Revolutionizing Oil Extraction: Lechinysin's Potential in Microbial Enhanced Oil Recovery as a Biosurfactant

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Abstract:
As conventional oil recovery techniques have numerous deficiencies in oil recovery rate (up to 40% OOIP), process safety, financial aspects, sustainability and environmental impacts other efficient techniques like MEOR had been invented that utilize microbes or their metabolites like biosurfactants to enhance oil recovery process from depleted reservoirs and increase the recovery rate up to 50% of remained oil in the reservoirs. Biosurfactants are the interesting chemicals that encompass a large group of compounds with unique properties to play crucial role in improving oil recovery. Among biosurfactants, lichenysin produced by B. licheniformis or B. mojavensis Jf-2 and it has several different variants based on the producing strains. It is an alternative candidate with amazing features like stability in extremely high temperature up to 140 °C, saving its optimal activity in a wide range of pH values from 6 up to 10 pH, high salinity up to 10% NaCl concentration, and a significant CMC from 10 to 20 mg/L that is the lowest CMC among studied biosurfactants suitable for MEOR. All these characteristics indicate its significance as a biosurfactant that has the capability to revolutionize the MEOR technique in the future.

Keywords: Biosurfactant, Lichenysin, Interfacial Tension Reduction, Wettability Alteration, Microbial Enhanced Oil Recovery.

Introduction
Traditional oil extraction methods, both in offshore and onshore settings, face several challenges that can impact efficiency, safety, and environmental sustainability. Here are some of the key challenges associated with traditional oil extraction methods:
extraction methods: 1- They can be extremely expensive due to the need for specialized equipment, infrastructure, and regulatory compliance. 2- Traditional oil extraction methods can have significant environmental impacts, particularly in offshore drilling. The potential for oil spills and leaks during drilling and extraction operations poses a risk to marine ecosystems and wildlife. Additionally, the release of greenhouse gases and other pollutants during the extraction and refining process contributes to climate change and air pollution. 3- There are limited resources for traditional oil extraction methods, because, they rely on finite resources, such as fossil fuels, which are becoming increasingly scarce. As oil reserves deplete, companies face the challenge of finding new sources and developing more efficient extraction techniques. Besides, technological limitations and safety risks for workers are other challenges of traditional oil recovery techniques (Sharma et al., 2022). All these limitations make the researchers to find new techniques for extracting oil optimally and effectively from the reservoirs.

Unlike conventional oil recovery techniques which is hindered by existing drawbacks, microbial enhanced oil recovery (MEOR) stands out as one of the innovative approaches that can be used as an alternative technique. Microbial-enhanced oil recovery (MEOR) encompasses the infiltration of live microorganisms and/or nutrient solutions that provide a friendly environment for microbial growth in the oil reservoirs. This process produces metabolites which promoted the movement of oil as well as its excavation. Denoted as an effective enhanced oil recovery technology, MEOR appears at the end of the primary and secondary recovery methods utilization. Instead of the existing strategies such as miscible gas injection, polymer flooding and thermal methods that normally recover between 10 to 40% of the original oil in place (OOIP), MEOR is capable of recovering of about 50% of the remaining oil (Quraishi et al., 2021). The inoculated microorganisms grow very fast, producing metabolites which are essential for the oil mobilization and recovery. Due to its capability to increase considerably the oil recovery rates, thus MEOR works as a helpful replacement of the traditional methods.

From numerous types of metabolites, that play a role in MEOR process, biosurfactants stand out as the most important group of these which required for the best performance of this process. Microbial biosurfactants are in charge as crucial factor in this context, which is a substance produced by microorganisms like bacteria. The presence of these compounds has attracted attention because of their unique characteristics and their ability to find applications in all industries, such as the oil and gas industry. Biosurfactants are generally classified to a number of families (for instance, glycolipids, lipopeptides, phospholipids, and polymeric biosurfactants) according to their chemical structure and the microbial origin. They create the conditions in which oil has a tendency to flow and recover by reducing intermolecular interaction and consequent reduction of surface tension, which plays an important role in the formation of emulsions and wettability (Khire 2010).

Lichenysin, Its Microbial Origin and Unique Features

Lichenysin, an anionic cyclic lipoheptapeptide biosurfactant, of Bacillus licheniformis is a powerful component. The key characteristic of this chemical is its ability to curtail the water surface tension, what resulted in applications in different industrial sectors and oil recovery from reservoirs. The variants of lichenysin, i.e., lichenysin A, B, C, D, G and surfactant BL86, produced by different different strains of B. licheniformis. It is noted that lichenysin synthetase - a multienzyme complex that bears resemblance to the structure and biosynthesis of surfactin - is partly responsible for its formation. Structurally, lichenysin is similar to surfactin, though there are certain modifications as shown by Figure 1. The homology to surfactin makes it a potential candidate for oil recovery by the methods of microbial enhanced oil recovery (MEOR) (Nerurkar 2010).
Lichenysin is a biosurfactant produced by different microorganisms, particularly Bacillus licheniformis that recently reclassified as Bacillus mojavensis JF-2, which has gained attention for its potential application in MEOR processes. Biosurfactants, such as lichenysin, play a crucial role in MEOR by reducing the interfacial tension between oil and water, enhancing oil mobilization, and improving oil recovery efficiency. Lichenysin is primarily produced by Bacillus licheniformis, a Gram-positive bacterium commonly found in soil and various environments (Dias & Nitschke 2023). This bacterium has been extensively studied for its ability to produce biosurfactants, including lichenysin. Bacillus licheniformis produces lichenysin through a fermentation process. The bacterium secretes lichenysin into the surrounding environment, where it acts as a surfactant, reducing the surface tension between oil and water. Lichenysin has shown promising potential in MEOR applications. Its surfactant properties enable it to enhance the mobilization of trapped oil, improve oil flow through porous reservoir rocks, and increase oil recovery rates (Pang et al., 2022).

Lichenysin is named a cyclic lipoheptapeptide biosurfactant due to its combination of a lipid part that is shortly called (lipo) and a seven amino acid peptide or heptapeptide. It possesses the following unique characteristics that make it suitable for use as a biosurfactant in MEOR. 1- It has the ability to significantly lower the surface tension of water, reducing it from 72 to 27 mN/m and decreases interfacial tension against decane, with a value as low as 6x10⁻³ mN/m. These properties are crucial in MEOR as they help to improve the spreading and wetting of the biosurfactant on the oil-water interface, facilitating the mobilization and recovery of trapped oil (Figure 2a). 2- It is an anionic biosurfactant, meaning it carries a negative charge. This characteristic enhances its ability to interact with and solubilize hydrophobic compounds, such as oil, by forming stable micelles that results to emulsification (Figure 2b). The anionic nature of lichenysin also contributes to its stability and effectiveness in harsh environments, including high salinity conditions often found in oil reservoirs. 3- Lichenysin demonstrates high biosurfactant activity, as evidenced by its low Critical Micelle Concentration (CMC) of 10 mg/L under optimal conditions (Nerurkar 2010). The low CMC indicates that only a small amount of lichenysin is required to achieve effective surfactant activity, making it a cost-effective option for MEOR applications. In addition, 4- It is synthesized through a nonribosomal biosynthesis pathway, involving a multienzyme complex called lichenysin synthetase (Nerurkar 2010). The uniqueness of biosynthetic pathway allows the production of a series of lichenysin variants that have various chemical structures. These offer customization options to address particular challenges in
MEOR applications. Furthermore, lichenysin shows a likeness in both structure and biosynthesis to surfactin, a well-investigated biosurfactant. Knowledge gained through the structure and biosynthesis of surfactin give a guideline to identifying the features of lichenysin in the process of lichenysin based biosurfactant research and development focused on MEOR applications (Claire et al., 2022).

MEOR and the Significance of Biosurfactants, with a Focus on the Role of Lichenysin

MEOR is a technique that utilizes microorganisms or their metabolites for enhancing oil recovery from reservoirs. It involves stimulating of endogenous microorganisms by injecting nutrient solution or live culture of specific exogenous microorganisms into the reservoirs with that can alter the properties of the reservoir and enhance the production of oil. This process works as following; microorganisms are injected into the reservoir, either as a nutrient solution or as live cultures. The microorganisms engage with both the oil and reservoir environment, leading to vast alterations that improve oil recovery. The microorganisms produce various metabolites that effect on oil or reservoir’s environment differently. For example; produced biopolymers effect on permeability condition and reduce the permeability of high permeability zones and divert the injected fluids into lower permeability zones, increase sweep efficiency, and leads to enhance oil recovery. While produced enzymes break down complex hydrocarbons, increase oil mobility by viscosity reduction. Besides, other produced metabolites effect on oil and reservoir’s conditions as well. MEOR owns many advantages over traditional techniques that cost effectiveness, eco-friendliness, easy application, high productivity and durability are some of them.

Figure 2. A Schematic Illustration of IFT Reduction (A), Emulsification (B) and Wettability alteration (C)
As it was mentioned biosurfactants are one of the main groups of microbial metabolites that play a crucial role in Microbial Enhanced Oil Recovery (MEOR) by reducing surface tension, interfacial tension, emulsification, wettability alteration, and enhancing oil recovery. For instance, 1- biosurfactants lower the oil/water surface tension that allows for better spreading and contacting between the two phases. This facilitates the displacement of trapped oil and improves its mobility (Wu et al., 2022). 2- biosurfactants reduce interfacial tension (IFT) between oil and water, making it easier for the oil to flow through the porous rock formations in the reservoir. This enhances oil recovery by improving the displacement of oil from the reservoir matrix as it is shown in Figure 2A. 3- Biosurfactants have the ability to form stable emulsions between oil and water. These emulsions increase the contact area between the oil and the water, enhancing the efficiency of oil recovery as it is shown in Figure 2B. 4- Biosurfactants can alter the wettability of the reservoir rock surfaces, making them more water-wet. This change in wettability improves the oil displacement efficiency and enhances oil recovery see Figure 2C. As a result, biosurfactants by creating the aforementioned alterations in the reservoir leads to enhanced oil recovery (McInerney et al., 1990).

Among a large number of biosurfactants, lichenysin is a very powerful biosurfactant that owns the capability of IFT reduction to values of lower than 10-2 mN/m even with minimal concentrations that may be around 10 to 60 mg/L. And it demonstrated considerable stability in extreme temperatures higher than 140 °C, pH values from 6-10, and salty conditions that salinity reaches up to 10% w/v NaCl (Khire, 2010). In core flooding experiments that were conducted for studying lichenysin effectiveness, partially purified lichenysin shows a considerable efficiency and recovered up to 40% of residual oil from sandstone cores although chemical surfactants recovered only 10%. As you can see the functionality of this biosurfactant in comparison with surfactin and rhamnolipid, two other well-known biosurfactants in Table 1 it was indicated this biosurfactant own its unique characteristics that make it a valuable candidate in MEOR process. The most noticeable properties that turned it to a really considerable candidate biosurfactant are its stability in really high temperature up to 140 °C and its effectiveness on IFT and ST reduction. As you can see a comparison of lichenysin with surfactin and rhamnolipid two other well-known biosurfactants in Table 1.

Table 1. A Comprison of Lichenysin Properties with Surfactin and Rhamnolipid

<table>
<thead>
<tr>
<th>Biosurfactants</th>
<th>ST and IFT Reduction</th>
<th>Temperatur e Stability</th>
<th>pH Stability</th>
<th>Salinity Stability</th>
<th>CMC</th>
<th>Ref</th>
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<tbody>
<tr>
<td>Surfactin</td>
<td>From 72 to 27 mN/m</td>
<td>From 1 to 120 °C</td>
<td>2-10 pH value</td>
<td>Up to 20% NaCl</td>
<td>154 mg/L</td>
<td>Wu et all.,2022</td>
</tr>
<tr>
<td>Rhamnolipid</td>
<td>From 72 to 35.26 mN/m</td>
<td>From 20-100 °C</td>
<td>4-8 pH value</td>
<td>Up to 9% NaCl</td>
<td>127 mg/L</td>
<td>El-Housseiny et all., 2020 &amp; Costa et all., 2010</td>
</tr>
<tr>
<td>Lichenysin</td>
<td>From 72 to 27 mN/m</td>
<td>From 0 °C up to Higher than 140 °C</td>
<td>6-10 pH value</td>
<td>Up to 10% NaCl</td>
<td>From 10 to 20 mg/L</td>
<td>Anuradha 2010</td>
</tr>
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Applications of Lichensin in MEOR and the Reservoir Conditions Well-Suited for Lichensin

Although purified lichenysin has not been utilized in field trials, producing microorganism (B. licheniformis or B. mojavensis) has been utilized in in situ MEOR projects around the world that Omani Oilfield can be one significant example of such projects. In this field trial the injection of B. licheniformis injection that is lichenysin producing microbe showed an oil production
rate by 13% along with interfacial tension reduction (Al-Sulaimani et al., 2010).

Lechinysin is a highly effective biosurfactant that can be tailored for specific oil reservoir conditions. Its unique properties, such as its effectiveness in reducing interfacial tension (IFT) and surface tension (ST), stability at high temperatures, low critical micelle concentration (CMC), stability in a wide range of pH values, and a significant stability in high salinity (as shown in Table 1), make it a promising candidate for microbial enhanced oil recovery (MEOR) applications. Based on the unique properties that it owns it is more suitable in reservoirs with high temperature, pH around 6-10 and salinity around 10%.

In addition, lichenysin has a number of valuable properties that make it a considerable eco-friendly compound in MEOR process such as; 1- biodegradability that means, it is degraded effectively by natural microbes in the nature. So it does not contaminate the environment. 2- ability to decrease surface tension that makes it a significant candidate for eliminating oil pollution of the environment, and 3- its production by B. licheniformis that demonstrates its sustainability (De Oliveira et al., 2017). All these properties made it a valuable candidate with potential applications in a wide range of industries, specifically, in MEOR.

**Challenges and Future Directions of Implementing Lichenysin in MEOR**

Besides all advantages of lechinysin over other biosurfactants that made it a very strong biosurfactant in MEOR process, its utilization in MEOR has some challenges and limitations as well. That we can name some of them as following; 1- as it is produced by certain bacteria so presence of these producing microorganisms is crucial in the reservoirs. Therefore, in the absence of these certain microorganisms or without the injection of purified lichenysin it is impossible to run the MEOR process by this chemical. 2- it needs specific conditions to function optimally, hence, creation of optimal conditions in the field projects can be another challenging task for utilizing lichenysin. 3- it is not compatible enough in all types of reservoirs that makes it challenging to accommodate the reservoirs’ conditions for applying lichenysin. And 4- regulatory considerations while utilizing lichenysin or its producing microorganisms is another challenge of utilizing lichenysin in MEOR process.

As lichenysin is the biosurfactant that generally utilized in MEOR process than any other industries it has been studied scarcely than other biosurfactants like surfactin. Despite scarce studies, there had been conducted some studies to optimize the production of lichenysin by B. licheniformis strains. For instance; genetic engineering approach that was conducted firstly by Lin et al., in 1998 that they increase lichenysin production from 33mg/L up to 391mg/L via random mutagenesis using N-methyl-N′-nitro-N-nitrosoguanidine (Qiu et al., 2014). Then researcher studied the result of replacing the native promotor of the operon lehA in B. licheniformis WX-02 by different promotors. The best result was obtained when Pleh was replaced by Psr showed a considerable increase. There was expansion of lichenysin production from 121mg/L up to 779mg/L by B. licheniformis WX-02. Then the production of lichenysin by this recombinant strain increase up to 2149 mg/L via culture medium optimization.

Another advancement in lichenysin application in MEOR is to increase the production of lichenysin by supplementing the culture medium with precursor amino acids (Asp, Glu, Leu, Ile, Val) (Zhu et al., 2017). In a study it was shown that B. licheniformis CodY null strain had the capability of producing 2356mg lichenysin/L in a culture medium containing 0.5g/L of precursor amino acids, while the parental strain produced 1798mg licnysin/L (Gudiña & Teixeira 2022).

**Conclusion**

Researches show that lichenysin is one of the most suitable biosurfactants for MEOR. This biosurfactant has several variants that differ based on the different producing strains of B. licheniformis. It is quite similar to surfactin and
their chemical structures has a very slight variance that leads to their similar functionality in MEOR process. As it has a considerable stability in extreme conditions of reservoirs like stability in extremely high temperatures up to 140 °C and high salinity it has the capability to survive in extreme temperatures of reservoirs and at high salt concentration that support it to save its properties to help oil recovery process. In addition, researches demonstrated that it has the lowest CMC rate among all other biosurfactants that indicates its budget friendliness and high effectiveness of this biosurfactant over other biosurfactants. Although, enough researches had not been conducted regarding to this biosurfactant with numerous advantages that change it to a highly recommended candidate in MEOR. As it owns valuable characteristics that make it suitable in MEOR it needs to be studied more.

References


