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An Overview of Microbial Enhanced Oil Recovery

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Abstract

Crude oil still stands as a major contributor to the energy sector. Initially, primary and secondary recovery methods are employed to extract the oil from the reservoirs in which it naturally occurs. Once these methods have been exhausted, tertiary recovery methods are used to recover the remainder of what is typically two-thirds of the Original Oil In Place (OOIP). The focus of this study was to provide an overview of the Microbial Enhanced Oil Recovery (MEOR) employed as a tertiary or Enhanced Oil Recovery (EOR) method. MEOR facilitates the use of microorganisms to enhance oil recovery and involves a series of oil-enhancing mechanisms spurred on by microbial activity. Microorganisms possess the ability to metabolise hydrocarbons to produce organic solvents such as alcohols, biopolymers, biosurfactants, gases, and acids as metabolites which then improve the fluidity of the crude oil, the metabolic process occurs either in-situ or ex-situ. All the additives utilised for MEOR are also biodegradable making it a more environmentally friendly process than other Chemical Enhanced Oil Recovery (CEOR) mechanisms, and they employ various mechanisms simultaneously making it more effective. Biosurfactants reduce the interfacial surface tensions and viscosity of the oil increasing its mobility, biopolymers aid in selective plugging and enhance the sweep efficiency of subsequent waterfloods, biogases increase the pressure of the reservoir which will aid in displacing the oil and they may be dissolved in the oil to reduce its viscosity, and the solvents and acids also play a role in viscosity and permeability alterations. Biodegradation of heavy oil constituents to light constituents can be undertaken through either aerobic or anaerobic degradation to increase oil mobility. Field trials conducted globally showed that MEOR technology could be effectively employed to enhance oil recovery. However, several factors hinder the widespread application of the technology such as inconsistency between laboratory tests and field trial results due to the unpredictable nature of the microbes, the complexity of the MEOR process, lower than expected oil recoveries, and lack of standardised reporting regulations. All the hindering factors have placed skepticism around the process. Standard reporting procedures and economic analyses of trials should become mandatory to increase confidence in the feasibility of the process. Novel technologies of Enzyme Enhanced Oil Recovery (EEOR) and Genetically Engineered Microbial Enhanced Oil Recovery (GEMEOR) may be breakthrough technologies in the further advancement of MEOR.

Keywords: *Enhanced Oil Recovery (EOR); Microbial Enhanced Oil Recovery (MEOR); Review; Petroleum; Reservoir; Production.*

1. Introduction

1.1. Enhanced Oil Recovery (EOR)

Crude oil still stands as a major contributor to the energy sector. It exists in complex capillary networks within porous underground reservoirs, and it is from these reservoirs that the oil is extracted. Traditional oil recovery consists of primary and secondary oil recovery mechanisms [1-3]. Primary oil production uses the earth's pressure as a natural driving force in the reservoir or it is done by pumping. As the efficacy of the primary production declines with a declining driving force, secondary production methods are employed, and this involves either waterflooding or gas flooding of the reservoir to introduce the driving energy into the reservoir [2].

Once this secondary method becomes economically exhausted, on average, only a third of the Original Oil In Place (OOIP) has been extracted meaning that two-thirds of the OOIL remains and cannot be extracted via these methods.

This is when tertiary or Enhanced Oil Recovery (EOR) methods may be used. The main reason for the traditional recovery methods being ineffective in recovering the residual oil is that the residual oil has a high viscosity which prevents it from flowing to the producing wells. In addition to this, there is also a high interfacial tension between the oil and water (from the waterflooding period) which increases the capillary forces that retain the crude oil in the reservoir rocks capillary pores [4]. EOR methods therefore need to effectively reduce the viscosity of the residual crude oil to improve its flow properties so that it may be recovered. EOR methods consist of Chemical Enhanced Oil Recovery (CEOR) methods such as polymer/surfactant/alkaline etc. flooding (these are the most commonly used methods), thermal methods such as steam injection, or Microbial Enhanced Oil Recovery (MEOR) [2].

1.2. Microbial Enhanced Oil Recovery (MEOR)

MEOR facilitates the use microorganisms to enhance oil recovery and involves a series of oil-enhancing mechanisms spurred on by microbial activity. As a result of decades worth of research, it is now known that carefully selected microorganisms possess the ability to metabolise hydrocarbons to produce organic solvents such as alcohols, biopolymers, biosurfactants, gases, and acids as metabolites which then improve the fluidity of the crude oil. An overview of MEOR is depicted in Figure 1. The microorganisms also can reduce the build-up of paraffin in the wells which will also lead to enhanced oil recovery. MEOR products are more advantageous than chemical-based EOR in that the cost is independent of crude oil prices as microorganisms can produce metabolites by utilising inexpensive raw materials such as molasses and other agricultural by-products.

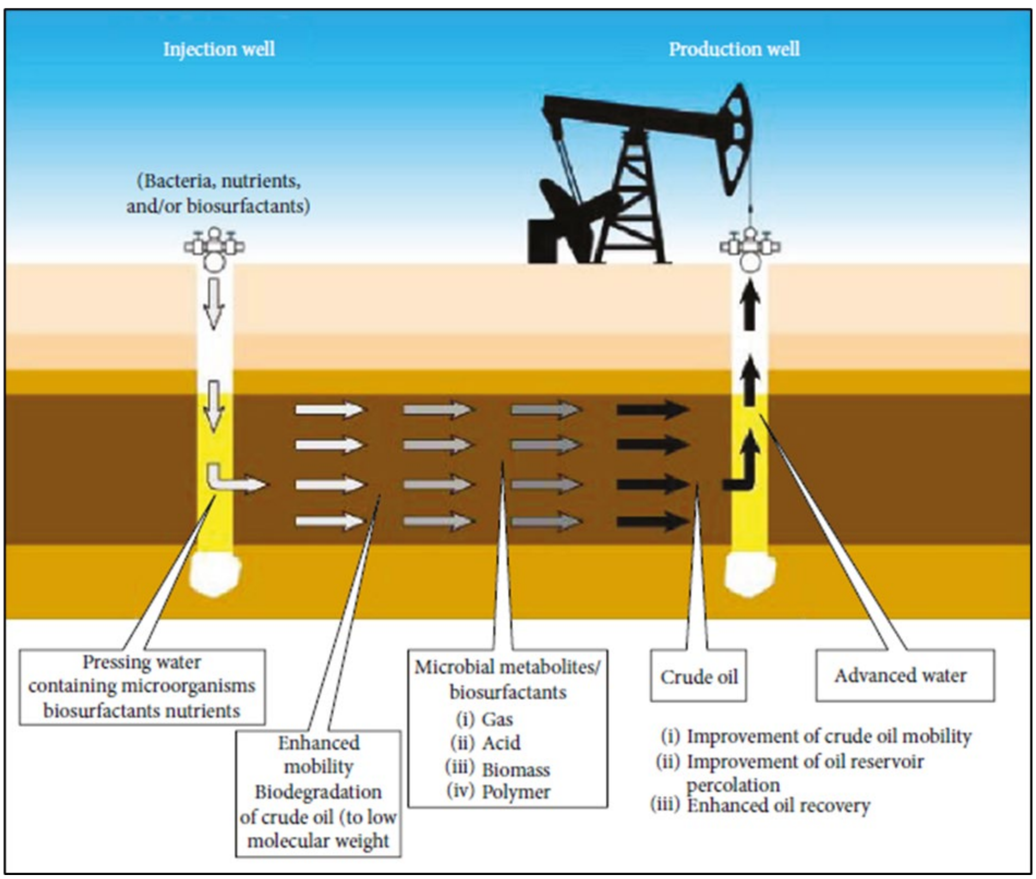

Figure 1. MEOR mechanisms(modified after [5]).

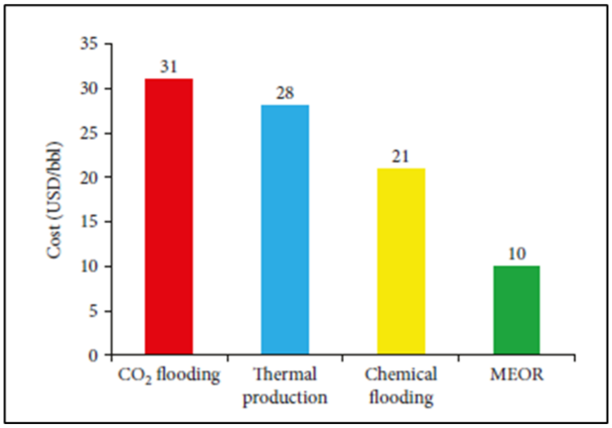

Figure 2. Cost estimations of EOR techniques (modified after [5]).

Figure 2 depicts the cost estimations of the different EOR techniques, from this, it can be seen that MEOR has a significantly lower cost than gas flooding, thermal production, and chemical flooding procedures. All the additives utilised for MEOR are also biodegradable making it a more environmentally friendly process as compared to other CEOR mechanisms. Additional benefits of MEOR over other tertiary recovery methods are that multiple mechanisms typically work simultaneously during this process resulting in a higher effectiveness, and indigenous microbes may be used which lowers the risk of losses due to the degradation.

The oil industry also utilises MEOR techniques for processes other than enhanced oil recovery, this includes remediation of the oil spill in groundwater and the soil, for the cleaning of boreholes, downhole equipment, and piping [6-7].

1.2.1. History and development of MEOR

Beckman first suggested back in 1926 that microorganisms could be utilised to remove oil from the porous media in reservoirs. Up until the 1940's not much was done to explore this, however, in 1947 ZoBell and his research group conducted a series of laboratory experiments to investigate this phenomenon. ZoBell presented their findings which described the main mechanisms that allowed for the oil to be released from the porous media. These mechanisms included processes such as the dissolution of inorganic carbonates undertaken by metabolites, bacterial gas production which dissolves into the oil thereby decreasing its viscosity and improving its flow, the production of wetting agents or surface-active substances, as well the bacteria's high affinity for solids. The first patent published by ZoBell employed the injection of the *Desulfovibrio hydrocarbonoclasticus* bacterium with oxidised sulphur compounds and lactose as a carbon source, but no field trials were conducted using this. He later published a patent that introduced the notion of the addition of oxygen-free hydrogen which was produced by a *Clostridium* bacterium species on a carbohydrate. ZoBell's patented processes' laboratory experiments involved the use of sandpacked columns; the bacteria in these processes produced gases, acids, surface-active agents, and solvents which released the oil from the sandpack columns. Updegraff later repeated these experiments and, in 1957, published a patent that involved the use of underground injected microorganisms, specifically a bacterium species of *Desulfoyibrio*, which were capable of converting a cheaper substrate, such as molasses, into the necessary oil recovery agents. However, no field trials were conducted for this process either [1-2,8]

During the early years of MEOR studies, it had not been conclusively proven that microorganisms could anaerobically metabolise hydrocarbons and information on the natural microbiology of the oil reservoirs was severely lacking. There was however no doubt surrounding whether or not these microorganisms were capable of actually enhancing oil recovery by some means as most of their mechanisms had already been known. For example, it was known that bacteria can produce acids from oil and dissolve carbonates which would increase permeability. They can produce biogases which increase the reservoir pressure and reduce the oil viscosity when the gas is dissolved in it. They can produce metabolites such as biosurfactants which decrease the viscosity of the oil, or biopolymers which would increase the viscosity of the water during the waterflooding procedure which leads to a more effective operation. Bacterial growth is also capable of selectively plugging the porous media formation which could improve the water injection profile during water flooding. The oil recovery enhancing capabilities were therefore not under scrutiny, but rather whether or not this process could be employed in an economically practical manner and one that follows a scientifically valid procedure.

Field trials would aid in getting closer to reasoning this. The first field trial for MEOR was conducted by Yarbrough in 1954. Following this, a large number of field trials were then conducted in the former Soviet Union and Eastern Europe. These trials employed anaerobic microorganisms for the oil recovery, and gas and acid producing bacteria were used for single simulation operation. In addition to this, Henningen put forth the utilisation of biopolymers for selective plugging to improve the swept area. At this stage, the MEOR mechanism had still only been proposed and recognised. However, in the 1970's, this technology became increasingly promoted as a result of the oil crises due to its apparent economic feasibility and it increasingly became a scientifically recognised mechanism. This was supported by further research and field trials which were undertaken in oil-producing countries such as the United States, Europe, China, Canada, Russia, and Australia [1,8].

2. MEOR methods, mechanisms, and field applications

2.1. MEOR methods

In the preliminary phase of MEOR techniques applications, certain investigations need to be undertaken. The crude oil and reservoir properties need to be assessed to determine their compatibility with the properties of the MEOR process that is to be employed. This compatibility screening takes into account the crude oil's physiochemical properties, the production performance of the reservoir, and the properties of the reservoir (such as temperature). Samples are extracted from the reservoir and this is tested with the proposed MEOR system. Tests are also conducted to identify the indigenous hydrocarbon-consuming bacteria that naturally occur in the reservoir and are thus suitably adapted to the conditions of the reservoir. From this information, a suitable process strategy can be developed [7].

There are two ways in which the MEOR technique can be applied on the individual oil wells and into the reservoir. Firstly, it could be applied directly from the well being treated, or secondly, it could be applied to the well being directly treated as well as adjacent wells of the same reservoir. The volume of the reservoir that is to be treated is used to determine the amount of biomaterial that is required to be injected. The prepared biological solution is then pumped through the injection well and is followed by water which aids the solution in reaching the oil-rich zones. The treated well in then shut for a period of between 1 to 7 days, after this period the oil production process is resumed. This procedure is typically repeated every 3 to 6 months as it aids the microorganisms to migrate deeper into the oil deposits. There are two methods in which the MEOR metabolites are produced, namely ex-situ production and in-situ production [7].

2.1.1.Ex-situ metabolite production

The ex-situ metabolite production for the MEOR process involves the use of exogenous or indigenous bacteria which naturally occur in the reservoir. These bacteria produce the necessary metabolites such as biosurfactants, biopolymers, and emulsifiers externally from the reservoir environment. That is, the microorganisms are typically cultivated in mobile plants or industrial fermenters and they are then injected back into the reservoir in an aqueous solution [7].

2.1.2. In-situ metabolite production

In-situ metabolite production involves metabolite formation which results from microbiological processes that take place directly in the reservoir. This can either be done through the use of indigenous bacteria or through the use of exogenous bacteria which are injected into the reservoir. This production process can further be divided into two processes. The first process involves the stimulation of the naturally occurring indigenous bacteria within the reservoir by injecting nutrients into the reservoir to promote their metabolism. The second or alternative process involves the injection or either indigenous or exogenous microbial cultures along with the necessary nutrients; this is the preferred application method. With either of these in-situ methods, the microbiological and physiochemical conditions of the reservoir oil bed must be known as the growth of a microorganism community depends greatly on the nutrients available to sustain it [7].

The in-situ metabolite production route involves a two-step process. The first step involves the pumping of water and oxygen into the oil reservoir. This water-air mixture contains salts, nitrogen, and phosphorous which aid in stimulating the indigenous microflora. This mixture promotes the aerobic bacteria to oxidize the hydrocarbons resulting in the production of organic acids, alcohols (such as methanol and ethanol), biosurfactants, and carbon dioxide which will increase the pressure of the reservoir. The second step involves the activation of the indigenous anaerobic bacteria through the injection of oxygen-free water. These bacteria metabolise crude oil to produce acids and biogases which increase the reservoir pressure as they accumulate. If the pressure induced by the biogases in the reservoir becomes high enough, the gas (typically methane or carbon dioxide) may be dissolved into the liquid oil phase which will reduce its viscosity thereby increasing its fluidity and subsequently improving the oil production. Carbon dioxide also can dissolve the carbonates in the rocks if it reacts with the minerals in the rocks and will thereby increase the permeability of the rock formation [7].

2.1.3. Comparison of in-situ and ex-situ process routes

The two metabolite production routes possess their characteristics and, with it, certain pros and cons. The in-situ production route is typically much cheaper than the ex-situ route as well as many other tertiary oil recovery processes, however, it does not have a very high effectiveness as the natural reservoir conditions are often not optimal to promote the growth and metabolisis of the microbes. This is therefore one of the main hindrances in the application of in-situ process routes as it becomes difficult to select or develop a microbial strain that will thrive under the extreme conditions that are present in most reservoirs [9]. With regards to the ex-situ process route, the metabolite products are typically higher than that obtained via the in-situ route, however, it has many additional production costs associated with it as it requires additional production and purification equipment that is otherwise not needed with the in-situ process [1].

Economically the in-situ process does present the more preferable solution, however, its effective application hinders the suitable screening and development of microbial strains that can adapt to the environment of the reservoir that is to be treated so that they may produce a higher yield of the necessary metabolites. In terms of having a higher success rate, however, the ex-situ process is preferable as this route results in metabolites that are much better suited to the reservoir conditions. There is a way, however, to possibly address the issues presented with both these routes and that could be done through Genetically Engineered MEOR (GEMEOR). GEMOER will involve the use of various genetic engineering processes and other techniques such as recombineering, protoplast fusion, and mutagenesis. The goal of this technique would be to increase the yield of the metabolite products and introduce the optimal environmental adaptability characteristics by combining the favourable traits of the different microbial strains. At present however, the field trials which are being conducted or have been conducted still typically employ the in-situ process route [1].

2.1.4. Simulation of the MEOR process

In the implementation of the MEOR process, it is necessary to ascertain important operation parameters of the field to develop a suitable prediction of the best process route to follow. This step may be aided by the establishment of a numerical simulation and mathematical model however, this can often be quite complex for the MEOR technique as it will involve a combination of physical, chemical as well as biological factors [1].

A numerical study of the MEOR process was undertaken in the 1980’s and this simulation provided both a qualitative and quantitative analysis of the process. An advantage attached to numerical simulations is that they are low-cost analysis techniques and have a high repeatability and can therefore be effectively used in the determination of the best implementation strategies, reduced risks, and optimal scientific decisions. The model was based on the black oil model and focused primarily on the movement of oil, water, microorganisms, nutrients as well as metabolites within the treated reservoir. Other parameters were also considered within this model such as the effects that the metabolites have on the reservoir's operating parameters, namely the viscosity of the oil, the interfacial tension between the oil and the water and the rock permeability. Certain factors were however not taken into consideration such as the salinity conditions of the water and the adsorption of the product which meant that the model was relatively simplified. In general, MEOR mechanism is quite complex which often leads to difficult solution strategies [1].

2.2. MEOR mechanisms

There are many ways in which microorganisms are utilised to enhance oil recovery in MEOR processes. Wells may be stimulated via the removal of wellbore damage which will increase the gas and oil production of the well; this process route involves utilising the microorganisms for the removal of paraffin from both inside and around the wells. Microorganisms may also be used to alter the permeability profile of the reservoirs; certain reservoirs may have a high permeability area which has an effect of reducing the sweep efficiency during water flooding. Microorganisms and nutrients may be injected into these channels, the microorganisms grow in them and effectively plug these areas causing any subsequent waterflooding to be directed towards regions that were previously unswept thus enhancing the oil recovery. This process may also be done with indigenous microorganisms, in this case, only the nutrients are injected into the reservoirs. Some bacteria promote oil biodegradation; these bacteria feed on and break long-chain hydrocarbons into smaller chained molecules. These smaller chained molecules generally have a lower viscosity, and this reduced viscosity enhances the oil recovery as it will be displaced by waterflooding much more easily. Biogas can be produced by the microorganisms which can reduce the viscosity of the oil; the two biogas products that are produced when the microbes metabolise are carbon dioxide and methane, if sufficient gas is produced then it may dissolve into the oil and effectively reduce its viscosity (this had been proved by laboratory tests). The biogas may also create an increased pressure in the reservoirs which would force the oil out of the pores. Finally, the microorganisms may produce bioproducts which have multiple ways of enhancing the oil recovery; these products include biosurfactants, alcohol, biopolymers, and acids. These products are produced during the metabolic process and are done so under the reservoirs' conditions. These products can release the trapped oil by reducing the capillary forces that hold the oil in place, and the acids can increase permeability by dissolving the carbonate rocks [6].

Generally, well stimulation is not considered an MEOR process as it does not primarily enhance oil recovery by increasing the amount of oil available for recovery but rather accelerates oil recovery. The other mechanisms mentioned, namely permeability profile alteration, oil biodegradation, biogas production, and bioproduct generation are taken as the true MEOR processes as they enhance oil recovery by reducing capillary and other trapping forces, reducing the viscosity, and improving sweep efficiency. Sweep efficiency is a measure of the effectiveness of the oil recovery process and is dependent on the volume of the reservoir that is effectively contacted by the injected fluid [6]. Looking primarily at the viscosity of the oil, there are two ways in which this is typically reduced; firstly, at a physical level and secondly at a chemical level. At a physical level, the oil-water interfacial tension is reduced, or the crude oil is emulsified by various bioproducts. At a chemical level, the oil viscosity is reduced when the microorganisms and enzymes degrade the heavy fractions of the oil. In general, it is fundamental that the microbial bioproducts induce a series of necessary changes to the physiochemical properties of the crude oil to enhance its recovery, as well as significantly improve the lithology of the reservoir rocks. To this end, MEOR technologies can often be quite complex as they integrate multiple recovery mechanisms with various bioproducts. The various mechanisms are depicted in Figure 2 [1].

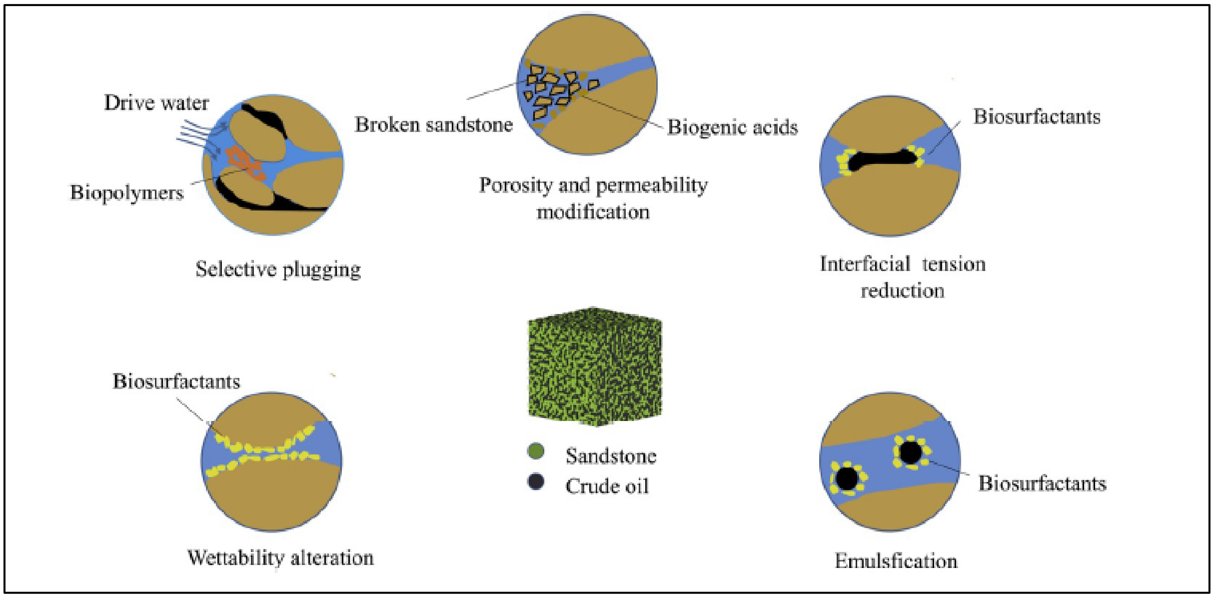

Figure 3. MEOR mechanisms (modified after [1])

2.2.1. Microbial classification

Field trials can often be classified following the type of bacterium that is used. The type of bacteria participating in the process is a crucial aspect as their ability to withstand reservoir conditions and their robustness will greatly influence the degree of enhancement of the oil recovery. The typical bacteria which are used in the trials are:

- *Bacillus*: This bacterium can be used to produce biosurfactants, alcohols as well as biogases.
- *Clostridia*: Used to produce acid and gases.
- *Pseudomonas*: This bacterium has enhanced microbial growth and therefore can be used in selective plugging applications to alter the reservoir permeability and well as produce biopolymers. It can also produce biosurfactants.
- Nitrate reducing bacteria: This is used to alter permeability and effectively combat any souring that may occur.
- Others: There are other bacterium utilised which can biodegrade hydrocarbons, alter the permeability of the reservoir, produce biogases and lower the oil viscosity.

The two most commonly used bacteria are *Bacillus* and *Clostridia* and out of these two, the spores of the *Clostridia* bacterium are used more frequently. Sulphate-reducing bacteria were previously used however their utilisation later became avoided. Nitrate reducing bacteria were highly effective in reducing the permeability of the reservoir. From the observations made by Maudgalya *et al.*, no relationship was found between the outcome of conducted field trials and the type of bacteria used as microbial behaviour is often inconsistent [6].

2.2.2. Nutrients

One of the largest contributors to the production cost of the MEOR process is the nutrients. The correct amount and composition need to be available as microorganisms require this carbon source from nutrients to grow and metabolise. This carbon source is usually made available to the microorganisms in the form of sugar or from the oil itself, however, studies by Jenneman and colleagues showed that the rate of metabolism and bioproduct generation typically slows down when the oil itself is utilised as the nutrient. To this end, it would be more favourable to introduce a nutrient into the reservoir. The most commonly used nutrient or carbon source is molasses as it is cheap, easily available, and can be pumped into a well as a slurry. Other nutrients which were utilised in field trials are nitrates and phosphorous salts which were taken from fertilizers [6].

2.2.3. Role of biosurfactants

Biosurfactants are one of the bioproducts produced from the metabolic action of the microbes. They are amphiphilic compounds that are surface-active and are typically produced from various microorganisms. They possess similar properties to surfactants that have been chemically synthesized but also present certain advantages over chemical surfactants in that they are also biodegradable, they are resistant to temperature, they have a low toxicity, they can endure saline conditions and they are pH-hardy. Biosurfactants that possess low molecular weights often exhibit excellent ability in reducing the surface and interfacial tension, whilst the larger molecules are more beneficial in forming stable emulsions as they can tightly arrange themselves at the interface. Glycolipids and lipopeptides are the most widely used biosurfactants within the MEOR field as they have the greatest commercial and industrial potential and in general, are one of the most promising tools in MEOR [1].

There are three ways in which they can enhance the recovery of crude oil, namely by reducing the interfacial tension between the oil and the water, altering the wettability, and lastly by emulsifying the crude oil. As the biosurfactants come into contact with the residual oil trapped in the pores of the reservoir, it decreases the interfacial tension between the oil and water and effectively improves the fluidity of the oil through the reduction of the capillary forces. The emulsifying effect of the biosurfactants produces an oil-in-water emulsion. This emulsion greatly improves the effectiveness of the waterflooding procedure which directly enhances the oil recovery. Recent studies have reported on the capabilities of biosurfactants in altering the wettability properties of the reservoir rocks which also plays an important role in enhancing oil recovery, this is driven by not only the biosurfactants but also by the biofilm that is formed. Armstrong *et al.* [10] undertook experiments that showed that the pore radius and pore morphology significantly impact the ability of the biosurfactant to improve the MEOR efficiency and alter the rock wettability. Generally, when the pore radius and sphericity increased, so did the MEOR efficiency. If the biosurfactant reduces the interfacial tension in wider rock pores, then the bigger oil drops will break into smaller droplets resulting in the emulsification of the oil and water. For these wider pores, it is also more favourable to have a rock surface that is water-wet as it maximises the contact angle of the oil rock which results in a larger capillary number. On the other hand, if the rock pores are narrow, a larger capillary force will result in an insufficient interfacial tension reduction brought on by the biosurfactants which do not effectively release the trapped oil. However, it is also possible for the bacteria at the interface within these narrow pores to produce biosurfactants which form emulsions that alter the fluidity of the crude oil and consequently plug the arrow pores [1].

There is typically a low yield of biosurfactants when the in-situ MEOR techniques are employed as the environment in which the microbial cultures grow has a large impact on biosurfactant production because they are formed during the second phase of microbial growth. For this reason, the primary means for production of the biosurfactants are in ex-situ fermenters. This ex-situ application means higher production costs related to these biosurfactants which may be an inhibitor of its application. The reason, however, that the use of this technology is still successful is that there is a low purity required for the MEOR process which eliminates purification costs. In addition to this, cheap and renewable agricultural carbon sources, such as molasses and dairy industry waste, significantly reduce the cost of the environment needed for biosurfactant production. The cheaper carbon sources used are often dependent on their availability in specific locations. For instance, Brazil, China, and India may use molasses as they are primarily oil producing companies, whilst date molasses may be used in the Arab region [1].

Despite the low purity requirement and alternative, cheaper cultivating routes, biosurfactants are typically more expensive than chemical surfactants. Another measure that could therefore be employed to reduce the cost of the biosurfactants would be to mix them with the chemical ones, and studies have shown that that this mixed product has an improved activity [11]. There are also reuse approaches available for biosurfactants; Long *et al.* [12] investigated that this can be done by changing the pH. Lastly, biosurfactants may also be used in the cleaning of oil tanks, the transportation of crude oil and bioremediation [1].

2.2.4. Role of biopolymers

A variety of microorganisms can metabolise to produce biopolymers which are high molecular weight molecules. These biopolymers contain hydroxyl groups that may cause the molecules to form dipole, ion-dipole, or hydrogen bonds with either itself or with other substances to form the polymer structures. These biopolymers possess desirable characteristics for EOR such as viscosifying abilities, shear resistance, and the ability to be stable in extreme environments. During displacement processes in the reservoir, such as water flooding, the fluid that is injected tends to flow chiefly through the zones or channels with high permeability. Biopolymers and other bacterial growth aid in selective plugging processes which block these high permeability zones and effectively direct the injected fluid to other areas of the reservoir that contain oil thus enhancing the recovery [1,13].

The process of selective plugging can either involve the injection of nutrients which stimulate the indigenous bacteria, or the injection of nutrients with exogenous bacteria. The injected material (either nutrients or nutrients with bacteria) preferably flows through the channels with high permeability. The bacteria then grow within these channels selectively plugging it and effectively reducing its permeability. This process also balances the permeability of the reservoir and increases the sweep efficiency. In EOR processes, the biopolymers may also be used as tackifiers which increase the viscosity of the aqueous phase during water flooding which will decrease the mobility ratio of the oil to water. The most widely used component in this sense is xanthan gum. Xanthan gum is popular as it possesses many technical advantages such as being water soluble, having thickening properties, being resistant to saline conditions, and having both shear and anti-pollution stability. In addition to these, xanthan gum also exhibits shear-thinning behaviour. This is beneficial as it will possess a low viscosity in the high flow velocity regions of the wells when it is injected and will then exhibit a high viscosity in the displacement regions of the reservoir where the flow velocity is much lower. This makes it effective in displacing the oil and thus enhancing its recovery [1].

2.2.5. Role of biogases, solvents, and acids

An initial MEOR mechanism involves the use of microorganisms to produce gases, solvents, and organic acids as reagents. The gases produced by the bacteria are typically carbon dioxide, nitrogen, and methane and they are produced via the fermentation of carbohydrates or hydrocarbons. Biogas production occurs in situ; an accumulation of this pressure will aid in restoring the pressure of the reservoir and the gases may also dissolve into the oil and reduce its viscosity. The bacteria also can produce solvents such as acetone and ethanol. These solvents can then reduce the viscosity of the oil by dissolving into it and the alcohols can work effectively with biosurfactants making them a desirable co-surfactant. Another possible product is acidic gases and low molecular weight organic acids such as acetic acid and formic acid; this is produced as a result of fermentation. These biologically produced acids can dissolve the carbonate in the reservoir rocks and thus improve the reservoir's permeability. This group of metabolites, unlike biosurfactants and biopolymers, typically result in common chemical products that do not have exclusive properties and are often easy to synthesize. For this reason, the most suitable production process is the in-situ process which utilises inexpensive substrate. The bacteria that had been proven to enhance oil recovery at a lower cost are the anaerobic bacteria, *Clostridium acetobutylicum, Enterobacter cloacae* and *Methanobacterium* amongst others [1].

2.2.6. Role of biodegradation

The biodegradation process involves the conversion of the heavy constituents in the oil to light constituents. This process effectively alters the properties of the crude oil chiefly by reducing its viscosity which in turn improves the fluidity of the oil thereby enhancing its recovery.

For this reason, this process has been one of the most attractive approaches in the MEOR technique.

There are two ways in which biodegradation may be undertaken, namely through the use of aerobic degradation or through the use of anaerobic degradation. With aerobic biodegradation, dissolved oxygen is usually introduced into the reservoir with the injected fluid and this promotes the aerobic biodegradation process. Field trial studies were conducted in the Daqing Oilfield in China; this study involved the injection of dissolved oxygen to promote aerobic biodegradation of the heavy components in the oil and thus enhance its recovery [14]. Generally, the environment that naturally occurs in the reservoir is primarily an anaerobic one and it has been proven through investigation that the degradation of hydrocarbons occurs deep within the underground reservoirs is dominated by anaerobic degradation [15]. Within this anaerobic environment, studies conducted have shown that the microorganisms can degrade hydrocarbons such as benzene, alkane, toluene, naphthalene, phenanthrene, branched alkanes, and other hydrocarbon mixtures [1].

Its application in MEOR techniques is still, however, very limited and could be a result of an inadequate selection of bacteria which promote oil degradation or unfavourable operating conditions within the reservoir for this. Out of the two possible routes, anaerobic degradation does present the more favourable technique to enhance oil recovery [1].

2.3. Field applications

2.3.1. Preliminary field screening

The environmental conditions of the treated reservoir have a significant impact on the effectiveness of the microorganisms that have been activated within or injected into the reservoir. The important factors that do play a role in this include the reservoir lithology, the properties of the reservoir, and the properties of the fluid amongst others. All these factors have a direct influence on the growth, movement, and metabolism of the microorganisms. The factors that have the highest influence over the process are temperature, porosity, stress, pH, salinity, and the viscosity of the crude oil. Temperature considerations of the reservoir are extremely important as highly unsuitable temperature conditions will directly impact how the microorganisms grow as well as how their metabolites perform. The reservoirs used in field trials typically had temperatures below 93°C which is generally the maximum temperature for which the microorganisms can be effective [6]. The porosity within the reservoir has a direct influence over the flow and dispersion patterns of the microorganisms and their metabolites, low porosity conditions are not favourable for optimal operation. Stress, especially at great depths, can have a negative influence on the microorganisms' growth and metabolism, however, it does not influence the survival chances of the microorganisms. The pH will affect the growth and metabolism of the bacteria as it influences the enzyme activity and availability of nutrients. Furthermore, the pH may also affect the effectiveness of a biosurfactant, with low pH conditions being unfavourable as it will cause the biosurfactants to clump. The salinity of the reservoir environment also influences the metabolic activity of the microorganisms. A majority of successful reservoirs in field trials had salinities that were less than 100 000 ppm [6]. Different countries experience different reservoir conditions and have varying degrees of progress in terms of reservoir research, for this reason, most of them have their reservoir screening standards that they adhere to before field trials [1].

2.3.2. Field trials

Initial field trials of the MEOR technique began in the 1950's and 1960's and were chiefly undertaken in the United States, the former Soviet Union and Eastern Europe. At this time the main nutrient source was sucrose, and all of the operations were single well stimulations with the reservoirs being mainly influenced by the acids and gases generated by anaerobic microorganisms. There was however no theoretical basis or analytical methods which could be employed to formulate a comparison between the field trials that were conducted. The early 1980's saw the beginning of laboratory tests, these resulted in substantial references which were then used for the subsequent MEOR field applications. Laboratory experiments showed that microorganisms could enhance tertiary oil recovery by 10 % and microbial flooding increased it by 5% [5]. However, owing to the conditions of the reservoir and the complexity of the indigenous microorganisms, these laboratory tests presented many limitations as true reservoir conditions could not always be simulated. The important parameters that were required for these field trials included the preliminary screening factors, the suitable microbial strain and its composition, the type of nutrient required, and the treatment period amongst others. In-situ field applications gained popularity as their use did not require any additional field devices beyond what was already being used for waterflooding. This meant that the equipment as well as labour costs would be significantly reduced and thus the employment of this technique grew rapidly in the 1990's. Nutrients contribute to the main production cost when it comes to MEOR applications. Presently, molasses is the most widely used nutrient source as it presents a lower cost [1,16].

Despite some of its economic advantages, MEOR is still not a widely used EOR method as there are factors that have limited its field application. Some of the limitations are that: the bacteria that are suitable for MEOR applications cannot withstand high temperature or high saline reservoir environments, the heavy metal components in the crude oil are toxic to the microorganisms and will therefore destroy them, and if other microorganisms are injected into the reservoir then these microorganisms will have to compete with the indigenous ones for nutrients [1].

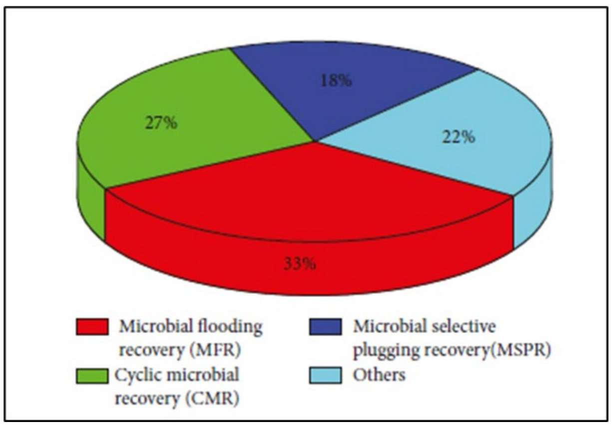

Figure 4. Survey results on MEOR types used ([5]).

The MEOR processes can be classed as microbial flooding recovery (MFR), cycle microbial recovery (CMR), microbial selective plugging recovery (MSPR), and microbial wax removal (MWR). The MFR type is the most widely used across the globe as it ranked first in a worldwide field trial survey that was conducted [5]. The results from this are depicted in Figure 4.

The field trials that have been conducted around the world in the past decades have all had varying degrees of success, but according to global statistics, more than 90% of the field tests yielded positive results [17].

In 1954, the United States conducted a field trial in the Lisbon oil field in Arkansas and did so by injecting molasses into the reservoir to stimulate the *Clostridium acetobutylicum* bacterium resulting in a process that employed recovery through the use of the gas, acid, and biosurfactant mechanisms. Field trials conducted in Oklahoma employed selective plugging methods; nutrients were injected into the reservoir to promote the growth of the indigenous microorganisms and these then blocked high-permeability areas and effectively reduced the permeability by 33% [18]. Field trials were also conducted in Oklahoma to test the in-situ biosurfactant production with the *Bacillus* bacteria strain. The results from this were that the concentration of the biosurfactants produced was nine times lower than the minimum that was required to improve the oil recovery [19]. MEOR field tests have also been conducted in several oilfields in China with processes that mainly employed the MWR and CMR routes. China has become one of the world leaders in the field of MEOR technology due to its successful MEOR applications in recent years. For example, before the end of 2012 the Daqing oilfield had recovered a total of 56 827 tons of oil after microbial flooding applications at 45 of the injection wells [16]. Field tests carried out in Romania employed the CMR and MFR processes which resulted in an average of 100% and 200% increase in oil production. The Piedra Coloradas oilfield in Argentina was injected with degrading bacteria that targeted hydrocarbons and with anaerobic fermentation bacteria for 12 months. This resulted in a 66% increase in the average production of the six injected wells, and the viscosity of the recovered oil had been significantly decreased [20]. The Vizacheres oilfield also in Argentina had been injected with facultative bacteria as well as nutrients for 19 months; this yielded a 20% increase in the oil production. In the Canadian Saskatchewan oilfield, indigenous microbial flooding tests were undertaken. The first stage of this test involved the infusing of the microorganisms which have been activated by nutrients, this resulted in the water content reducing by 10%. The second stage involved the employment of the MFR process. This test was conducted over 3 weeks, at the end of which the oil recovery increased from 10.18m^3/d to 16.7m^3/d [21]. The Oil and Natural Gas Corporation (ONGC) Limited, The Energy and Resources Institute (TERI), and the Institute of Reservoir Studies (IRS) in India all collaborated in the undertaking of field trials. These trials employed an anaerobic bacteria population and resulted in a threefold improvement of oil production [9].

2.3.3. Analysis of field trials

An analysis of the field trials that were conducted before 2007 was undertaken and reported by Maudgalya and colleagues, their analysis will be reported herein. Microorganisms do not typically thrive in environments that have a salinity greater than 100 000 ppm. However, half of the field trials which were analysed and had salinities greater than 100 000 ppm were successful. A possible reason for this is that these field trials were conducted in reservoirs that had been exhaustibly waterflooded with low salinity water which may have had the effect of lowering the salinity of some of these reservoirs. Single well trials seemed to be the preferred mode of testing as they used the least amount of time, money, and nutrients. These tests were considerably successful however since the injection and production well location were the same it could not be ascertained whether the success was a result of the MEOR process or well stimulation. It would be easier to determine the effects of the microorganisms in mobilising the oil if it were instead allowed to flow from one well to another, this concept is rigorously tested with waterflooding. Results obtained from these types of tests as opposed to single well injection tests will instill more confidence in the MEOR process abilities and encourage its application more. Another inhibiting factor for MEOR application is that there is inconsistent behaviour between what is observed in the laboratory tests and what may be observed in the field trials, as the field conditions could not easily be simulated in the laboratory. This inconsistency will make companies hesitant to invest their money in applying this tertiary recovery process.

Some of the field trials were conducted on reservoirs that were nearly depleted making it unlikely for any tertiary recovery method to increase the oil production in these reservoirs. As a result of this, the results from the MEOR application we not satisfactory which does not place the process in a good light as its true oil recovery enhancing abilities were not tested. The reason that these types of reservoirs were used is that investors were hesitant to apply this to other reservoirs to avoid the risk of causing permanent damage to them due to skepticism around the process. Small improvements in oil recovery were observed for certain trials where large volumetric improvements in the oil recovery were expected. A possible reason for this is that bioproduct concentrations from metabolisis are much lower than that which is observed with synthetic surfactants, and if losses such as adsorption are also taken into consideration, then these bioproduct concentrations will not be sufficient to release large amounts of oil. Another possible reason is that there had been extensive waterflooding in these reservoirs and thus great improvements in the oil recovery would not be possible. To this end, larger companies may not feel the need to invest in this process if it will only yield small improvements as it may not be economically feasible for them. Small companies however may be more inclined to apply this process as a marginal increase will add economic benefit to them. The type of fields that are however best suited to MEOR processes are waterflooded fields which possess a relatively high oil saturation level with low oil rates. Successful trials from these types of fields resulted in a production improvement from 1 bbl/d to 700 bbl/d.

The tests conducted confirmed that the microbes and nutrients can grow and travel in the porous reservoirs as their presence was detected in wells neighbouring the injector well. Oil biodegradation can be very useful in the recovery of heavy oil as some tests have shown this. It is still unclear however which specific species promotes this, but studies have reported that anaerobic degradation may be very slow. Permeability alteration was a method that had repeated success indicating that it is a very effective method. Results have further shown that it is not specific to one species type as it depends on microbial growth. Thus any type of bacterium can be utilised as long as it has a sufficient nutrient supply and can withstand the operating conditions.

Maudgalya *et al.* [6] further concluded that there had been a lack of standardization in the reporting of the field trial results which resulted in missing information and contradictory explanations. In addition to this, there had been no data supporting the economic advantages of these tests. This further creates skepticism amongst investors and within the oil industry about the process's feasibility.

3. Advantages, disadvantages, and recommendations

3.1. Advantages of MEOR

The most apparent advantage of the MEOR process is that it involves a low capital cost investment, and it is environmentally friendly. Furthermore, the metabolites may be produced in-situ, that is directly in the reservoir formation, which makes it more effective. The typical advantages of this process are [7]:

- An increase in the productivity of the oil wells resulting in a more efficient operation of the oil fields,
- A reduction in the mobility of the formation water as a result of the biopolymers produced from the metabolic processes,
- Its set-up costs are not as expensive when compared to other tertiary oil recovery methods,
- There is a low energy requirement for this process to be carried out which further reduces the cost,
- Heavy hydrocarbon components can be degraded
- The composition of light alkanes (< C_{20}) increases whilst the content of C_{20} – C_{40} alkanes is reduced,
- Crude oil can be emulsified such that its mobility to the production well increases,
- Aromatic ring structures and phenolic ring structures are split.

3.2. Disadvantages of MEOR

Whilst the MEOR process presents many advantages, there are still some drawbacks to its application. Some disadvantages of the process are [2,6]:

- The microorganisms may cause unfavourable plugging in the wells and may contribute to corrosion should they produce hydrogen sulphide,
- The by-products of the bacteria may also cause plugging,
- Effective penetration may be inhibited if the microorganisms begin producing their bioproducts at the time of injection,
- Laboratory tests are often inconsistent with field trial results,
- There is no standardized procedure around reporting trial results,
- There is a lot of skeptisism within the oil industry around the feasibility of the MEOR process,
- Insufficient reporting on the economic advantages of the process.

3.3. Recommendations

There are evident technical disadvantages to the MEOR process which creates skepticism around it and hinders its application. There are ways however in which the industry can address these. To avoid the plugging of the good bore, methods such as filtration should be employed before the well injection or the microbials can be absorbed onto the rock surface. Reservoirs less than 50 mD should not be used to avoid dispersion issues. Nitrates should be included with the injected nutrients as they will inhibit the production of hydrogen sulphide [8].

To promote the MEOR process toward a greater level of acceptability in the field, the development process of the MEOR techniques needs to be improved. The laboratory experiments should be detailed and should follow the simplest and most effective method so that the behaviour of the microbes can be well understood. Laboratory studies should then be applied to field trials so that the process may be tested under the conditions of the reservoir. More focus should be placed on the development of low-cost but highly effective procedures. This will be beneficial to small business operators as they tend to have reservoirs that have high oil saturation levels, low oil flowrates with high water to oil ratios and even a small increase in the oil production rate can provide increased profits for these companies. Presenting results purely in terms of an increase in a volumetric production rate without an accompanying economic analysis does not aid the industry in understanding the true feasibility of the process and thus these economic analyses should always be presented [6].

To aid in a faster process design, the further development of a more accurate numerical model should be explored. The model should include the simulation of properties such as the control of mobility, the effects of salinity, and the effects of reservoir temperatures. A more accurate simulation method will enable a faster and more accurate means to develop suitable process routes [6].

Tests should be shifted away from single well tests and should be more focused on waterfloods. These types of tests would make it more efficient in concluding whether or not the oil is being mobilised as a result of the microbial activity. Furthermore, a waterflood is the precise condition under which the mechanisms of MEOR are designed for, one in which the metabolites flow across wells to displace the residual oil. The MEOR tests should trail a maximum of two recovery mechanisms at a time; this allows for a more simplified process with a much easier analysis. In addition to this, nutrients will be consumed more efficiently as there will be fewer bioproducts which may lead to a higher success rate and thus an effective test procedure. Finally, the reporting of trial results should become a standardized procedure to allow for effective analysis and comparison of results across all field trials [6].

4. Novel technologies

There are two novel technologies stemming from microbial-enhanced oil recovery, namely Enzyme Enhanced Oil Recovery (EEOR) and Genetically Engineered Microbial Enhanced Oil Recovery (GEMEOR). EEOR is a fairly new technology within the petroleum industry that employs enzymes. Enzymes are high molecular proteins that serve as biological catalysts, can degrade undesirable components when it is dissolved into a solution or it can aid in producing other required substances. Early application of enzymes in the oil industry primarily focused on the pre-treatment of biopolymers, gel breaking, desulphurization, and the production of acetic acid through in-situ catalytic activity. Later studies have shown that enzymes also possess the ability to alter the wettability of the reservoir through adsorption. It has also been discovered that hydrolases, which are a type of enzyme that uses water to break chemical bonds, exhibit the ability to degrade the heavy components in the crude oil, altering its properties such that it becomes easier to recover. In the field trials for EEOR, the reagent that is used is either a mixture of different biological enzymes, or a mixture that contains biological enzymes as well as surfactants (as surfactants stabilize and improve the enzyme's active sites). The enzyme that is the most commonly used commercially is Greenzyme which contains both an enzyme and a surfactant that serves as a stabiliser. Other enzymes that are used include proteinases, hydrolases, and dehydrogenases. Alterations to wettability and the reduction of interfacial tension are currently the primary mechanisms of EEOR, however, chemical or bio surfactants can attain similar results at a lower cost which does not make this EEOR mechanism desirable. The desirable properties of the EEOR method over that of MEOR or other EOR methods is enzymes ability to convert heavy components into light ones, and thus the focus of the EEOR research has been on the hydrolases and the development of their ability to do just that. The main limitation with the exploration of this method is its high cost, however, field trials are being conducted in China, Myanmar, and Malaysia. GEMEOR technology utilises genetic engineering tools in order to fuse the desirable characteristics of the microbial strains. These strains are those involved in in-situ and ex-situ MEOR processes, both of which possess unique traits that make them beneficial over the other in certain aspects. It is anticipated that GEMEOR technologies will be able to develop microbial strains that can withstand harsh environmental conditions in a reservoir whilst also producing substantial desirable metabolites [1].

5. Conclusions

In comparison to other tertiary or EOR processes, MEOR possesses advantageous application properties in that it is the more environmentally friendly option as all its constituents are completely biodegradable by nature. MEOR can utilise inexpensive raw materials such as molasses to produce by-products making it cheaper than chemical-based EOR processes.This process employs the use of either indigenous or exogenous microorganisms along with nutrients which are injected into the reservoir. Metabolic activity promotes these microorganisms to produce metabolites such as biosurfactants, biopolymers, biogases, solvents, and acids all of which play an active role in enhancing the oil recovery. This is done either through ex-situ metabolite production or in-situ metabolite production.

Biosurfactants reduce the interfacial surface tensions and viscosity of the oil increasing its mobility, biopolymers aid in selective plugging and enhance the sweep efficiency of subsequent waterfloods, biogases increase the pressure of the reservoir which will aid in displacing the oil and they may be dissolved in the oil to reduce its viscosity, and the solvents and acids also play a role in viscosity and permeability alterations.

Biodegradation of heavy oil constituents to light constituents can be undertaken through either aerobic or anaerobic degradation. This process presents low capital costs as it may utilise the existing equipment from waterflooding procedures. MEOR has various mechanisms that could be employed simultaneously that could lead to increased recoveries. Reservoir properties need to be screened to design a suitable process application.

The field trials conducted globally showed that MEOR technology could be effectively employed to enhance oil recovery. There are still several factors that hinder the widespread application of the technology such as inconsistency between laboratory tests and field trial results due to the unpredictable nature of the microbes, the complexity of the MEOR process, lower-than-expected oil recoveries, and lack of standardised reporting regulations. All the hindering factors have placed skepticism around the process. Standard reporting procedures and economic analyses of trials should become mandatory to increase confidence in the feasibility of the process.Novel technologies of EEOR and GEMEOR may be breakthrough technologies in the further advancement of MEOR.

References

[1] Niu J, Liu Q, Lv J, and Peng B. Review on microbial enhanced oil recovery: Mechanisms, modeling and field trials. Journal of Petroleum Science and Engineering, 2020; 192: 107350.

[2] Brown LR. Microbial enhanced oil recovery (MEOR). Curr. Opin. Microbiol. 2010; 13 (3): 316–320.

[3] Mohsenatabar A, Zargar G, Khaksar Manshad A, Mohammadi AH. An Experimental Investigation into Enhanced Oil Recovery (EOR) by Polymer Flooding in Sandstone Reservoirs under High Temperature and High Salinity Using a Combination of two Synthetic Polymers. Petroleum & Coal, 2019; 61(1): 1-9.

[4] Gudiña EJ, Pereira JFB, Costa R, Coutinho JAP, Teixeira JA, Rodrigues LR. Biosurfactant-producing and oil-degrading Bacillus subtilis strains enhance oil recovery in laboratory sandpack columns. J Hazard Mater, 2013; 261:106–113.

[5] She H, Kong D, Li Y, Hu Z, Guo H. Recent advance of microbial enhanced oil recovery (MEOR) in China. Geofluids, 2019; 1–16.

[6] Maudgalya S, Knapp RM, and McInerney M. Microbially enhanced oil recovery technologies: a review of the past, present and future. In Production and Operations Symposium. Society of Petroleum Engineers, January 2007.

[7] Yernazarova A, Kayirmanova G, Baubekova A, and Zhubanova A., Microbial enhanced oil recovery. In Chemical Enhanced Oil Recovery (cEOR)-a Practical Overview, 2016, p. 200.

[8] Lazar I, Petrisor I, Yen TE. Microbial enhanced oil recovery (MEOR). Petrol. Sci. Technol. 2007; 25 (11–12): 1353–1366.

[9] Sen R. Biotechnology in petroleum recovery: the microbial EOR. Prog. Energy Combust. Sci. 2008; 34 (6), 714–724.

[10] Armstrong RT, Wildenschild D, Bay BK. The effect of pore morphology on microbial enhanced oil recovery. J Petrol Sci Eng, 2015; 130: 16–25.

[11] Onaizi S.A., Nasser M.S., Twaiq F.A., Micellization and interfacial behavior of a synthetic surfactant–biosurfactant mixture. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 2012; 415: 388-393.

[12] Long YF, Wang WH, Xu YL. The research on bio-chemical combination drive and its application in Y9 reservoir in block ZJ2 of Jing'an Oilfield. J Oil Gas Technol. 2013; 35: 142–145.

[13] Xu L, Qiu Z, Gong H, Zhu Ch, Sang Q, Li Y, Dong M. Synergy of microbial polysaccharides and branched-preformed particle gel on thickening and enhanced oil recovery. Chem. Eng. Sci., 2019; 208: 115138.

[14] Nazina TN, Pavlova NK, Tatarkin YuV, Shestakova NM, Babich TL, Sokolova DSh, Ivoilov VS, Khisametdinov MR, Ibatullin RR, Tourova TP, Belyaev SS, & Ivanov MV. Microorganisms of the carbonate petroleum reservoir 302 of the romashkinskoe Oilfield and their biotechnological potential. Microbiology, 2013, 82 (2): 190–200.

[15] Aitken CM, Jones DM, Larter SR. Anaerobic hydrocarbon biodegradation in deep subsurface oil reservoirs. Nature, 2004; 431 (7006): 291–294.

[16] Gao C. Experiences of microbial enhanced oil recovery in Chinese oil fields. J. Petrol. Sci. Eng., 2018; 166: 55–62.

[17] Safdel M, Anbaz MA, Daryasafar A, Jamialahmadi M. Microbial enhanced oil recovery, a critical review on worldwide implemented field trials in different countries. Renew. Sustain. Energy Rev., 2017; 74: 159–172.

[18] Jenneman GE, Geverrtz D, Davey ME, Clark JB, Wood WA, Stevens JC, Tankersley C. Development and application of microbial selective plugging process. [In:] Bryant R.S., Sublette K.L. (Eds.), Proceedings 5th International Conference on Microbial Enhanced Oil Recovery and Related Problems for Solving Environmental Problems (CONF-9509173). National Technical Information Service. Springfield 1995, VA: 7–26.

[19] Youssef N, Simpson DR, Duncan KE, McInerney MJ, Folmsbee M, Fincher T, Knap RM. In situ biosurfactant production by Bacillus strains injected into a limestone petroleum reservoir. Appl. Environ. Microbiol., 2007; 73 (4): 1239–1247.

[20] Maure MA, Dietrich FL, Dia, VA, Arganaraz H. Microbial Enhanced Oil Recovery Pilot Test in Piedras Coloradas Field. Society of Petroleum Engineers, Argentina, 1999.

[21] Town K, Sheehy AJ, Govreau BR. MEOR success in southern Saskatchewan. SPE-158022-PA, 2010, 13 (5), 773–781.

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