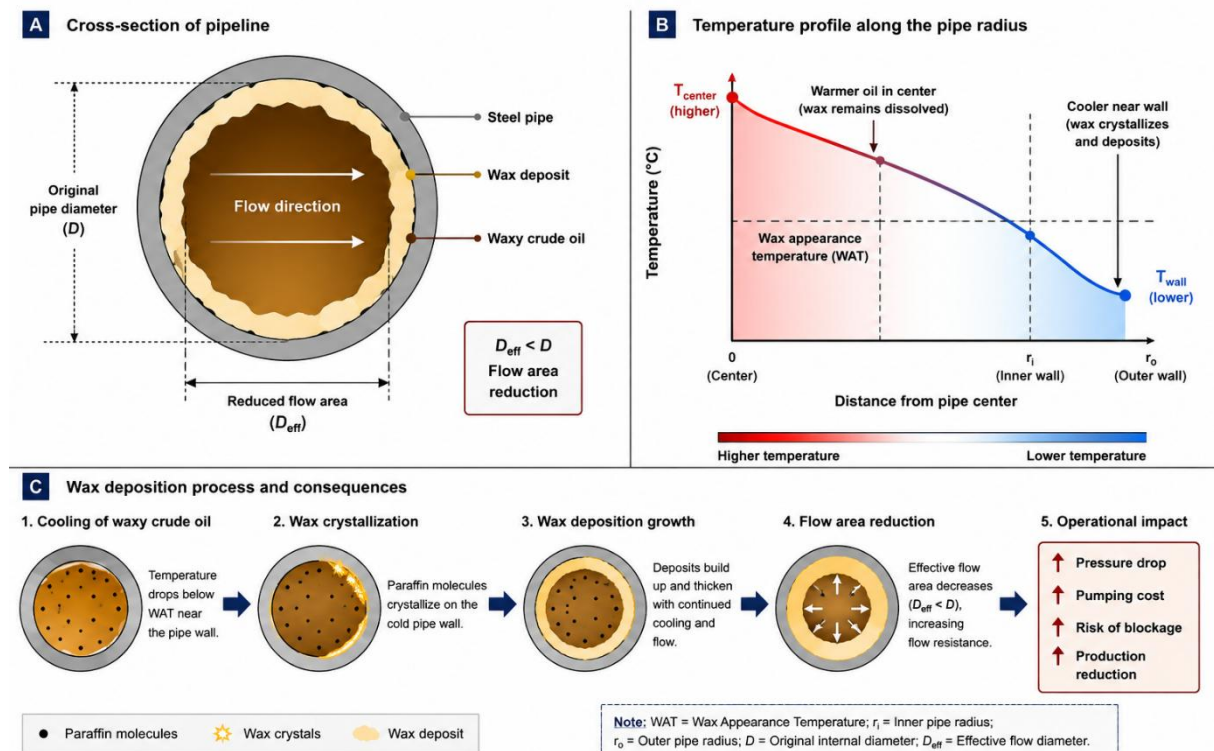


Figure 2. Schematic of wax deposition and temperature distribution in a petroleum pipeline, conceptualized based on Kiyngi et al. (2022)

Despite these advances, the targeted application of biosurfactants to high-wax crude oil remains comparatively underexplored, particularly regarding the combined effects of wax degradation, interfacial activity, wettability alteration, and hydrocarbon mobilization. Previous studies on microbial treatment of waxy crude oil have shown reductions in wax-related flow restrictions, crude-oil viscosity, and wax appearance temperature, indicating the potential of biosurfactant-producing microorganisms to mitigate paraffin-related production problems (Etoumi, 2007; Sharma et al., 2018). However, the available evidence remains dispersed across studies addressing different biosurfactants, microorganisms, crude-oil characteristics, and reservoir conditions. Therefore, this literature review synthesizes published evidence on the application of glycolipid biosurfactants, particularly rhamnolipids and sophorolipids, for high-wax crude oil EOR, with particular emphasis on interfacial tension reduction, wettability alteration, hydrocarbon mobilization, wax degradation, and stability under varying temperature, pH, and salinity conditions. The review further seeks to identify the principal mechanisms governing biosurfactant effectiveness and to provide a technical basis for future development and field-oriented application of sustainable biosurfactant-based EOR systems.

LITERATURE REVIEW

To address the physical and environmental limitations of conventional tertiary oil recovery, a clear understanding of the molecular structures, physicochemical properties, and fluid–fluid interactions of biological surface-active agents is required. This literature review synthesizes key studies on glycolipid biosurfactants, principally rhamnolipids and yeast-derived sophorolipids, with particular emphasis on their ability to interact with waxy hydrocarbons and facilitate enhanced oil recovery (EOR). By comparing experimental findings under different reservoir-relevant conditions, this review examines critical micelle concentration (CMC), surface and interfacial tension reduction, wax and hydrocarbon mobilization, and rock wettability alteration. These mechanisms provide the theoretical basis for evaluating the potential application of glycolipid biosurfactants in technically challenging high-wax crude-oil systems.

Theoretical Background

The extraction of hydrocarbons from mature reservoirs is perennially constrained by capillary forces that trap a significant portion of residual oil within the microscopic pores of reservoir rocks. This challenge is severely compounded in reservoirs containing high-wax crude oil. As reservoir temperature drops below the wax appearance temperature (WAT), heavy paraffinic fractions (C₁₈ to C₄₄) precipitate as solid crystals, dramatically increasing crude oil viscosity, causing pore-throat plugging, and severely reducing formation permeability (Patowary et al., 2018; Rehman et al., 2021). Traditional tertiary recovery or Enhanced Oil Recovery (EOR) techniques rely on synthetic chemical surfactants (sodium dodecyl sulfate, alkylbenzene sulfonates) to reduce interfacial tension (IFT) and alter rock wettability. However, these petrochemical-derived surfactants suffer from high adsorption rates onto rock matrices, thermal instability, and severe environmental toxicity. Consequently, sustainable biological alternatives have gained significant traction (Nikolova & Gutierrez, 2021). Among these, glycolipid biosurfactants, principally rhamnolipids and sophorolipids, have emerged as highly promising agents, exhibiting low toxicity, complete biodegradability, and superior surface activity under extreme reservoir conditions (Pal et al., 2023).

Chemical Structure of Glycolipid Biosurfactants

Rhamnolipids are low-molecular-weight glycolipid biosurfactants predominantly produced as secondary metabolites by *Pseudomonas aeruginosa*. Their molecular structure contains hydrophilic and hydrophobic components, including a carboxyl group that gives the molecule an anionic nature and a rhamnosyl moiety that contributes to the relatively bulky hydrophilic head group (Eslami et al., 2020; Zhao et al., 2020). In general, rhamnolipids comprise one or two rhamnose units connected through a β -glycosidic linkage to a hydrophobic moiety consisting of one or more β -hydroxy fatty acid chains (Patowary et al., 2018). Based on the number of rhamnose units, they are commonly categorized as mono-rhamnolipids, which contain a single rhamnose moiety, and di-rhamnolipids, which contain two rhamnose units, with representative structures such as Rha-C₁₀-C₁₀ and Rha-Rha linked to a fatty acid tail, respectively (Patowary et al., 2018). Analytical techniques such as liquid chromatography mass spectrometry (LC-MS) have shown that wild-type microbial strains can generate diverse rhamnolipid congeners with different fatty acid chain lengths, commonly within the C₈-C₁₄ range. Rhamnolipids commonly occur as mono-rhamnolipids and di-rhamnolipids, distinguished by one or two rhamnose moieties, respectively, as illustrated in Figure 3 (Arkhipov et al., 2023).

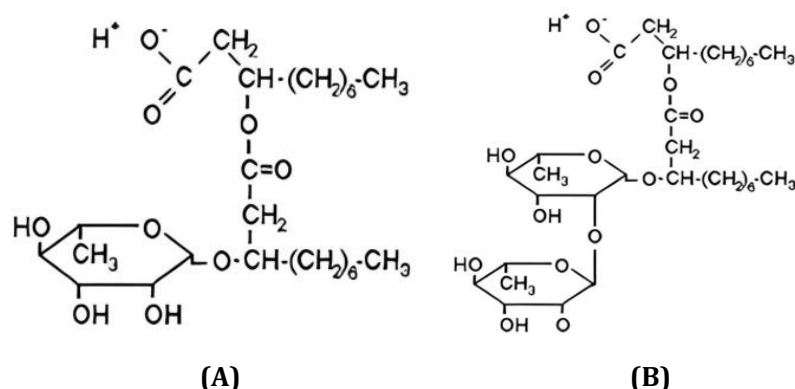


Figure 3. General structures of Rhamnolipid Molecules: (A) Mono-rhamnolipids and (B) Di-rhamnolipids, adapted from [Arkhipov et al. \(2023\)](#).

In comparison, sophorolipids are glycolipid biosurfactants mainly synthesized by yeasts, including *Candida bombicola* and *Candida keroseneae*, and consist of a sophorose disaccharide head group attached to a long-chain hydroxy fatty acid ([Ganji et al., 2020](#); [Pal et al., 2023](#)). Variations in congener composition influence the hydrophilic–lipophilic balance (HLB) of these biosurfactants, which in turn affects their interfacial properties, solubility, and potential effectiveness in enhanced oil recovery (EOR) applications within porous media.

Critical Micelle Concentration (CMC) and Micellization

Surfactant surface and interfacial activity is closely related to its critical micelle concentration (CMC). At low bulk concentrations, biosurfactant molecules primarily exist as monomers and preferentially adsorb at air–water or oil–water interfaces. As the concentration increases and the interface approaches saturation, additional molecules spontaneously self-assemble into micelles ([Mishra et al., 2021](#)). [Rehman et al. \(2021\)](#) reported CMC values of 40 mg/L for rhamnolipids produced by *Pseudomonas aeruginosa* and 50 mg/L for sophorolipids produced by *Meyerozyma* sp., with corresponding reductions in water surface tension to 29 and 33 mN/m, respectively. These results demonstrate that relatively low concentrations of glycolipid biosurfactants can provide substantial surface activity.

Wax and Paraffin Precipitation Mechanisms

In reservoirs containing high-paraffin crude oils, pressure and temperature reductions trigger the crystallization of heavy alkanes into solid wax matrices, forming interlocking paraffin networks that trap liquid hydrocarbons, escalate viscosity, and block pore throats. Glycolipid biosurfactants mitigate wax deposition through both physical and biological pathways. Physically, above the CMC, the hydrophobic cores of biosurfactant micelles encapsulate hydrophobic wax crystals, mobilizing them into the aqueous phase and preventing growth or agglomeration, which significantly reduces viscosity ([Patowary et al., 2018](#); [Rehman et al., 2021](#)). Biologically, biosurfactants act as cellular promoters by releasing lipopolysaccharides (LPS) from outer bacterial membranes, increasing cell surface hydrophobicity (CSH). This allows specialized hydrocarbonoclastic bacteria (*Fictibacillus phosphorivorans* RP3 or *Pseudomonas aeruginosa*) to adhere directly to the paraffinic phase, metabolizing complex long-chain alkanes into simpler, short-chain liquid fractions ([Saborimanesh & Mulligan, 2015](#); [Pandey et al., 2021](#)).

Interfacial Tension (IFT) Reduction and Wettability Alteration

Capillary forces are a major mechanism responsible for trapping residual oil within

reservoir pore throats, thereby limiting oil displacement during conventional waterflooding. Biosurfactants can overcome this capillary resistance through a dual mechanism involving interfacial tension (IFT) reduction and wettability alteration. First, biosurfactant monomers adsorb at the crude oil-brine interface, significantly reducing oil-water IFT and consequently lowering the capillary forces that retain oil within the pore structure. For example, sophorolipids have been reported to reduce oil-water IFT from 23.8 mN/m to ultra-low values ranging from 5.6 to 2.13 mN/m (Elshafie et al., 2015).

Second, biosurfactants alter the solid-liquid interfacial energies of reservoir minerals, shifting conditions from strongly oil-wet (contact angles of approximately 140°) toward intermediate- to highly water-wet conditions (contact angles ranging from 58° to 87°) (Hou et al., 2022). The combined effects of IFT reduction and wettability alteration decrease capillary resistance and facilitate spontaneous water imbibition into smaller pore spaces, mobilizing residual oil and improving tertiary oil recovery by approximately 15.4%-27.27% (Elshafie et al., 2015; Sakthipriya et al., 2021). Moreover, incorporating silica nanofluids with sophorolipids can further increase structural disjoining pressure, helping mobilize heavy oil fractions trapped within complex or unconventional pore matrices (Hou et al., 2022). Thus, the synergistic interaction between biosurfactant-induced IFT reduction, wettability alteration, and nanoparticle-enhanced disjoining pressure provides a mechanistic basis for improving residual oil mobilization and EOR performance. Table 1 summarizes the characteristics, study types, objectives, and principal findings of the literature included in this review.

Table 1. Summary of Literature Studies

No	Title	Study Type	Objective	Description
1	Sophorolipids Production by <i>Candida bombicola</i> ATCC 22214 and its Potential Application in Microbial Enhanced Oil Recovery (Elshafie et al., 2015)	Core-flood EOR experiment	Test the efficacy of yeast-derived sophorolipids in EOR using core-flood experiments.	Sophorolipids recovered 27.27% of residual oil trapped in sandstone pores and demonstrated high thermal stability.
2	Biosurfactants and Their Applications in the Oil and Gas Industry: Current State of Knowledge and Future Perspectives (Nikolova & Gutierrez, 2021)	Review article	Presents the state of the art for biosurfactants in MEOR and oil spill dispersion.	Identifies research needs to improve biosurfactant application in EOR under challenging conditions.
3	Evaluation of Hydrocarbon Emulsification and Heavy Metal Detoxification Potentials of Sophorolipid Biosurfactants (Ahuekwe et al., 2016)	Laboratory emulsification study	Investigate hydrocarbon emulsification using sophorolipids from agro-industrial waste.	Achieved a 40.0% emulsification index for crude oil and demonstrated hydrocarbon-solubilization potential.
4	Synergistic Effect of Silica Nanofluid and Biosurfactant on Bitumen Recovery from Unconventional Oil (Hou et al., 2022)	Laboratory recovery study	Analyze the synergistic impact of silica nanoparticles and sophorolipids on	The combination increased structural disjoining pressure and altered rock surfaces from oil-wet toward water-wet

No	Title	Study Type	Objective	Description
			bitumen.	conditions.
5	Petroleum Hydrocarbon-Contaminated Soil Bioremediation Assisted by Isolated Bacterial Consortium and Sophorolipid (Feng et al., 2021)	Soil bioremediation experiment	Enhances TPH biodegradation through a combined bacterial consortium and biosurfactants.	Demonstrates that sophorolipids serve as carbon sources for co-metabolism and change cell surface morphology, increasing hydrocarbon availability and TPH degradation to 57.7%.
6	Effect of Sophorolipid Biosurfactant on Oil Biodegradation by the Natural Oil-Degrading Bacteria (Saborimanesh & Mulligan, 2015)	Oil biodegradation experiment	Determine the role of natural bacteria and sophorolipids in weathered-oil degradation.	Confirmed that sophorolipids significantly increase micellar dispersion of hydrocarbons, accelerating metabolic uptake by indigenous microbial phyla.
7	Effect of Biosurfactant Sophorolipids on <i>Rhizomucor miehei</i> Lipase Fermentation by <i>Aspergillus oryzae</i> (Zhang et al., 2021)	Fermentation experiment	Explore cellular metabolic responses to exogenous sophorolipid addition during fermentation.	Sophorolipids reduce broth viscosity and alter cell membrane morphology to an energetic state, increasing lipase enzyme secretion activity by 25%.
8	Isolation and Characterization of a Novel Hydrocarbonoclastic and Biosurfactant-Producing Bacterial Strain: <i>Fictibacillus phosphorivorans</i> RP3 (Pandey et al., 2021)	Microbial isolation and degradation study	Identify and characterize a novel indigenous strain for kerosene and diesel degradation.	The bacterium RP3 degraded petroleum hydrocarbons by $\geq 90\%$, promoting cell-surface adhesion to waxy phases.
9	Application of Biosurfactant for Enhancement of Bioremediation Process of Crude Oil Contaminated Soil (Patowary et al., 2018)	Soil bioremediation experiment	Evaluated rhamnolipid mixtures to remediate persistent polyaromatic hydrocarbons (PAHs).	Characterized mono- and di-rhamnolipid congeners from <i>P. aeruginosa</i> SR17 that achieved 86.1% TPH degradation and unblocked soil porous structures.
10	Crude Oil Biodegradation Potential of Biosurfactant-Producing <i>Pseudomonas aeruginosa</i> and	Biosurfactant characterization and biodegradation	Investigated the crude oil-degrading potential of	Revealed that <i>P. aeruginosa</i> MF069166 and <i>Meyerozyma</i> sp. MF138126 produce

No	Title	Study Type	Objective	Description
	<i>Meyerozyma</i> sp. (Rehman et al., 2021)	study	biosurfactant producers.	glycolipids, achieving up to 91% crude oil biodegradation efficiency.
11	Biosurfactant is a Powerful Tool for the Bioremediation of Heavy Metals from Contaminated Soils (Mishra et al., 2021)	Review article	Describes the interaction mechanisms underlying biosurfactant-pollutant complexation.	Discusses mechanisms of biosurfactant-assisted contaminant mobilization and interaction.
12	Sophorolipids: A Comprehensive Review on Properties and Applications (Pal et al., 2023)	Review article	Highlights physicochemical properties and unique structures of sophorolipids.	Emphasizes the high production yields (>400 g/L) and structural robustness (pH, temperature, salinity) of sophorolipids for EOR applications.
13	A Novel Sophorolipid-Producing <i>Candida keroseneae</i> GBME-IAUF-2 as a Potential Agent in MEOR (Ganji et al., 2020)	Microbial isolation and biosurfactant characterization study	Isolate and characterize a thermo-tolerant yeast strain from oily soil for MEOR applications.	Discovered a yeast preserving 97.25% activity at 120°C and 100% in high salinity, making its sophorolipid a superior active agent for alkaline thermal EOR.
14	Impact of Biosurfactants, Surfactin, and Rhamnolipid Produced from <i>Bacillus subtilis</i> and <i>Pseudomonas aeruginosa</i> , on the Enhanced Recovery of Crude Oil and Its Comparison with Commercial Surfactants (Sakthipriya et al., 2021)	Porous-media EOR experiment	Recover crude oil using biosurfactants in porous sandstone media.	Demonstrated that 200 ppm of surfactin or rhamnolipid can produce a 15.4% increase in oil recovery, rivaling the performance of chemical surfactants.

RESEARCH METHOD

This study employed a narrative literature review to examine the application of glycolipid biosurfactants, particularly rhamnolipids and sophorolipids, for enhanced oil recovery (EOR) and hydrocarbon mobilization in high-wax crude-oil systems. A narrative review was selected because the available literature encompasses heterogeneous study designs, experimental conditions, biosurfactant types, and measured outcomes, making statistical pooling inappropriate. This approach enables the integration and critical interpretation of diverse evidence while maintaining explicit boundaries for literature selection and analysis (Snyder, 2019; Sukhera, 2022). The

methodology consisted of literature search and selection, data extraction, and comparative analysis.

Literature Search and Study Selection

Relevant studies were identified through ScienceDirect, PubMed, and SpringerLink using combinations of the keywords: biosurfactant, glycolipid, rhamnolipid, sophorolipid, enhanced oil recovery, microbial enhanced oil recovery, high-wax crude oil, paraffin, wax degradation, viscosity reduction, interfacial tension, and wettability. The search primarily covered publications from 2015 to 2025, while earlier studies were included when they provided relevant foundational information on biosurfactant properties or EOR mechanisms. The final literature search was conducted on 25 June 2025.

The database searches identified 185 records. After removing duplicates and clearly irrelevant records, we screened 42 records by title and abstract, followed by full-text assessment of 28 articles. Studies were included if they addressed rhamnolipids, sophorolipids, or closely related biosurfactants and reported findings on surface or interfacial tension, critical micelle concentration (CMC), emulsification, wettability alteration, viscosity, hydrocarbon biodegradation, stability, or oil-recovery performance. Studies unrelated to petroleum applications, those focused exclusively on synthetic surfactants without a relevant biosurfactant comparison, or those lacking sufficient information for analysis were excluded. Fourteen studies were ultimately included in the review, as summarized in Table 1.

The primary author conducted the initial screening and eligibility assessment using the predefined inclusion and exclusion criteria. The primary author discussed borderline cases with coauthors until consensus was reached; however, no independent second-reviewer screening was performed.

Data Collection and Analysis

Information from the selected studies was compiled into a structured evidence table covering biosurfactant type, producing microorganism, crude-oil or hydrocarbon system, experimental method, temperature, salinity, pH, biosurfactant concentration, CMC, surface or interfacial tension, emulsification, wettability, viscosity, biodegradation, and oil-recovery performance. The methodological relevance of each study was assessed based on the clarity of reported procedures, completeness of results, availability of quantitative data, and relevance to reservoir conditions. Core-flooding and porous-media displacement studies were treated as direct EOR evidence, whereas hydrocarbon-degradation, bioremediation, and biosurfactant-characterization studies were treated as supporting mechanistic evidence.

The extracted data were analyzed through descriptive quantitative comparison and qualitative synthesis. Numerical results were compared across studies to identify reported performance ranges and variations in experimental conditions, while qualitative synthesis was used to evaluate recurring mechanisms, including interfacial-tension reduction, emulsification, wettability alteration, hydrocarbon mobilization, biodegradation, and stability under reservoir-relevant conditions. Because of methodological heterogeneity among the selected studies, no meta-analysis or statistical pooling was performed. Previously published experimental procedures were interpreted from the original publications and, where consulted, their associated supplementary materials; no new laboratory or field experiments were conducted.

FINDINGS AND DISCUSSION

The reviewed studies report that high-wax crude-oil systems present significant recovery challenges because wax precipitation and paraffin deposition can restrict hydrocarbon mobility

and fluid flow. Glycolipid biosurfactants, particularly rhamnolipids and sophorolipids, may address these limitations by reducing interfacial tension, emulsifying oil, altering wettability, and improving hydrocarbon accessibility. This review's novelty lies in critically integrating these mechanisms for high-wax crude-oil recovery while distinguishing direct EOR evidence from supporting biodegradation and bioremediation studies. This distinction is important because improvements observed in soil or batch degradation experiments cannot be directly interpreted as reservoir-scale oil recovery. Accordingly, the following discussion compares reported performance with the strength of the available experimental evidence.

Comparative Performance of Reviewed Biosurfactants

The reviewed studies report substantial surface activity for both rhamnolipids and sophorolipids, although performance varies with microbial origin, formulation, and experimental conditions. [Rehman et al. \(2021\)](#) reported critical micelle concentrations (CMC) of 40 mg/L for rhamnolipids produced by *Pseudomonas aeruginosa* and 50 mg/L for sophorolipids produced by *Meyerozyma* sp., with corresponding surface tensions of approximately 29 and 33 mN/m. The same study reported crude-oil biodegradation efficiencies of 91% and 87%, respectively. These results demonstrate strong hydrocarbon interaction but provide evidence of biodegradation rather than direct porous-media displacement.

[Elshafie et al. \(2015\)](#) reported more direct EOR evidence: sophorolipids from *Candida bombicola* ATCC 22214 reduced surface tension to approximately 28.6 mN/m and oil-water interfacial tension to 2.13 mN/m, followed by 27.27% additional residual-oil recovery in a sandstone core-flood experiment. The biosurfactant was reported to remain stable at temperatures up to 100°C. In comparison, [Ganji et al. \(2020\)](#) evaluated sophorolipid produced by *Candida keroseneae* GBME-IAUF-2 and reported that high surface activity was retained at 110-120°C. Thus, the 120°C thermal-stability value should be attributed to *C. keroseneae*, not *C. bombicola*. This comparison indicates that sophorolipid thermal stability depends on strain and formulation rather than a single universal temperature limit.

Table 2. Comparative physicochemical, stability, biodegradation, and oil-recovery performance of reviewed biosurfactants

Biosurfactant Type / Microbial Origin	CMC (mg/L)	SF/IFT Reduction (mN/m)	Temperature and Salinity Tolerance	Recovery / Biodegradation Efficiency	Reference
Rhamnolipid / <i>Pseudomonas aeruginosa</i> MF069166	40	ST reduced to 29 mN/m; E24 = 87%	Stable under varying pH, NaCl, and temperature conditions	91% crude-oil biodegradation	Rehman et al. (2021)
Sophorolipid / <i>Meyerozyma</i> sp. MF138126	50	ST reduced to 33 mN/m; E24 = 84%	Stable under varying pH, NaCl, and temperature conditions	87% crude-oil biodegradation	Rehman et al. (2021)
Sophorolipid / <i>Candida bombicola</i> ATCC 22214	NR	ST: 53.69 -> 28.56 mN/m; IFT: 23.37 -> 2.13	Stable up to 100°C; 13-15% NaCl; pH 2-12	27.27% additional residual-oil recovery (core flood)	Elshafie et al. (2015)

Biosurfactant Type / Microbial Origin	CMC (mg/L)	SF/IFT Reduction (mN/m)	Temperature and Salinity Tolerance	Recovery / Biodegradation Efficiency	Reference
		mN/m (72 h)			
<i>Sophorolipid / Candida keroseneae GBME-IAUF-2</i>	NR	ST: 72 → 29.1 mN/m; maximum E24 = 60%	92.06-97.25% activity retained at 110-120°C; 96.66-100% in tested extreme salinity	High MEOR potential; no core-flood recovery reported	Ganji et al. (2020)
<i>Rhamnolipid / Pseudomonas aeruginosa</i>	NR	IFT reduction identified as the principal displacement mechanism	Reported stable under high salinity, pH, pressure, and temperature conditions	15.47% additional oil recovery at 200 ppm (porous media)	Sakthipriya et al. (2021)

Note. ST = surface tension, IFT = interfacial tension, CMC = critical micelle concentration, E24 = 24-h emulsification index, NR = not reported in the cited study. Surfactin is discussed in the text only as a lipopeptide comparator and is not included in the glycolipid evidence table.

Hydrocarbon Mobilization and Wax-Related Implications

For high-wax crude oil, glycolipid biosurfactants are most relevant for their ability to interact with hydrophobic hydrocarbon fractions through emulsification, solubilization, and micellar association. Above the CMC, biosurfactant molecules self-assemble into aggregates with hydrophobic domains that can increase the apparent accessibility and dispersion of petroleum components. These mechanisms matter in waxy systems because poorly mobile paraffinic fractions can restrict flow when they precipitate or accumulate.

However, the reviewed sources do not provide sufficient evidence to support a general claim of a 20-30% bulk crude-oil viscosity reduction. [Patowary et al. \(2018\)](#) evaluated 1.5 g/L crude biosurfactant (CBS) produced by *P. aeruginosa* SR17 in crude-oil-contaminated soil, whereas [Rehman et al. \(2021\)](#) primarily reported emulsification and crude-oil biodegradation. These studies support enhanced hydrocarbon accessibility and degradation, but they do not establish the previously stated 20-30% viscosity reduction under reservoir conditions. Therefore, viscosity reduction should be discussed as a potential consequence of hydrocarbon dispersion or compositional modification rather than as a quantitatively verified result of these studies.

Interfacial-Tension Reduction and Wettability Alteration

Interfacial-tension (IFT) reduction and wettability alteration provide the strongest physicochemical basis for glycolipid-assisted oil displacement. Biosurfactant molecules adsorb at the oil-water interface and reduce interfacial free energy, thereby decreasing capillary forces that retain residual oil in pore spaces. [Elshafie et al. \(2015\)](#) reported an oil-water IFT of 2.13 mN/m for *C. bombicola*-derived sophorolipids under the reported test conditions. This low IFT was accompanied by measurable tertiary recovery in sandstone cores, linking interfacial activity directly with oil displacement.

A complementary mechanism was reported by [Hou et al. \(2022\)](#), who investigated sophorolipids in combination with silica nanoparticles. The combined system enhanced structural disjoining pressure and shifted mineral-surface wettability away from oil-wet conditions,

supporting the liberation of strongly retained heavy-hydrocarbon fractions. Taken together, these studies show that EOR performance is not governed by IFT alone. Wettability, mineral surface interactions, pore structure, adsorption, emulsification, and operating conditions can act simultaneously, which helps explain why biosurfactants with similar surface activity do not necessarily produce identical recovery increments.

Critical Comparison of Experimental Evidence

The reviewed evidence can be separated into two principal categories: direct displacement experiments and supporting hydrocarbon-degradation studies. Core-flooding and porous-media experiments provide the stronger evidence for EOR because they directly measure hydrocarbon displacement through porous rock. [Elshafie et al. \(2015\)](#) reported 27.27% additional residual-oil recovery with sophorolipids, while [Sakthipriya et al. \(2021\)](#) reported approximately 15.4% additional oil recovery using 200 ppm rhamnolipid in porous sandstone media. These results directly support the ability of glycolipid biosurfactants to improve oil displacement.

[Sakthipriya et al. \(2021\)](#) also evaluated surfactin under the same experimental framework. Surfactin is a lipopeptide rather than a glycolipid; therefore, it is included only as a microbial-biosurfactant comparator and should not be interpreted as part of the glycolipid evidence base. Its inclusion is useful because it provides a direct benchmark against which rhamnolipid performance can be compared under similar porous-media conditions.

In contrast, [Patowary et al. \(2018\)](#), [Feng et al. \(2021\)](#), and [Rehman et al. \(2021\)](#) mainly provide evidence of biodegradation or bioremediation. Reported total petroleum hydrocarbon degradation reached 57.7-86.1% in the soil-based studies, while [Rehman et al. \(2021\)](#) reported crude-oil biodegradation efficiencies of 91% for *P. aeruginosa* and 87% for *Meyerozyma* sp. These findings demonstrate improved hydrocarbon accessibility and microbial utilization, but they cannot be directly converted into expected tertiary oil recovery because the mechanisms, timescales, and environmental conditions differ substantially from reservoir displacement.

Overall, the reviewed evidence indicates that glycolipid biosurfactants combine several mechanisms relevant to high-wax crude-oil recovery, including IFT reduction, wettability modification, emulsification, and improved hydrocarbon accessibility. However, the strength of the evidence differs across studies. Direct porous-media experiments provide the most relevant evidence for incremental oil recovery, whereas biodegradation and bioremediation studies mainly provide mechanistic support. By explicitly separating these evidence types and interpreting them in the context of high-wax crude-oil systems, this review provides a clearer, more technically defensible synthesis of glycolipid-based EOR performance and identifies the need for additional reservoir-condition core-flood and field-scale validation.

CONCLUSIONS

This narrative review indicates that glycolipid biosurfactants, particularly rhamnolipids and sophorolipids, have promising potential for enhanced oil recovery (EOR) in high-wax crude-oil systems through interfacial-tension reduction, wettability alteration, emulsification, and improved hydrocarbon accessibility. Direct porous-media studies reported approximately 15.47–27.27% additional oil recovery, while biodegradation and bioremediation studies provided supporting evidence of strong biosurfactant-hydrocarbon interactions. The reviewed data also show that biosurfactant stability depends on formulation and strain; for example, *Candida bombicola*-derived sophorolipids were reported to remain stable up to 100°C and 13–15% NaCl, whereas *Candida keroseneae*-derived sophorolipids retained high activity at 110–120°C under the tested conditions.

This review's main contribution is the critical separation of direct EOR evidence from supporting biodegradation and bioremediation evidence, providing a clearer basis for interpreting

glycolipid performance specifically in high-wax reservoirs. Overall, the available evidence supports glycolipid biosurfactants as promising sustainable EOR agents, but the present conclusions should be interpreted within the predominantly laboratory-scale evidence base.

LIMITATIONS & FURTHER RESEARCH

This review is limited to 14 selected studies and did not apply a formal risk-of-bias or study-quality grading framework. The literature search was restricted to ScienceDirect, PubMed, and SpringerLink and primarily to English-language publications, which may have introduced database and language bias. In addition, much of the available evidence derives from laboratory characterization, soil bioremediation, and biodegradation studies rather than reservoir-condition displacement experiments. Study screening was conducted without an independent second reviewer; borderline inclusion decisions were resolved through team discussion rather than independent duplicate screening. Field- and pilot-scale evidence also remains scarce. Consequently, any screening criteria or engineering ranges derived from this review should be regarded as provisional and should not be interpreted as field-validated design limits.

Practical Implications and Future Research

For practical application, biosurfactant selection should be based on reservoir-specific temperature, salinity, pH, rock-fluid interactions, adsorption behavior, and the concentration required to achieve effective interfacial activity. A 0.2–0.5 pore-volume injection slug may be examined only as a preliminary engineering extrapolation for future sensitivity analysis; this range was not directly established by the 14 reviewed studies and therefore should not be treated as a validated field recommendation.

Future research should prioritize core-flood experiments using high-wax crude oil under representative reservoir pressure, temperature, salinity, and anaerobic conditions, together with adsorption and retention measurements, long-term thermal stability assessment, reservoir-scale simulation, and techno-economic evaluation. These steps should be followed by carefully designed pilot tests to determine the technical and economic feasibility of glycolipid-based EOR under field conditions.

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