RSF Conference Proceeding Series: Engineering and Technology Vol. 4 No. 1 (2025) https://doi.org/10.31098/

Check for updates

Research Paper

Effect of Rhamnolipid Biosurfactant on Enhanced Oil Recovery Through Imbibition Performance of Crude Oils: A Literature Review

Harry Budiharjo Sulistyarso[1*], Indah Widiyaningsih[1], Rahma Mustika[1], Yulius Deddy Hermawan[1], Joko Pamungkas[1], Sayoga Heru Prayitno[1]

[1]UPN Veteran Yogyakarta, Indonesia

Received: September 15, 2025	Revised: September 25, 2025	Accepted: September 29, 2025	Online: October 15, 2025

Abstract

Biosurfactants applied in enhanced oil recovery (EOR) have attracted significant attention due to their biodegradability, low toxicity, and ability to modify the interactions between oil, rock, and brine. Rhamnolipids—glycolipid biosurfactants synthesized by bacterial species—have a unique amphipathic structure that can alter the characteristics of crude oil at the molecular and macroscopic levels. This study examines the impact of rhamnolipid biosurfactant on the imbibition performance of crude oils, exploring it as a potential green alternative to conventional surfactants. Laboratory experiments were designed to evaluate the reduction of interfacial tension and oil displacement efficiency under various reservoir conditions. The results demonstrate that rhamnolipid significantly enhances oil recovery by promoting water-wet conditions and improving spontaneous imbibition rates, with recovery increments surpassing those observed in conventional systems. The novelty of this work lies in the direct integration of rhamnolipid biosurfactant into imbibition-driven recovery processes, which has rarely been addressed in previous EOR studies. While prior works have primarily focused on coreflooding and micellar flooding performance, this study provides mechanistic insights into how rhamnolipids modulate capillary forces and rock–fluid interactions during imbibition. By coupling environmental sustainability with improved oil recovery efficiency, the findings highlight rhamnolipid as a dual-function agent—both as an effective surfactant and as a sustainable alternative for next-generation EOR strategies.

Keywords *rhamnolipids, biosurfactant, chemical composition, imbibition, enhanced oil recovery*

INTRODUCTION

Biosurfactants, especially rhamnolipids synthesized by Pseudomonas spp., have surfaced as eco-friendly agents for Enhanced Oil Recovery (EOR) because to their low toxicity, biodegradability, and potent interfacial activity that can alter oil–brine–rock interactions. Recent research indicates that rhamnolipids significantly decrease surface tension and stabilize oil-water dispersions, facilitating enhanced mobilization of entrapped hydrocarbons while adhering to sustainability principles (Ahmad et al., 2021; Zeng et al., 2018; Zhao et al., 2015).

Despite comprehensive studies demonstrating the effectiveness of rhamnolipids in diminishing interfacial tension (IFT), forming emulsions/nanoemulsions, and promoting hydrocarbon dispersion, the mechanistic relationships between molecular compositional alterations in crude oil and core-scale imbibition performance remain insufficiently explored—especially regarding light versus medium crude oils. Most studies concentrate on either (i) compositional or remediation endpoints (e.g., GC–MS fingerprints during biodegradation) or (ii) petrophysical outcomes such as wettability alteration and spontaneous imbibition, rarely integrating both across various crude grades utilizing a singular biosurfactant chemistry (Lu et al., 2023; Sharma et al., 2023; Wang et al., 2023).

Simultaneous progress has clarified the physics of imbibition and the design parameters, including surfactant type, salinity, and nanoparticle/surfactant hybrids. Studies on spontaneous imbibition in sandstone and carbonate formations have demonstrated that surfactant-induced

Corresponding author's email: harry_hb@upnyk.ac.id

wettability modification and reduction of interfacial tension can significantly enhance oil recovery.

Methodological advancements, including the identification of optimal surfactant concentration via spontaneous imbibition prior to forced imbibition or CO_2 co-injection, have produced enhanced outcomes. Nevertheless, these efforts seldom align with biosurfactant-specific alterations in crude composition, as verified by GC–MS (Austad & Standnes, 2003; Standnes, 2001).

Biosurfactants have demonstrated the ability to reduce crude oil viscosity and improve flowability through dispersion and emulsification. Rhamnolipid-stabilized oil-in-water nanoemulsions exemplify this effect across various pH and salinity conditions. However, a quantitative comparative analysis of viscosity differences in rhamnolipid–crude mixtures for light versus medium crudes, alongside simultaneous compositional and imbibition metrics, is lacking—especially under ionic conditions pertinent to enhanced oil recovery (Ahuekwe et al., 2016; Gayathiri et al., 2022; Hadia et al., 2019).

This study aims to investigate spontaneous imbibition in representative core samples to establish a mechanistic relationship between the composition, rheology, and capillarity of rhamnolipid biosurfactants. We assert that rhamnolipids selectively modify the distribution of hydrocarbon classes (e.g., enhancing the solubility of specific aromatics and n-alkanes) and reduce the viscosity of the mixture and interfacial tension (IFT), thereby improving performance via spontaneous imbibition. This comprehensive, multidimensional approach aims to develop formulation strategies for enhanced oil recovery (EOR) using biosurfactants, directly applicable to field conditions.

LITERATURE REVIEW

Rhamnolipids, biosurfactants, have emerged as eco-friendly agents for Enhanced Oil Recovery (EOR) due to their low toxicity, biodegradability, and potent interfacial activity, which can alter oil–brine–rock interactions. Rhamnolipids significantly reduce surface tension and stabilize oil-water dispersion, and are more effective in facilitating the mobilization of trapped hydrocarbons while adhering to sustainability principles. The literature study in this research compiled information on the latest developments in biosurfactant applications for enhanced oil recovery (EOR), with a particular focus on rhamnolipids. A summary of relevant studies is presented in Table 1.

Table 1. Summary of Literature Studies

Title	Object	Description
Impactof Biosurfactants, Surfactin, and Rhamnolipid Produced from Bacillussubtilis and Pseudomonas aeruginosa, on the Enhanced Recovery of Crude Oil and Its Comparison with Commercial Surfactants (Sakthipriya et al., 2021).	The main objective of this study is to recover crude oil using biosurfactants produced by microorganisms.	The study identifies a gap in the understanding of the performance of biosurfactants in microbial-enhanced oil recovery (MEOR) within porous media.
Rhamnolipids Produced by Indigenous Acinetobacter junii from Petroleum Reservoir and its Potential in Enhanced Oil Recovery (Dong et al., 2016).	The main objective of this study is isolate a novel biosurfactant-producing strain, Acinetobacter junii BD, from a petroleum reservoir.	The study aimed to evaluate the ability of the isolated strain to reduce surface tension and emulsify crude oil.

Application of rhamnolipid biosurfactant produced by Pseudomonas aeruginosa in microbial enhanced oil recovery (MEOR) (Câmara et al., 2019).	The main objective of this study is evaluate the effectiveness of biosurfactants produced by Pseudomonas aeruginosa for use in Microbial Enhanced Oil Recovery (MEOR).	This study aims to compare the effects of different concentrations of rhamnolipids above the critical micelle concentration (CMC) on oil recovery efficiency.
Di- and Mono-Rhamnolipids Produced by the Pseudomonas putida PP021 Isolate Significantly Enhance the Degree of Recovery of Heavy Oil from the Romashkino Oil Field (Tatarstan, Russia) (Biktasheva et al., 2022).	The main objective of this study is obtain and characterize biosurfactants produced by the Pseudomonas putida PP021 isolate.	The study focuses on the potential of biosurfactants, specifically those produced by the Pseudomonas putida PP021 isolate, as an environmentally friendly alternative for enhancing oil recovery.
Controlled Salinity-Biosurfactant Enhanced Oil Recovery at Ambient and Reservoir Temperatures—An Experimental Study (Udoh & Vinogradov, 2021).	The main objective of this study is investigate enhanced oil recovery through controlled salinity-biosurfactant injection under typical reservoir temperature conditions.	This research is the first thorough experimental study to explore the combined effects of controlled salinity brine and biosurfactants on oil recovery in carbonate rock samples.
A Novel Biosurfactant-Based Oil Spill Response Dispersant for Efficient Application under Temperate and Arctic Conditions. (Farooq et al., 2024).	The main objective of this study is develop sustainable alternatives to synthetic oil spill dispersants by utilizing natural biosurfactants.	This study investigates the interfacial properties of various glycolipid-based biosurfactants and their efficacy in dispersing crude oil in seawater.
Basis for formulating biosurfactant mixtures to achieve ultra low interfacial tension values against hydrocarbons (Youssef et al., 2007).	The main objective of this study is formulate biosurfactant and synthetic surfactant mixtures that achieve ultra low interfacial tension (IFT) values against light non-aqueous phase liquids (LNAPLs).	The research aims to formulate biosurfactant and synthetic surfactant mixtures that can achieve ultra-low IFT values, enhancing the effectiveness of remediation efforts against LNAPLs.
Rhamnolipid produced by Pseudomonas aeruginosa USM-AR2 facilitates crude oil distillation (Noh et al., 2012).	The main objective of this study is evaluate the effectiveness of rhamnolipid produced by Pseudomonas aeruginosa USM-AR2 in facilitating the distillation process of crude oil.	This paper discusses the use of Pseudomonas aeruginosa USM-AR2, a biosurfactant-producing and hydrocarbon-utilizing bacterium, to enhance the conventional distillation process of crude oil.
A detailed and systematic study on rheological and physicochemical properties of rhamnolipid biosurfactant	The main objective of this study is conduct a detailed and systematic investigation of the rheological	The paper focuses on rhamnolipid, a bacterial biosurfactant produced by Pseudomonas aeruginosa,

solutions (Khan & Sasmal, 2022).	characterization of rhamnolipid biosurfactant solutions.	which is widely used in various industrial applications, including cosmetics and the petroleum industry.
An industrially potent rhamnolipid-like biosurfactant produced from a novel oil-degrading bacterium, Bacillus velezensis S2 (Sultana et al., 2024).	The main objective of this study is produce a biosurfactant from the oil-degrading bacterium Bacillus velezensis S2.	The study focuses on the isolation of a novel oil-degrading bacterium, Bacillus velezensis S2, from oil-contaminated sites, which demonstrates significant crude oil degradation.

RESEARCH METHOD

This study was designed as a spontaneous imbibition-based laboratory experiment combined with mechanistic analysis to evaluate the effect of rhamnolipid biosurfactants on oil recovery efficiency. The research design focused on measuring interfacial tension (IFT), wettability alteration, and oil recovery factor (RF) by comparing rhamnolipid systems, commercial surfactants, and conventional brine as a control.

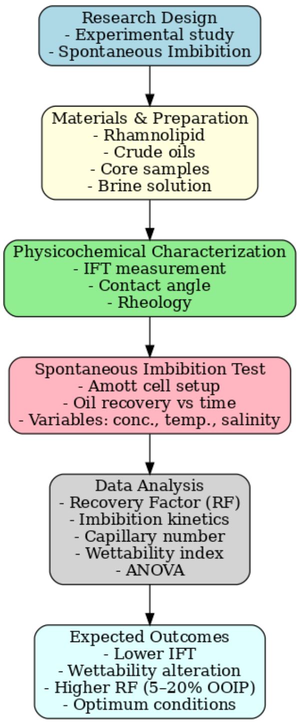

Figure 1. Research Flowchart

FINDINGS AND DISCUSSION

Comparative Performance of Biosurfactants vs Chemical Surfactants

Biosurfactants, including rhamnolipids and lipopeptides (e.g., surfactin), exhibit oil recovery efficiency comparable to that of traditional chemical surfactants, while offering the advantages of reduced toxicity and biodegradability. In a research, 200 ppm of surfactin and rhamnolipid each produced around a 15.4% increase in oil recovery, comparable to or marginally superior to a conventional synthetic surfactant under the same conditions. This verifies that microbial surfactants can equal the efficacy of petrochemical surfactants in mobilizing residual oil. Furthermore, in contrast to several chemical surfactants that provide environmental risks owing to their non-biodegradable and harmful characteristics, biosurfactants serve as more environmentally benign alternatives. Their application in Enhanced Oil Recovery (EOR) can enhance sustainability by reducing the environmental impact of oil production. Researchers have observed that the application of biosurfactants in enhanced oil recovery yields significant results comparable to synthetic surfactants, without the disadvantages of environmental persistence or toxicity. These findings provide compelling evidence for replacing or augmenting conventional surfactants with biosurfactants in reservoir operations.

Mechanisms of Oil Recovery by Rhamnolipids

The efficacy of biosurfactants in oil recovery is primarily attributed to two fundamental mechanisms: a decrease in interfacial tension (IFT) and modification of wettability. Biosurfactant molecules possess amphiphilic properties and spontaneously aggregate at oil-water interfaces, where they markedly reduce the interfacial tension between the entrapped oil and the brine. A minimal quantity of rhamnolipids can diminish water's surface tension from approximately 72 mN/m to around 30 mN/m or lower. The significant reduction in interfacial tension facilitates the mobilization of oil droplets formerly retained in pores by capillary forces. Experiments demonstrate that the injection of a rhamnolipid solution into an oil-saturated medium liberates otherwise entrapped oil by augmenting the capillary number, thereby surmounting capillary resistance. Biosurfactants can concurrently modify the wettability of rock surfaces from oil-wet to water-wet conditions. This alteration in wettability enhances oil displacement, allowing water to penetrate pores and expel oil more readily. A reservoir-isolated strain of Acinetobacter junii, which produces rhamnolipids, was observed to enhance oil recovery in a glass micromodel by reducing interfacial tension and modifying the wettability of pore surfaces. The emulsification of crude oil is an additional result of biosurfactant activity. Rhamnolipids and other glycolipids form stable oil-in-water emulsions, efficiently dispersing oil into smaller droplets.

This emulsification enhances the fluidity of thick crude. In summary, by significantly decreasing interfacial tension and altering wettability, biosurfactants facilitate the flow of previously trapped oil, which is the primary reason for their effectiveness in microbial enhanced oil recovery (MEOR).

Spontaneous Imbibition of Rhamnolipids

The literature review shows that the use of rhamnolipid biosurfactants has a significant impact on the efficiency of spontaneous imbibition in the Enhanced Oil Recovery (EOR) process. The primary mechanism identified is a combination of a decrease in interfacial tension (IFT) and a change in rock wettability towards a more water-wet state, which directly increases the adequate capillary pressure. Studies by Dong et al. (2016) and Câmara et al. (2019) confirm that rhamnolipid biosurfactants can accelerate the imbibition rate and increase the recovery factor (RF) compared to conventional brine, even in reservoirs with high salinity. Furthermore, research by Biktasheva et al. (2022) on heavy oil shows that rhamnolipid-based imbibition can overcome the limitations of viscous oil mobility by reducing residual oil saturation through the release of smaller oil droplets. This efficiency is even more evident in carbonate reservoirs, which tend to be oil-wet, where spontaneous imbibition is usually inhibited. Udoh and Vinogradov (2021) demonstrated that combining controlled salinity waterflooding with biosurfactants resulted in a significant incremental recovery. Overall, this analysis confirms that the novelty of the research lies in the direct testing of the effect of rhamnolipids in the spontaneous imbibition mechanism. This capillary pathway has been relatively unexplored in previous EOR literature, which has generally focused on core flooding or micellar flooding. Thus, this research not only expands our understanding of the role of rhamnolipids in enhancing recovery but also opens up the potential for their application as an environmentally friendly and cost-effective solution for carbonate and sandstone reservoirs with varying wettability conditions.

CONCLUSIONS

It can be concluded that rhamnolipid biosurfactants exhibit efficacy equivalent to, and potentially superior to, traditional chemical surfactants in enhancing oil recovery, while also being environmentally benign and biodegradable. The primary mechanisms involve a substantial decrease in interfacial tension, an alteration in rock wettability that favors a more water-wet state, and the capacity to emulsify oil, thereby enhancing fluid movement. The role of rhamnolipids in the spontaneous imbibition process improves both the rate and efficiency of oil recovery, even in challenging reservoir conditions such as heavy oil and oil-wet carbonate formations. This validates the originality of the research by emphasizing the direct involvement of rhamnolipids in the spontaneous imbibition mechanism, while presenting prospects for its use as a more sustainable and cost-effective enhanced oil recovery option.

LIMITATIONS & FURTHER RESEARCH

Although this study highlights the potential of rhamnolipid biosurfactants to enhance imbibition-driven oil recovery, several limitations remain that warrant further investigation. The experiments primarily focused on simplified laboratory conditions, which may not fully replicate the complex thermochemical environments of real reservoirs, such as variable salinity, temperature, and pressure. Additionally, the interaction between rhamnolipid molecules and diverse crude oil compositions—especially heavy crudes rich in asphaltenes—remains underexplored. Future research should extend toward multiscale analyses that couple laboratory imbibition tests with molecular dynamics simulations and field-scale modeling to better understand interfacial phenomena at pore and reservoir levels. Moreover, long-term stability, biodegradation kinetics, and economic feasibility assessments of rhamnolipid formulations are essential to validate their scalability for industrial EOR applications and ensure alignment with sustainability and carbon reduction objectives.

ACKNOWLEDGEMENTS

This research was funded by Lembaga Penelitian dan Pengabdian Masyarakat (LPPM) UPN Veteran Yogyakarta.

REFERENCES

Ahmad, Z., Zhang, X., Imran, M., Zhong, H., Andleeb, S., Zulekha, R., Liu, G., Ahmad, I., & Coulon, F. (2021). Production, functional stability, and effect of rhamnolipid biosurfactant from Klebsiella sp. on phenanthrene degradation in various medium systems. *Ecotoxicology and Environmental Safety*, *207*, 111514. https://doi.org/10.1016/j.ecoenv.2020.111514

Ahuekwe, E. F., Okoli, B. E., Stanley, H. O., & Kinigoma, B. (2016). Evaluation of hydrocarbon emulsification and heavy metal detoxification potentials of sophorolipid biosurfactants produced from waste substrates using yeast and mushroom. *Society of Petroleum Engineers - SPE African Health, Safety, Security and Environment and Social Responsibility Conference and Exhibition 2016*, *October*, 81–96. https://doi.org/10.2118/183578-ms

Austad, T., & Standnes, D. C. (2003). Spontaneous imbibition of water into oil-wet carbonates. *Journal of Petroleum Science and Engineering*, *39*(3–4), 363–376. https://doi.org/10.1016/S0920-4105(03)00075-5

Biktasheva, L., Gordeev, A., Selivanovskaya, S., & Galitskaya, P. (2022). Di- and Monorhamnolipids Produced by the Pseudomonas putida PP021 Isolate Significantly Enhance the Degree of Recovery of Heavy Oil from the Romashkino Oil Field (Tatarstan, Russia). *Processes*, *10*(4). https://doi.org/10.3390/pr10040779

Câmara, J. M. D. A., Sousa, M. A. S. B., Barros Neto, E. L., & Oliveira, M. C. A. (2019). Application of rhamnolipid biosurfactant produced by Pseudomonas aeruginosa in microbial-enhanced oil recovery (MEOR). *Journal of Petroleum Exploration and Production Technology*, *9*(3), 2333–2341. https://doi.org/10.1007/s13202-019-0633-x

Dong, H., Xia, W., Dong, H., She, Y., Zhu, P., Liang, K., Zhang, Z., Liang, C., Song, Z., Sun, S., & Zhang, G. (2016). Rhamnolipids produced by indigenous Acinetobacter junii from petroleum reservoir and its potential in enhanced oil recovery. *Frontiers in Microbiology*, *7*(NOV), 1–13. https://doi.org/10.3389/fmicb.2016.01710

Farooq, U., Szczybelski, A., Ferreira, F. C., Faria, N. T., & Netzer, R. (2024). A Novel Biosurfactant-Based Oil Spill Response Dispersant for Efficient Application under Temperate and Arctic Conditions. *ACS Omega*, *9*(8), 9503–9515. https://doi.org/10.1021/acsomega.3c08429

Gayathiri, E., Prakash, P., Karmegam, N., Varjani, S., Awasthi, M. K., & Ravindran, B. (2022). Biosurfactants: Potential and Eco-Friendly Material for Sustainable Agriculture and Environmental Safety—A Review. *Agronomy*, *12*(3), 1–35. https://doi.org/10.3390/agronomy12030662

Hadia, N. J., Ottenheim, C., Li, S., Hua, N. Q., Stubbs, L. P., & Lau, H. C. (2019). Experimental investigation of biosurfactant mixtures of surfactin produced by Bacillus Subtilis for EOR application. *Fuel*, *251*(May), 789–799. https://doi.org/10.1016/j.fuel.2019.03.111

Khan, M. B., & Sasmal, C. (2022). A detailed and systematic study on rheological and physicochemical properties of rhamnolipid biosurfactant solutions. *JCIS Open*, *8*(October), 100067. https://doi.org/10.1016/j.jciso.2022.100067

Lu, L., Rughöft, S., Straub, D., Joye, S. B., Kappler, A., & Kleindienst, S. (2023). Rhamnolipid Biosurfactants Enhance Microbial Oil Biodegradation in Surface Seawater from the North Sea. *ACS ES and T Water*, *3*(8), 2255–2266. https://doi.org/10.1021/acsestwater.3c00048

Md Noh, N. A., Abdullah, A. A. A., Mohamad Ibrahim, M. N., & Mohd Yahya, A. R. (2012). Rhamnolipid produced by Pseudomonas aeruginosa USM-AR2 facilitates crude oil distillation. *Journal of General and Applied Microbiology*, *58*(2), 153–161. https://doi.org/10.2323/jgam.58.153

Sakthipriya, N., Kumar, G., Agrawal, A., Doble, M., & Sangwai, J. S. (2021). Impact of Biosurfactants, Surfactin, and Rhamnolipid Produced fromBacillus subtilisandPseudomonas aeruginosa, on the Enhanced Recovery of Crude Oil and Its Comparison with Commercial Surfactants. *Energy and Fuels*, *35*(12), 9883–9893. https://doi.org/10.1021/acs.energyfuels.1c00679

Sharma, N., Lavania, M., & Lal, B. (2023). Biosurfactant: an emerging tool for the petroleum industries. *Frontiers in Microbiology*, *14*(September), 1–7. https://doi.org/10.3389/fmicb.2023.1254557

Standnes, D. (2001). *Enhanced Oil Recovery from Oil-Wet Carbonate Rock by Spontaneous Imbibition of Aqueous Surfactant Solutions.* *1*(1285), 90. http://mdh.diva-portal.org/smash/record.jsf?pid=diva2:121656%5Cn

Sultana, S., Sultana, R., Al-Mansur, M. A., Akbor, M. 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

Udoh, T., & Vinogradov, J. (2021). Controlled salinity-biosurfactant enhanced oil recovery at ambient and reservoir temperatures—an experimental study. *Energies*, *14*(4). https://doi.org/10.3390/en14041077

Wang, H., You, Q., Zhang, T., Adenutsi, C. D., & Gao, M. (2023). Experimental Investigation on Spontaneous Imbibition of Surfactant Mixtures in Low Permeability Reservoirs. *ACS Omega*, *8*(15), 14171–14176. https://doi.org/10.1021/acsomega.3c00973

Youssef, N. H., Nguyen, T., Sabatini, D. A., & McInerney, M. J. (2007). Basis for formulating biosurfactant mixtures to achieve ultra low interfacial tension values against hydrocarbons. *Journal of Industrial Microbiology and Biotechnology*, *34*(7), 497–507. https://doi.org/10.1007/s10295-007-0221-9

Zeng, Z., Liu, Y., Zhong, H., Xiao, R., Zeng, G., Liu, Z., Cheng, M., Lai, C., Zhang, C., Liu, G., & Qin, L. (2018). Mechanisms for rhamnolipids-mediated biodegradation of hydrophobic organic compounds. *Science of the Total Environment*, *634*, 1–11. https://doi.org/10.1016/j.scitotenv.2018.03.349

Zhao, F., Shi, R., Zhao, J., Li, G., Bai, X., Han, S., & Zhang, Y. (2015). Heterologous production of Pseudomonas aeruginosa rhamnolipid under anaerobic conditions for microbial enhanced oil recovery. *Journal of Applied Microbiology*, *118*(2), 379–389. https://doi.org/10.1111/jam.12698.