Factors Affecting the Production of Biosurfactants and their Applications in Enhanced Oil Recovery (EOR). A Review

C N Sari¹, R Hertadi², M Gozan³* and A M Roslan³

¹Bioprocess Engineering Study Program, Department of Chemical Engineering, Universitas Indonesia (UI), Depok 16421, Indonesia.
²Departement of Chemistry, Institut Teknologi Bandung (ITB), Bandung 40132, Indonesia.
³Department of Bioprocess Technology, Universiti Putra Malaysia (UTM), Serdang Selangor, Malaysia

*Email: misrigozan@gmail.com

Abstract. Biosurfactants are surface-active compounds synthesized by microbes. They have the ability to reduce the surface tension of a liquid and interfacial tension (IFT) between two different phases. Thus, they can be applied in water-oil emulsification. The development of enhanced oil recovery (EOR) technology has led to increased interest in biosurfactants. The purpose of this review was to compile information on important components of biosurfactant production. Understanding the characteristics of biosurfactants, especially IFT derivation and effects of alterations in the wettability of reservoir rocks can aid the applications in EOR. Both the microbe type and growth substrate influence the yield and type of biosurfactant produced. The type of fermenter also affects the efficiency of surfactant production. The use of batch type fermentors and the use of Pseudomonas and Bacillus bacteria in the previous research was superior whereas the sugar group and plant base oil as substrates. The measurement methods of biosurfactants in microbial culture are of considerable importance to be done prior to characterization of biosurfactant products. Furthermore, some reservoir components discussed in this review are the keys to the success of biosurfactant flooding in the field.

1. Introduction

Biosurfactants are surface-active molecules produced by microorganisms, such as bacteria and fungi. Biosurfactants have hydrophilic and hydrophobic components, which are divided into groups with a low molecular mass and high molecular mass [1]. Major classes of surfactants with a low molecular mass include glycolipids, lipopeptides and phospholipids, all of which reduce surface tension and interfacial tension (IFT). In contrast, surfactants with a high molecular mass (i.e. polymer surfactants and particulate surfactants) are effective emulsion stabilizers [2]. Biosurfactants are widely used in food production, cosmetics, pharmaceuticals, detergents, textiles and petroleum [3, 4]. They also have environmental applications due to their properties, such as biodegradability, low toxicity, emulsification, pH- and temperature tolerance and ionic strength [3, 4]. Furthermore, biosurfactants play an important role in bioremediation, such as treatment of oil spills at sea and crude oil removal [5]. Biosurfactants are particularly important in enhanced oil recovery (EOR) [5].

Currently, the demand for biosurfactants in the global market continues to increase. According to Global Market Insights, Inc., 370,000 tons of biosurfactants were required by industries in 2015 [6]. In 2018, demand is estimated to reach 476,500 tons, equal to 2.21 billion USD [6]. By 2023, demand for...
biosurfactants is estimated to equate to a value of 2.69 billion USD [6]. Given the increasing market demand, the production of biosurfactants is attracting attention. In nature, the chemical structure and physicochemical properties of biosurfactant products are highly dependent on the type of microorganism (producer), carbon source, fermentation type and environmental conditions [2].

In oil and gas industries, biosurfactants are used as agents in the recovery of oil trapped inside reservoir rocks. They have many advantages, such as a simple means of application. In addition, they are eco-friendly. EOR is expected to be one of the major technologies in the future to improve oil recovery [7]. The interactions between the surface active molecules and oil-water interface and reservoir rock surface determine the amount of oil which could be produced as a result of an EOR process [8].

2. Biotechnology for Biosurfactants

Surfactants have been in use since the time of the Babylonians 2,800 years who used them in the production of soaps [9]. Today, most surfactants are obtained by chemical processes from petrochemical and oleochemical resources. In the late 1960s, biosurfactants were first produced by microbes through hydrocarbon fermentation in the form of extracellular compounds. These compounds reduce surface tension and interfacial stress and have biological activities (e.g. antiviral, antimicrobial, insecticidal and haemolytic). In recent years, there has been a shift towards more environmentally friendly surfactants due to growing awareness of both consumers and companies of the adverse effects that surfactants can have on the environment.

Biosurfactant technology is used in various sectors due to its role as a foaming agent. Some studies reported that biosurfactants, such as rhamnolipids, had excellent foaming properties [10, 11], whereas others (e.g. sophorolipids and glycolipids from yeast) had moderate foaming abilities. These foaming properties can be exploited to reduce the viscosity of oil. Biosurfactants are used as detergents in cleaning crude oil storage tanks. Joshi-Navare et al. [12] reported that sophorolipids produced from jatropha oil by Candida bombicola (ATCC22214) were capable of functioning as a stain cleaner. When combined with detergents, microbial sophorolipids act as strong stain removers due to their high wetting performance, thereby reducing the immersion time required during the washing process. A fabric leaching analysis showed that a crude biosurfactant of Pseudozyma sp. NII08165 consisted of a combination of three mannosylerythritol lipid (MEL), together with some unknown glycolipids, and that these removed stains by fusion and could be used in a laundry detergent formulation [13]. Biosurfactants are also used in textiles, drug solvents pesticides, tertiary oil dewatering and fungicidal plant sprays, as well as on various biological surfaces.

3. Research Development of EOR

Recently, EOR technology has been applied in oil recovery in Indonesia. Central Sumatra and South Sumatra are the largest potential areas for EOR, especially chemical flooding and CO₂ injection [14]. Chemical injection had been conducted in several fields, including Tanjung Borneo (Pertamina), Kaji Semoga field, Rimau Asset, South Sumatra (PT Medco Energi Nasional) and Minas (Chevron Indonesia). The steam flood method has been used at Duri Chevron field since 1981. The field testing phase of the surfactant polymer method in Minas Chevron and Kaji Medco showed good results [14]. In the U.S., CO₂-EOR has been used for more than 30 years. In the Permian Basin oil fields, CO₂-EOR uses natural CO₂ obtained from New Mexico and Colorado. The Department of Energy has estimated that additional production of 240 billion barrels (38 km³) of recoverable oil resources would be possible by the full use of CO₂-EOR in the U.S. [15].

Newswire 2017 reported that Petronas Caligari Sdn Bhd planned to invest USD 2.3 billion in an EOR project in Sarawak in offshore Malaysia. According to Petroleum Development Oman, production will increase in the EOR sector from 11% in 2015 to 33% by 2024. In 2016, the Norwegian Petroleum Directorate encouraged operators to use EOR techniques in old fields in which the productive period was over (i.e. when oil production decreased from 3 MMBbl/d in 2005 to 1.9 MMBbl/d) [16].
In addition to the successes of EOR, there are several failures of this technology in the field caused by irregularity of rocks, uncontrolled operation conditions and other issues. For example, the application of EOR in Tanjung Priok Field EP resulted in failure to reach the recovery target [14].

4. Working Mechanism of Biosurfactants in EOR

There are some suggestion regarding the working mechanism of biosurfactant in EOR, including interfacial tension, thermal stability, phase behavior, wettability, compatibility and core flooding. The main functions of biosurfactants in EOR are reducing the IFT and changing the wettability of reservoir rocks [17]. The mechanism of oil recovery via biosurfactants is based on their ability to reduce the IFT of oil-water and change the wettability of rocks from oil-wet to water-wet [8] (Figure.1).

![Figure 1](image)

**Figure 1** a) entrapped residual crude oil; b) wettability alteration at oil/rock interface: changing from oil-wet to water wet (release crude oil from sand grand/rock surface; reduction in IFT: breaks bigger oil dropets in to smaller drops, forms emulsion (oil/water or water/oil), release oil with water/brine; c) recovered extra crude oil with biosufactant.

4.1. Derivation of IFT

Changes in the oil-water IFT are denoted by the relation between the capillary number and residual oil saturation. The capillary number \(N_c\) is defined as below, where \(u\) is the shear force, \(\mu\) is the viscous force and \(\sigma\) is the capillary force:

\[N_c = \frac{u\mu}{\sigma(\cos\theta)}\]  \hspace{1cm} (1)

Experimental data have shown that if the capillary number increases, residual saturation decreases [18]. The relation between residual saturation and capillary number is termed the capillary desaturation curve. Studies of the capillary number and residual oil saturation showed that to reduce residual oil saturation remaining after waterflooding by 50%, the capillary number had to be increased 1,000 times from a typical number of 10−7 for waterflooding [19]. Based on the definition of capillary number and the assumption that \(\cos\theta\) is omitted, the following three parameters are calculated to determine the dewatering activity: (1) increasing the injection fluid velocity \(u\), (2) increasing the displacement fluid viscosity \(\mu\) and (3) reducing the IFT \(\sigma\) [17]. Assuming an IFT value of \(10^{-3}\) for biosurfactant injection, the presence of biosurfactants causes the capillary number to increase 1,000 times. Under these conditions, oil droplets are trapped in reservoir rocks, allowing them to flow easily and merge with water to form an oil bank [19].

Another mechanism involving the use of biosurfactants in EOR involves an emulsification process, which occurs when the water and oil phases combine to form a middle phase. A mixture of these two phases causes swelling of the oil volume, resulting in an increase in saturation in the oil phase and oil permeability, thus rendering oil is more readily produced [17].

Parameters affecting IFT values include the surfactant type, surfactant concentration, solvent concentration, oil composition and water-oil ratio, in addition to temperature and salinity [17].
4.2. Alteration of reservoir rock wettability
Wettability of rock is an important factor in the success of EOR [20]. Wettability of rock is divided into two categories: oil-wet and water-wet, and the type of reservoir rock being targeted are a reservoir carbonate rocks. Carbonate rocks tend to be oil-wet [21]. When a surfactant is injected into the reservoir, the rock matrix changes to water-wet. This results in water absorption and the formation of a matrix, which replaces the oil position. In this way, residual oil saturation is reduced.

Sheng [21] analysed the effects of different mechanisms underlying EOR using surfactants and compared the effects of alterations in wettability and reductions in IFT. In a simulation, Sheng showed that alterations in wettability played a vital role in high IFT and that these were effective in the early period EOR. The same study demonstrated that IFT played a significant role in the presence and absence of wettability alterations and that it was effective during the EOR process. On the other hand, Kumar and Mandal [8] reported that the addition of zwitter ions on a surfactant significantly decreased the IFT value and altered the wettability of rocks. The subsequent surfactant was a candidate for EOR applications. Mahdi et al. [22] reported similar results, using the method of drop sessile in a heavy oil layer to wet the oil surface. Other research reported that a cationic surfactant (C12TAB) showed better alteration of rock wettability than an anionic surfactant (SDS) [23]. SDS and CTAB changed the wettability of rocks and were more effective than tween 80 [23].

5. Biosurfactant-Producing Microorganisms, Carbon Source and Product Type
Biosurfactants are produced by various microorganisms (i.e. bacteria, fungi and mould) isolated from waste, contaminated soil and wastewater [5]. The number and type of biosurfactant are highly dependent on the individual microbe (Table 1).

To improve the efficiency of production, two factors are important: 1) low-priced raw material to reduce initial production costs and 2) bioprocess development, including the optimization of microbial culture, and different types of substrates from foodstuffs to waste has been used in biosurfactant production studies. [5].

| No | Biosurfactant product | Carbon source | Microorganism | Fermentation System | Yield (g/L) | Ref. |
|----|-----------------------|---------------|---------------|---------------------|-------------|------|
| 1  | Rhamnolipid           | n-hexadecane  | *Pseudomonas aeruginosa* | Batch              | 9.8         | [24] |
|    |                       | n-eicosane    | *Pseudomonas fluorescens* | Batch              | 8.2         |      |
| 2  | Surfactin             | Date molasses | *Bacillus subtilis* | Batch              | 2.29±0.38   | [25] |
| 3  | Surfactin             | Molasses/cheese whey | *Bacillus subtilis* | Batch              | 35.4±0.20  | [26] |
| 4  | Lichenysin            | Molasses/cheese Whey | *Bacillus licheniformis* | Batch              | 41.0±0.51  | [26] |
| 5  | Lipopeptide           | Glucose/date molasses | *K51* | Batch              | 0.3±0.5    | [27] |
| 6  | Lipopeptide           | Waste soybean oil | *Bacillus subtilis* B30 | Batch              | 10 mg/ml   | [28] |
| 7  | Rhamnolipid           | Mineral medium and palm oil | *Klebsiella sp.* | Batch/Sequencing | No data    | [29] |
|    |                       |               | *Pseudomonas aeruginosa* | Batch              |             |      |
| 8  | Rhamnolipid           | D-mannitol and yeast extract | *SP4* | Batch              | 1.12        | [30] |
| 9  | Glycolipid            | Glucose and olive oil | *Pseudomonas taiwanensis* L1011 | Batch | 2.6          | [31] |
|    |                       |               | *Wickerhamomyces anomalus CCMA 0358* | Batch | No data | [32] |
|    |                       |               | Serratia marcescens strain DSM12481 | Batch | No data | [33] |
| 10 | Lipopeptide           | No data       | *Candida lipolytica* UCP0988 | Batch              | No data    |      |
| 11 | No data               | Animal oils and fat | *Bacillus subtilis* CN2 | Batch              | No data    | [34] |
| 12 | Lipopeptide           | Crude oil     | *Paenibacillus alvei* and *Bacillus mycodes* | Batch | No data | [35] |
| 13 | No data               | No data       | *Bacillus licheniformis* TKU004 | Batch | 0.55       | [36] |

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Table 1. List of Biosurfactant-producing microorganisms and its yield
Biosurfactants have also been produced from tropical agronomic crop residues, such as cassava peel, as well as from soybean [45], sugar beet [46], sweet potato/potato peel and stem, sweet sorghum [47], rice, wheat, bran, straw and corn [48]. Furthermore, biosurfactants have been produced from coffee processing industry residues (husks and powder) and fruit processing industry residues (pomace of grapes and pineapple carrot processing and banana waste), in addition to waste from oil processing mills (coconut cake, soybean cake and peanut cake), including palm oil mills (canola and corncobs) [49]. Food industrial waste, such as soybean waste, used cooking oil, palm oil mill effluent and olive oil mill effluent, are alternative substrates for the production of biosurfactants [50-52]. From the review, it can be observed that the type of molasses substrate produces the highest biosurfactant yield. The type of substrate above is important because it is easily obtained, with cheap raw material prices and a solution in handling waste in the environment. Several strategies to overcome the cost of biosurfactant production costs are the use of waste and low substrate for fermentation media formulations. Also, the development of efficient successfully optimized bioprocesses, including optimization of the culture conditions and cost-effective recovery processes for maximum biosurfactant production and recovery [5].

Various types of biosurfactants can be synthesized in several types of carbon sources by many microorganisms [49]. However, there have been examples of the use of a water-soluble substrate for biosurfactant production by microorganisms [44]. The type, quality and quantity of biosurfactant produced are influenced by the nature of the carbon substrate, the concentration of nitrogen, phosphor, magnesium, ferric, and manganese ions in the medium and the culture conditions, such as pH, temperature, agitation and dilution rate in continues culture [53].

6. Measurements of Various Aspects of Biosurfactants in Microbial Culture

6.1. Surface tension

Surface tension measurements of biosurfactants are conducted by measuring the fermentation liquids or purified biosurfactant extracts. A decrease in the surface tension of the biosurfactant indicates that microbes are producing certain surface-active compounds [29].

There are several methods available for surface tension measurements, including the capillary rise method, Du Nouy method, Wilhelmy plate method, release method and drop-weight method [54]. The principle of the capillary rise method is that when a capillary tube containing a liquid is inserted in a flask containing a liquid, the liquid generally rise in the tube up to a certain distance (Figure 1), so the surface tension can be determined because of the counterbalance of the gravity force and weight of the liquid [55].

\[ \gamma = \frac{1}{2} rh\rho \]  

(2)

The working principle of the Du Nouy method is that the force required to remove a platinum-iridium ring placed on a surface or interface is equal to the surface tension or IFT, the required force is measured in dyne units, which esures the weight of the liquid detached from the interfacial plane just before the
ring drops [55]. The Wilhelmy plate method is a direct measurement of the force imposed on a platinum plate at the interface and this method is relatively simple and gives accurate results. When the suspended vertical plate touches the surface, the force (F) correlates with the surface tension or IFT (σ) and with the contact angle (θ) according to the following equation: [56]

\[ \sigma = \frac{F}{L \cdot \cos \theta} \]  

The release method is the most widely used process for determining surface tension and IFT. This method depends on the measurement of the force required to remove a wire ring from a liquid surface [57]. The drop-weight method is based on the fact that the droplet weight, which drops from a pipe, depends on the surface tension of the liquid. This method requires a correction factor because only a portion of the droplet reaches the size of the instability to fall (i.e., some remains attached to the capillary end) [57].

Surface tension and interfacial tension play an important role in product development. Departments of research and development around the world measure surface tension and interfacial tension on surfactants to improve the quality of their products. Surfactant formulations are optimized to increase the effective power with lower and more amounts and work at the right temperature. In the oil industry, especially in the field of enhanced oil recovery, interfacial and surface tension, it is designed to optimize the sweeping oil process when the injection activity is optimal [17].

6.2. Interfacial Tension

Interfacial tension is a measure of the cohesive energy present at the interface, for example, a liquid phase and a liquid phase or a gas phase and a liquid phase. IFT measurements are conducted in the same way as surface tension measurements. IFT is measured in mN/m units.

Capillary pressure, caused by interfacial tension (IFT) between reservoir fluids is the most basic rock-fluid property in multiphase flow [58]. Capillary forces resist externally applied viscous forces and hence, to a large extent govern the mobility of the reservoir fluids [58]. For example, capillary forces can cause large quantities of oil to be left behind in well-swept zones of waterflooded oil reservoirs [18]. This trapping is best expressed as a competition between viscous forces, which mobilise the oil, and capillary forces, which trap oil. The most common experimental observation is the capillary desaturation curve, a relationship between residual oil saturation and the capillary number, a dimensionless ratio of viscous to capillary forces [17]. At low capillary numbers, the residual oil saturation is roughly constant [58]. However, above some critical capillary number, the residual saturation begins to decrease. Hence, additional oil can be recovered by lowering the IFT. For significant effect, though, the IFT must be lowered by several orders of magnitude.

In oil recovery, interfacial tension is the key factor in enhanced oil recovery. Different enhanced oil recovery methods such as surfactant flooding are used to increase the recovery rates. After surfactant was injected into an oil reservoir, it contacts and interacts with the reservoir oil and brine, thus changing both reservoir equilibrium conditions as well as fluid properties [17]. The effectiveness of enhanced oil recovery is related to issues like surfactant penetration into the reservoir pores, as well as its ability to displace the brine and oil in the reservoir and lower the viscosity of the oil. Interfacial tension between surfactant–water and surfactant-oil is thus important for effective oil recovery [17]. Measurement of low IFT at reservoir pressure and the temperature is therefore required for evaluating the potential of EOR processes where lowering IFT is the primary means of oil recovery [58].

6.3. Colorimetric method

The colorimetric method is used to measure biosurfactant production in microbial cultures because this method is simple, fast and accurate. This method consists of the orcinol method and the Bradford method. The orcinol method is used for rhamnolipid-type surfactant determination. In the assay, cell-free supernatant from microbial cultures is diluted ten times, and 100 μl of the sample is then added to 900 μl of fresh orcinol reagent (0.9% orcinol in 53% sulfuric acid). The sample is then incubated in a water bath at 80°C for 30 min and cooled to room temperature for 15 min. By comparing the standard
curve (using an L-rhamnose concentration of 0-5 μg/ml), the rhamnose content can be calculated. The rhamnolipid concentration is obtained by multiplying the rhamnose content by 3.0, (the rhamnolipid/rhamnose correlation) [59].

There are two fundamental problems with the use of the orcinol method for glycolipid biosurfactant determination. First, the reagents react with pentose sugar and are not specific to rhamnose. Second, this method is an indirect measurement of rhamnolipid content [60]. As a result, the orcinol method always overestimates the amount of rhamnolipid present, occasionally to an alarming degree.

As with the orcinol method, the Bradford method provides an indirect measurement of the glycolipid pentose portion. The Bradford method is used to estimate proteins for lipopeptide biosurfactants quantification [61]. This method is popular because it uses a single addition of the dye reagent to the sample. The test is conducted in a 100 μl volume containing samples between 5 and 100 μg of protein. If the tested lipopeptide is insoluble in the Bradford reagent, 1 M NaOH is added to each sample. Standards containing 5–100 μg of suitable proteins (e.g., albumin) are used for calibration of the assay. After adding 5 ml of Bradford reagent to each sample, the sample is incubated for 5 min, and the absorbance is then measured at 595 nm. Bradford reagents reaction is highly dependent on the composition of the tested peptide like arginine, histidine, tyrosine, lysine, tryptophan and phenylalanine residues [60]. Like the orcinol method, this method has limitations in calculating the quantification of biosurfactant production and is stated not as an absolute quantification method [60].

6.4. Gravimetric analysis
The simplest quantification method is gravimetric, which isolates or separates and directly weighs the number of products. All precipitation gravimetric analysis share two important attributes. First, the precipitate must be of low solubility, of high purity, and known composition if its mass is to accurately reflect the analyte’s mass. Second, the precipitate must be easy to separate from the reaction mixture [60]. However, a disadvantage of this method when applied to biosurfactant measurements is that after purification, the biosurfactant is contaminated with fatty acids derived from the substrate of bacterial growth media. In extraction, the use of hexane solvents can be used, but effective removal of fatty acids is very difficult to determine [60]. The purity of the final isolated biosurfactant can be examined using direct injection mass spectrometry before gravimetric analysis is carried out [62].

7. Biosurfactant Production Method
The type of fermentation method used has a major influence on the biosurfactant yield. Common fermentation methods employed in biosurfactant research are batch, fed-batch and continuous batch [27, 29, 30, 52, 63-70].

7.1. Batch process
In batch process fermentation, media and inoculum are added simultaneously to the bioreactor, and the product is collected at the end of the fermentation [44]. During the process, bioreactor conditions change (i.e., nutrients and products and waste were reduced). There have been many studies on the production of biosurfactants using batch reactors [27, 30, 63-66]. Rodrigues [52] reported that the use of soybean waste as a substrate was capable of producing biosurfactant and biomass with concentrations of 11.70 g/L and 11.5g/L, respectively. Pansiripat et al. [29] used an oil-glucose ratio of 40:1 as a carbon source. They reported that the biosurfactant reduced surface tension by 58.5%.

Batch-type bioreactors have additional advantages. For example, they can be used when a material is available at certain times and suitable for high solid (25%) content. Batch-type reactors are also more suitable than continuous flow-type reactors for fibrous material, which is difficult to process, as the length of the process can be increased [67]. If the process has to be stopped, for example, because of the presence of toxic materials, the process can be stopped and started again. Avili et al. [68] report, in batch fermentation, results in the highest biomass and the lowest rhamnolipid concentrations compared to the fed batch alternatives. The biomass concentration reached its maximum value after 20 h, while rhamnoliopid accumulated in the medium up to 100 h with a maximum concentration of about 1 g/L.
7.2. **Continuous process**

In the continuous process, substrate streaming and product collection are carried out continuously at any time after the maximum product concentration, or substrate limits have reached an almost constant concentration. In this case, substrates and inocula can be added together continuously, allowing the exponential phase to be extended [67]. Biosurfactant production studies using this type of fermentation have not been widely reported due to difficulties in controlling substrate availability. These difficulties are due to the addition of new media that must reach a fixed volume while maintaining output cultures in a constant cell physiology phase [67].

7.3. **Fed-batch process**

In a fed-batch system, new media are added regularly, without removing the culture fluid present in the fermenter, thereby resulting in a gradual increase in the culture volume. In this type of system, the regular addition of nutrients (e.g., Carbon and Nitrogen sources) prevents nutrient depletion until a product close to maximum yield is obtained [71].

He et al. [69] reported the production of biosurfactant in a fed-batch type fermenter, with a rhamnolipid yield of 150 g/L and productivity of 0.4 g/L for 17 days. This yield was better than that obtained using a batch system under the same conditions. Therefore, they recommended the use of the fed-batch type at industrial scales due to reduced economic costs. Another study reported a significant increase in the formation of rhamnolipids in batch (0.047 g/g) versus fed-batch (0.110 g/g) systems and improved biomass yield (0.421 g/g batch vs. 3.098 g/g fed batch) by Pseudomonas aeruginosa USM-AR2 [70]. Based on statistical calculations avili et al. [68] also reported, fed batch runs were better than batch in term of rhamnolipid production, and among the fed batch runs the maximum amount of rhamnolipid. (4.12 g Rhamnose Equivalent/l) was for the fed batch run with the the carbon source in the feed. Another trial also reported the use of bioreactors operating in a fed-batch, a concentration value of up to 16.9 g/L rhamnolipid was achieved when supplying additional nitrogen and carbon to the system by strains of Pseudomonas aeruginosa for over two weeks of operation [71].

8. **Criteria for Surfactant Flooding of Reservoirs**

8.1. **Reservoir formation and water salinity**

Most anionic surfactant flooding projects have been carried out in sandstone reservoirs, with fewer projects conducted in carbonate reservoirs. One reason for the reduced use of surfactant flooding in carbonate reservoirs is that anionic surfactants have a high carbonate adsorption capacity. Low clay content is needed for the application of surfactants in EOR due to high surfactant adsorption by clay [17].

Generally, technical screening criteria are used to provide a guide on the formation of water salinity and divalents [72]. The reservoir water salinity should be close to that of the injected water before surfactant injection, and the injection water salinity for surfactants should be close to the optimum salinity at which the lowest IFT between oil and water can be reached. The optimum salinity depends on various factors, such as the type of crude oil and surfactants. For most surfactants, the optimum salinity is not very high [17].

8.2. **Reservoir temperature and depth**

The resistance of surfactants to temperature varies greatly, depending on the surfactant type. The temperature used in steam-foam flooding can be as high as 250°C. Although surfactants that can be applied in high-temperature reservoirs are available, most researchers have proposed 93.3°C as the limit for the reservoir temperature [73]. The reservoir depth is not a limiting factor for surfactant flooding as long as not violating the reservoir temperature limit [74].
8.3. Oil saturation

The flooding mechanism of the surfactant can reduce residual oil saturation in the reservoir, which is related to the capillary number [75]. When the injection process is operated at a low capillary number (NC < 10^5), the residual oil saturation will remain constant [75]. In a flooded field, surfactant flooding is performed to restore oil springs. If residual oil saturation is high, then surfactant flood activity is performed to enable oil recovery. Based on field research, which found that oil saturation before surfactant flooding was 0.4, a criterion of So > 0.3 has been proposed [17]. An increment of the capillary number will have the effect of lowering the residual oil saturation.

8.4. Formation permeability

As surfactants can reduce the residual saturation, the relative permeability increases. Thus, the effective permeability also increases. Surfactants, for example, an alkaline-surfactant solution, are sometimes injected into a low-permeability reservoir to increase the good injectivity [17, 76].

8.5 Storage capacity

The porosity is related to permeability. If the permeability is high, the porosity is also high [76]. Kamari and Mohammadi [77] reported several parameters for EOR screening. Examples of cases of EOR in oilfields are summarized in Table 2.

9. Conclusions

The type of fermenter, as well as type of bacterial growth substrate, influences biosurfactant production. Most of the research uses batch system fermentors, plant oil base, and sugar substrate, and also Pseudomonas and Bacillus type. Based on the results of the review, for production with high biomass, batch types are widely used. As for the production of high yield rhamnolipids, fed batch types are highly recommended. The use of appropriate standards in measurement methods, in conjunction with techniques that allow accurate quantification, can help provide accurate and reproducible yield data. Such data are required to evaluate the economic feasibility of the EOR process. The development of criteria related to the EOR method and the properties of formation and fluids can contribute to useful and constructive screening for successful injection in the field.

Table 2. Results of screening in an oil field in southwestern Iran prior to EOR [77]

| Properties                        | Unit      | Value      |
|-----------------------------------|-----------|------------|
| Formation Type                    | Fractured carbonate |
| Permeability md                   |           | 50         |
| Porosity %                        |           | 19.5       |
| Depth ft                          |           | 1450       |
| Viscosity cp                      |           | 2000       |
| Irreducible water saturation %    |           | 20         |
| Oil saturation %                  |           | 80         |
| Reservoir pressure psi            |           | 1200       |
| Reservoir temperature °F          |           | 140        |
| Layer dip Degree                  |           | 17         |
| Gross pay ft                      |           | 1100       |
| Net pay ft                        |           | 312        |
| API Degree                        |           | 14         |
| Rock heat capacity Btu/ft^°F      |           | 30         |
| OOIP bbl                          |           | 0.832×10^9 |
| Wells Number                      |           | 7          |
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References
[1] Pacwa-Plociniczak M, Plaza G A, Piotrowska-Seget Z and Cameotra S S 2011 Environmental Applications of Biosurfactants: recent advances International Journal of Molecular Sciences 12 633-654
[2] Velioglu Z and Urek R O 2016 Physicochemical and Structural Characterization of Biosurfactant Produced By Pleurotus Djamor In Solid-State Fermentation Biotechnology and Bioprocess Engineering 21 430-438
[3] Van Bogaert I N, Buyst D Martins J C, Roelants, S L, and Soetaert W K 2016 Synthesis of Bolaform Biosurfactants by an Engineered Starmerella bombicola yeast Biotechnology and bioengineering 113 2644-2651
[4] Nitschke M and Costa S G V A O 2007 Biosurfactants in Food Industry Trends in Food Science & Technology 18 252-259
[5] Saharan B S, Sahu R K and Sharma D 2011 A Review on Biosurfactants: Fermentation, Current Developments and Perspectives Genetic Engineering and Biotechnology Journal 2011 1-14
[6] Global Market Insights 2016 Biosurfactant Market Size By Product, By Application, Industri Analysis Report, Regional Outlook, Application Potential, Price Trend. Competitive Market Share & Forecast, 2016-2023 https://www.gminsights.com/industry-analysis/biosurfactants-market-report (Accessed 17 November 2017).
[7] Zhao F, Shi R, Cui Q, Han S, Dong H and Zhang Y 2017 Biosurfactant Production Under Diverse Conditions by Two Kinds of Biosurfactant-Producing Bacteria for Microbial Enhanced Oil Recovery Journal of Petroleum Science and Engineering 157 124-130
[8] Kumar A and Mandal A 2017 Synthesis and Physicochemical Characterization of Zwitterionic Surfactant for Application in Enhanced Oil Recovery Journal of Molecular Liquids 243 61-71
[9] Geys R, Soetaert W and Van Bogaert I 2014 Biotechnological Opportunitiesi in Biosurfactant Production. Current Opinion in Biotechnology 30 66-72
[10] Özdemir G Peker S and Helvaci S S 2014 Effect of pH on the Surface and Interfacial Behavior of Rhamnolipids R1 and R2 Colloids and Surfaces A: Physicochemical and Engineering Aspects 234 135-143
[11] Cohen R and Exerowa D 2007 Surface Forces and Properties of Foam Films From Rhamnolipid Biosurfactants Advances in Colloid and Interface Science 134 24-34
[12] Joshi-Navare K Khanvilkar P and Prabhune 2013 A Jatropha oil Derived Sophorolipids: Production and Characterization as Laundry Detergent Additive Biochemistry Research International 2013 1-11
[13] Sajna K V, Sukumaran R K, Jayamurthy H, Reddy K K, Kanjilal S, Prasad R B and Pandey A 2013 Studies on Biosurfactants from Pseudozyma sp. NII 08165 and Their Potential Application as Laundry Detergent Additives Biochemical Engineering Journal 78 85-92
[14] Ministry of Energy and Mining Resources Republic of Indonesia (ESDM), Strategic Planning of ESDM 2015-2019 (in Bahasa) http://prokum.esdm.go.id/renstra%202015/DATA%20to%20MAIL%20NEW%20REV%20B UKU%20RENSTRA%202015.pdf (Accessed 13 March 2018).
[15] Logan J, Venezia J and Larsen K 2007 Opportunities and Challenges for Carbon Capture and Sequestration WRI Issue Brief 1 1-8
[16] Global Market Insight. Enhanced Oil Recovery Market to cross $140bn by 2024: Global Market Insights, Inc. https://globenewswire.com/news-release/2017/10/02/1138618/0/en/Enhanced-Oil-Recovery-Market-to-cross-140bn-by-2024-Global-Market-Insights-Inc.html (Accessed 16 March 2018).
[17] Sheng J J 2015 Status of Surfactant EOR Technology Petroleum 1 97-105
[18] Lake L 1989 *Enhanced Oil Recovery* (New Jersey: Prentice Hall Englewood Cliffs) pp 195-197
[19] Sheng J 2010 *Modern Chemical Enhanced Oil Recovery: Theory and Practice* Gulf Professional Publishing
[20] Ziauddin M, Montaron B, Hussain H, Habashy T, Seleznev N, Signer C and Abdallah W 2007 Fundamentals of Wettability *Schlumberger Oilfield Review* 19 40-67
[21] Sheng J J 2013 Review of Surfactant Enhanced Oil Recovery in Carbonate Reservoirs *Advances in Petroleum Exploration and Development* 6 1-10
[22] Mohajeri M, Hemmati M, and Shekarabi A S 2015 An Experimental Study on Using a Nanosurfactant in an EOR Process of Heavy Oil in a Fractured Micromodel *Journal of petroleum Science and engineering* 126 162-173
[23] Kumar S and Mandal A 2016 Studies on Interfacial Behavior and Wettability Change Phenomena by Ionic and Nonionic Surfactants in Presence of Alkalis and Salt for Enhanced Oil Recovery *Applied Surface Science* 372 42-51
[24] Sakhthipriya N, Doble M. and Sangwai, J S 2015 Biosurfactant From Pseudomonas Species with Waxes as Carbon Source–Their Production Modeling and Properties *Journal of Industrial and Engineering Chemistry* 31100-111
[25] Al-Bahry S N, Al-Wahaibi Y M, Elshafie A E, Al-Bemani A S, Joshi S J, Al-Makhmari H S and Al-Sulaimani H S 2013 Biosurfactant Production By Bacillus Subtilis B20 Using Date Molasses and Its Possible Application in Enhanced Oil Recovery *International Biodeterioration & Biodegradation* 81141-146
[26] Joshi S, Bharucha C, Jha S, Yadav S, Nerurkar A and Desai A J 2008 Biosurfactant Production using Molasses and Whey Under Thermophilic Conditions *Bioresource technology* 99 195-199
[27] Al-Wahaibi Y, Joshi S, Al-Bahry S, Elshafie A, Al-Bemani A and Shibulal B 2014 Biosurfactant Productionb By Bacillus Subtilis B30 and Its Application in Enhancing Oil Recovery *Colloids and Surfaces B: Biointerfaces* 114 324-333
[28] Lee S C, Lee S J, Kim S H, Park I H, Lee Y S, Chung S Y and Cho Y L 2008 Characterization of New Biosurfactant Produced from Klebsiella Sp. Y6-1 Isolated from Waste Soybean Oil *Bioresource Technology* 99 2288-2292
[29] Pansiripat S, Pornsunthornwadee O, Rujiravanit R, Kitiyanan B, Somboonthanate P and Chavadej S 2010 Biosurfactant Production by Pseudomonas Aeruginosa SP4 Using Sequencing Batch Reactors: Effect Of Oil-To-Glucose Ratio *Biochemical Engineering Journal* 49 185-191
[30] Liu C, You Y, Zhao R, Sun D, Zhang P, Jiang J, Zhu A and Liu W 2017 Biosurfactant Production From Pseudomonas Taiwanensis L1011 and Its Application in Accelerating the Chemical and Biological Decolorization of Azo Dyes *Ecotoxicology and Environmental safety* 145 8-15
[31] Souza K S T, Gudiña E J, Azevedo Z, de Freitas V, Schwan R F, Rodrigues L R, Diaz J A and Teixeira J A 2017 New Glycolipid Biosurfactants Produced by The Yeast Strain Wickerhamomyces Anomalus CCMA 0358 *Colloids and Surfaces B: Biointerfaces* 154 373-382
[32] Thies S, Santiago-Schübel B, Kovačić F, Rosenauf F, Hausmann R and Jaeger K E 2014 Heterologous Production of The Lipopeptide Biosurfactant Serrawettin W1 in Escherichia coli *Journal of Biotechnology* 181 pp 27-30
[33] Santos D K, Brandão Y B, Rufino R D, Luna J M, Salgueiro A A, Santos V A and Sarubbo L A 2014 Optimization of Cultural Conditions for Biosurfactant Production from Candida lipolytica *Biocatalysis and Agricultural Biotechnology* 3 48-57
[34] Bezza F A and Chirwa E M N 2015 Production and Applications of Lipopeptide Biosurfactant for Bioremediation and Oil Recovery by Bacillus subtilis CN2 *Biochemical Engineering Journal* 101168-178
[35] Najafi A R, Roostaazad R, Soleimani M, Arabian D, Moazed M T, Rahimpour M R and Mazinani S 2015 Comparison and Modification of Models in Production of Biosurfactant for Paenibacillus alvei and Bacillus mycoides and Its Effect on MEOR Efficiency *Journal of Petroleum Science and Engineering* 128 177-183
[36] Chen Y C, Chiang T J, Liang T W, Wang I L and Wang S L 2012 Reclamation of Squid Pen by Bacillus licheniformis TKU004 for the Production of Thermally Stable and Antimicrobial Biosurfactant Biocatalysis and Agricultural Biotechnology 1 62-69

[37] Hamlata B, Selvin J and Tukaram K 2015 Optimization of Iron Chelating Biosurfactant Production by Stenotrophomonas maltophilia NBS-11 Biocatalysis and Agricultural Biotechnology 4 135-143

[38] de França I W L, Lima A P, Lemos J A M, Lemos C G F, Melo V M M, de Sant’ana H B and Gonçalves L R B 2015 Production of a Biosurfactant by Bacillus subtilis ICA56 Aiming Bioremediation of Impacted Soils Catalysis Today 255 10-15

[39] Elazzazy A M, Abdelmoneim T S and Almaghribi O A 2015 Isolation and Characterization of Biosurfactant Production Under Extreme Environmental Conditions by Alkali-Halo-Thermophilic Bacteria from Saudi Arabia Saudi Journal of Biological Sciences 22 466-475

[40] Thavasi R, Jayalakshmi S and Banat I M 2011 Application of Biosurfactant Produced from Peanut Oil Cake by Lactobacillus delbrueckii in Biodegradation of Crude oil Bioresource Technology 102 3366-3372

[41] Sundaram S and Thakur I S 2015 Biosurfactant Production by a CO2 Sequestering Bacillus sp. Strain ISTS2 Bioresource technology 188 247-250

[42] Sajna K V, Sukumaran R K, Gottumukkala L D and Pandey A 2015 Crude Oil Biodegradation Aided by Biosurfactants from Pseudozyma sp. NII 08165 or Its Culture Broth Bioresource technology 191 133-139

[43] El-Sheshhtawy H S and Doheim M M 2014 Selection of Pseudomonas aeruginosa for Biosurfactant Production and Studies of Its Antimicrobial Activity Egyptian Journal of Petroleum 23 1-6

[44] Zouari R, Ellouze-Chaoubouni S and Ghribi-Aydi D 2014 Optimization of Bacillus subtilis SPB1 Biosurfactant Production Under Solid-State Fermentation Using by-Products of a Traditional Olive Mill Factory Achievements in the Life Sciences 8 162-169

[45] De Lima C J B, Ribeiro E J, Servulo E F C, Resende M M and Cardoso V L 2009 Biosurfactant Production by Pseudomonas aeruginosa Grown in Residual Soybean Oil Applied Biochemistry and Biotechnology 152 156

[46] Onbasli D and Aslim B 2009 Biosurfactant Production in Sugar Beet Molasses by Some Pseudomonas spp Journal of Environmental Biology 30 161-163

[47] Makkar R and Cameotra S 2002 An update on The Use of Unconventional Substrates for Biosurfactant Production and Their New Applications Applied Microbiology and Biotechnology 58 428-434

[48] Krieger N, Neto D C and Mitchell D A 2010 Production of Microbial Biosurfactants by Solid-State Cultivation Biosurfactants 672 203-210

[49] Pandey A, Soccol C R and Mitchell D 2000 New Developments in Solid State Fermentation: I-Bioproducts and Processes Process Biochemistry 35 1153-1169

[50] Nawawi W M F W, Jamal P and Alam M Z 2010 Utilization of Sludge Palm Oil as a Novel Substrate for Biosurfactant Production Bioresource Technology 101 9241-9247

[51] Pekin G, Vardar-Sukan F and Kosaric N 2005 Production of Sophorolipids from Candida bombicola ATCC 22214 Using Turkish Corn Oil and Honey Engineering in Life Sciences 5 357-362

[52] Rodrigues M S, Moreira F S, Cardoso V L and de Resende M M 2017 Soy Molasses as a Fermentation Substrate for the Production of Biosurfactant using Pseudomonas aeruginosa ATCC 10145 Environmental Science and Pollution Research 24 18699-18709

[53] Roy A 2017 Review on the Biosurfactants: Properties, Types and its Applications J Fundam Renewable Energy Appl 8 2

[54] Hubbard A 2004 Surface and Interfacial Tension: Measurement, Theory and Applications Stanley H (Ed.) (New York: Dekker) pp 619

[55] Martin A 1993 Coarse dispersions, Physical Pharmacy, fourth ed. William and Wilkins USA pp 496-502
Advancing your Surface Science Wilhelmy plate method. 
https://www.kruss.de/services/education-theory/glossary/wilhelmy-plate-method/.

Hidayat Y, Rahardjo S B and Syarief S 2010 Optimization of Glycerol Adsorption Capacity on \( \text{Å} \text{Zr}_{\text{A}} \text{-Al}_{\text{O}_3} \) and Its Surface Tension Effect on Adsorptive Capacity As a Preliminary Study of Separation of Glycerol on Biodiesel Wastes. *Eksains* 2

Jiravivitpanya J, Maneenintr K and Boonpromate T 2017 Experiment on Measurement of Interfacial Tension for Subsurface Conditions of Light Oil from Thailand. *MATEC Web of Conferences* 95 18007

Abalos A, Pinazo A, Infante M R, Casals M, Garcia F and Manresa A 2001 Physicochemical and Antimicrobial Properties of New Rhamnolipids Produced by Pseudomonas aeruginosa AT10 from Soybean Oil Refinery Wastes. *Langmuir* 17 1367-1371

Marchant R and Banat I M 2017 Protocols for Measuring Biosurfactant Production in Microbial Cultures. *In Hydrocarbon and Lipid microbiology protocols* (Berlin: Springer) pp 119-128

Bradford M M 1976 A Rapid and Sensitive Method for the Quantitation of Microgram Quantities of Protein Utilizing the Principle of Protein-Dye Binding. *Anal Biochem* 72 248-254

R. Ardianingsih 2010 The use of High Performance Liquid Chromatography (HPLC) in the Process of Ion Detection Analysis. *Berita Dirgantara* 10 4

Brumano L P, Antunes F A F, Souto S G, dos Santos J C, Venus J, Schneider R and da Silva S S 2017 Biosurfactant Production by Aureobasidium pullulans in Stirred Tank Bioreactor: New Approach to Understand the Influence of Important Variables in the Process. *Bioresource Technology* 243 264-272

Rita de Cássia F, Almeida D G, Meira H M, Silva E J, Farias C B, Rufino R D and Sarubbo L A 2017 *Production* and Characterization of a New Biosurfactant from Pseudomonas cepacia Grown in Low-Cost Fermentative Medium and Its Application in the Oil Industry. *Biocatalysis and Agricultural Biotechnology* 12 206-215

Aparna A, Srinikethan G and Smitha H 2012 Production and Characterization of Biosurfactant Produced by a Novel Pseudomonas sp 2B. *Colloids and Surfaces B: Biointerfaces* 95 23-29

Alvarez V M, Jurelevicius D, Marques J M, de Souza P M, de Araújo L V, Barros T G, Alves de Souza R O M, Freire D M G and Seldin L 2015 Bacillus amyloliquefaciens TSBSO 3.8 a Biosurfactant-Producing Strain with Biotechnological Potential for Microbial Enhanced Oil Recovery. *Colloids and Surfaces B: Biointerfaces* 136 4-21

Rusmana I 2008 *Fermentation Operation System* (Bogor: Departement of Biology, IPB University)

Avili M G, Fazaelipoor M H, Jafari S A and Ataei S A 2012 Comparison Between Batch and Fed-Batch Production of Rhamnolipid by Pseudomonas aeruginosa. *Iranian Journal of Biotechnology* 10 263-269

He N, Wu T, Jiang J, Long X, Shao B and Meng Q 2017 Toward High-Efficiency Production of Biosurfactant Rhamnolipids Using Sequential Fed-Batch Fermentation Based on a Fill-and-Draw Strategy. *Colloids and Surfaces B: Biointerfaces* 157 317-324

Md Noh N A, Mohd Salleh S and Yahya A R M 2014 Enhanced Rhamnolipid Production by Pseudomonas aeruginosa USM-AR 2 via Fed-Batch Cultivation Based on Maximum Substrate Uptake Rate. *Letters in applied microbiology* 58 617-623

Kronemberger F A, Borges C P and Freire D M 2010 Fed-Batch Biosurfactant Production in a Bioreactor. *International Review of Chemical Engineering* 2 513-518

Aghaeifar Z, Strand S, Austad T, Puntervold T, Aksulu H, Navratil K, Storas S and Håmsø D 2015 Influence of Formation Water Salinity/Composition on the Low-Salinity Enhanced Oil Recovery Effect in High-Temperature Sandstone Reservoirs. *Energy & Fuels* 29 4747-4754

Kargarpoor M A 2017 Investigation of Reservoir Temperature in a Gas Reservoir in Middle East: Case Study. *Journal of Petroleum Exploration and Production Technology* 7 531-541

Sheng J J 2017 *Enhanced Oil Recovery. Field Case Studies, Foams and Their Applications in Enhancing Oil Recovery* Chapter 11 Elsevier Lubbock (2013) pp 251-280
[75] Hakiki F, Maharsi D A and Marhaendrajana T 2015 Surfactant-Polymer Coreflood Simulation and Uncertainty Analysis Derived from Laboratory Study Journal of Engineering and Technological Sciences 47 706-725

[76] Yang S 2017 Physical Properties of Reservoir Fluids Under Reservoir Conditions. In Fundamentals of Petrophysics (Berlin: Springer) pp 135-177

[77] Kamari A and Mohammadi A H 2014 Screening of Enhanced Oil Recovery Methods (USA: Handbook on Oil Production Research Nova Science Publishers Inc)