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Invited review

Microbial improved and enhanced oil recovery (MIEOR): Review of a set of technologies diversifying their applications

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Abstract:
Microbial improved and enhanced oil recovery (MIEOR) deploys microbes into wellbores and subsurface oil reservoirs and/or stimulates in-situ microbes to generate biochemicals that induce positive changes to reservoir and/or fluid conditions. MIEOR has a history of laboratory testing and field trials stretching back many decades, but few large-scale commercial projects. This review describes mechanism and components involved and the challenges in scaling-up laboratory performance to field-wide commercial applications. Microbes tend to exist in consortia with the ability to generate a wide range of biochemicals and biomass capable of performing various useful MIEOR actions and some actions that are detrimental (e.g., reservoir souring, facilities corrosion, formation damage). The complexity of the microbial consortia makes it difficult to unravel the net consequences of growing a microbial community in a specific reservoir. This requires extensive experimental studies coupled with long-term field trials and the outcomes of several recent examples are provided. These complexities and requirements have historically slowed down the commercialization of MIEOR. Significant advances in recent years have provided improved modelling and simulation tools capable of representing more realistically the evolution of MIEOR actions at the micro and macro scales. The advantages and disadvantages of MIEOR are identified and explored. Future expectations for the development and exploitation of MIEOR technologies are discussed considering the recent advances it has achieved.

1. Introduction

Microbial improved and enhanced oil recovery (MIEOR) involves primarily bacteria and their associated metabolic products harnessed in various ways to improve production performance and enhance oil reservoir sweep and ultimate resource recovery from sub-surface reservoirs. Here, the acronym “MIEOR” is introduced to go beyond the more widely used acronym “MEOR”, because some of the microbial processes involved are applicable to earlier stages of reservoir development (primary and secondary, e.g., reducing the density of heavy crude oil) and wellbore clean-up, not just tertiary oil recovery processes implied by the MEOR label.

Biosurfactants are one of the useful microbial metabolic products that function by reducing interfacial tension (IFT) of reservoir fluids and inducing changes to reservoir wettability. Biopolymers, on the other hand, change the viscosity of the reservoir fluids improving oil sweep efficiency. Biofilms are another group of exploitable metabolic products that can block fluid flow through pore throats, also change reservoir wettability, and re-direct fluid flow to more desirable flow channels within a reservoir (i.e., those that are prone to be less-well swept by formation or injected fluids). Specific microbes are also well-established as environmentally-safe solutions for treating wellbore and surface oil processing facilities to reduce wax deposition (Brown, 1992), and for biodegrading hydrocarbon contaminants of surface soils or related to oil spills (Baggi et al., 1987).

1.1 Early history of MIEOR

The actions of bacteria on mineral oil were identified in the 1920s (Beckman, 1926) with laboratory tests of microbial actions on crude oil commencing in the 1940’s (ZoBell, 1946; Zahid and Sajid, 2007). In 1954, the first MIEOR field test was conducted in Lisbon oil field Arkansas (USA) (Yarbrough and Coty, 1982). Since then hundreds of patents have been granted related to MIEOR (Hames et al., 2014). Most of the early MIEOR field tests involved cyclic stimulation treatments of single producing wells (Bryant and Burchfield, 1989). Numerous potential improved oil recovery (IOR) applications

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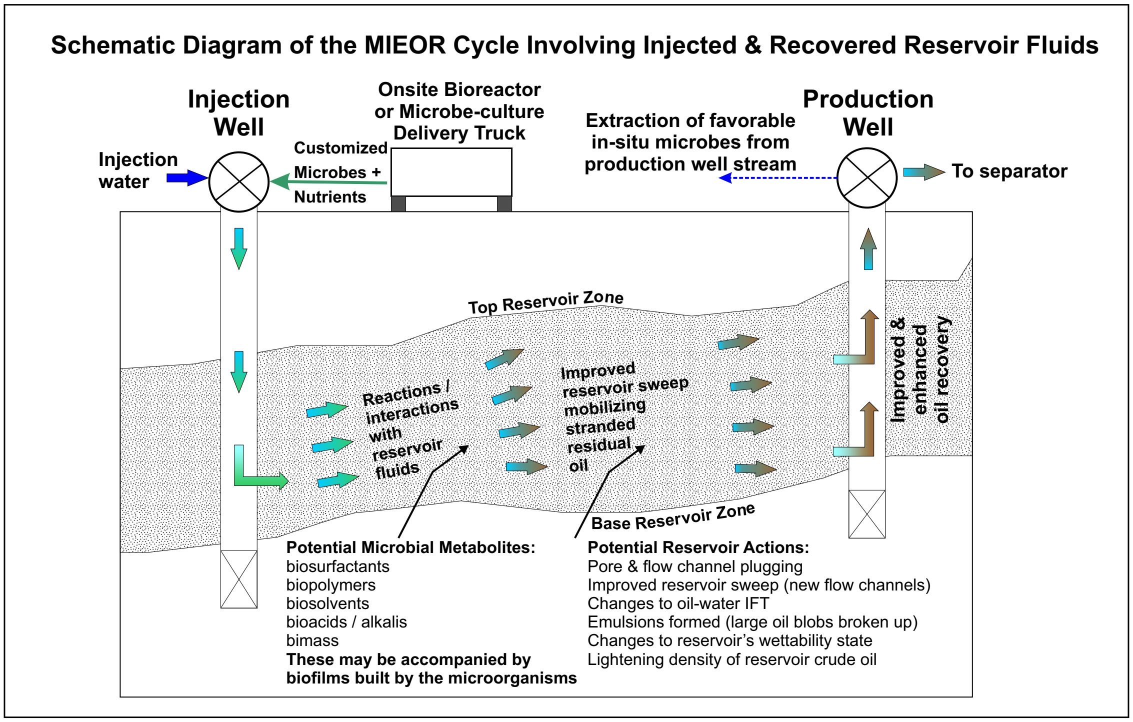

Fig. 1. Schematic of typical MIEOR reservoir injection-production cycle highlighting the bioproducts involved and their impacts within an oil reservoir.

involving biotechnology and microbiology have also been identified and tested going back over many decades (Fujiwara et al., 2008).

1.2 Laboratory versus field performance

Despite a plethora of laboratory-based studies and many small-scale field pilot studies of limited duration the oil industry remains slow to take up MIEOR on a large commercial scale (Lazar, 1991; Brown, 2010; Al-Sulaimani et al., 2011). This leaves question marks over the scalability of many of the techniques proposed. However, several successful field tests in China (Guo et al., 2015; Ke et al., 2018a) and improved screening criteria have expanded interest in MIEOR in recent years. Also, the markets for biologically generated chemicals are reported to be growing rapidly (De Almeida et al., 2016).

Many laboratory studies testing multiple microbial species suggest MIEOR processes are effective at that scale (e.g., Cresente, 2008; Armstrong and Wildenschild, 2011, 2012a; Armstrong et al., 2015). However, the results of field-scale studies have been inconsistent, working in some cases, but not others (Hiltzmann, 1988; Lazar et al., 2007). Explanations for this include: 1) the difficulties of certain microbial species to cope with extreme reservoir conditions (i.e., temperature, pressure, fluid chemistry); 2) the difficulties associated with propagating and/or dispersing the microbes throughout a reservoir or, at least, to an extent that they can achieve tangible impacts; and, 3) complex mechanisms at work at the pore scale within reservoirs that determine fluid dynamic behaviors at the rock-fluid and fluid-fluid interfaces that restrict the benefits of MIEOR processes.

1.3 Mechanisms driving MIEOR

Yousef et al. (2009) reviewed the mechanisms involved as: 1) reduction of IFT; 2) changing wettability from those prevailing at reservoir conditions (i.e., water-wet to more oil-wet conditions, or vice versa); 3) films that clog pore throats to redirect fluid flow to alternative, less-well swept channels; 4) generating biogenic gases (methane or carbon dioxide) within the reservoir fluids leading to increases in pore pressure, or to mix (in dissolved or adsorbed forms) with the oil phase, thereby reducing its viscosity and enhancing its ability to flow; and 5) biodegradation of oil, with the bacteria using some of the carbon in the oil as its food source, leading to more hydrogen-rich hydrocarbon molecules with lower viscosity and density, improving its ability to flow.

In most reservoirs it is likely that more than one of these mechanisms are at work, but it is not always easy to identify which ones are dominant. Also, as microbes tend to occur as consortia, it is not always easy to identify which microbes are responsible for the beneficial actions, and which might be potentially having negative impacts on oil recovery. The key to understanding optimal MIEOR conditions is to identify the active mechanisms and drivers associated with specific reservoirs (Afropoli et al., 2011). Once those reservoir-specific mechanisms are established, then it is possible to design microbial inoculations (Fig. 1) to focus upon them.

In many mature oil reservoirs that have experienced long-term production through primary and secondary recovery methods, it is apparent that residual oil remains in these reservoirs as isolated globules surrounded by formation/injected fluids and rock matrix. Many of these isolated oil globules are bypassed by the established and active flow channels.

The isolated and fragmented oil is unable to flow through the surrounding pore throats maintaining it in its isolated state. The ratio of viscous forces (that enhance flow) over capillary forces (resisting flow) is a useful one (Armstrong and Wildenschild, 2012a) for evaluating this common, mature-reservoir condition (Eq. (1)):

$$N_{ca} = \frac{v\mu}{\sigma} \tag{1}$$

where N_{ca} = capillary number (unitless); v = advancing phase's velocity; μ = advancing phase's viscosity; σ = IFT of immiscible phases.

As N_{ca} increases for a specific reservoir, the influences of the capillary forces diminish, which potentially promotes fluid flow in that reservoir (Gray et al., 2008). The blob-size distribution of the non-aqueous globules can be usefully expressed as Eq. (2):

$$F(d) = 1 - [1 + (\beta d)^m]^{\frac{1}{m}-1} \tag{2}$$

where $F(d)$ = mass% of blobs with size < d; β = fitting metric. As the mean of d decreases, β increases; d = blob size; m = fitting metric. As d becomes more uniform, m increases.

This relationship was developed by Armstrong and Wildenschild (2012a) to access the performance of key MIEOR processes in laboratory-scale "oil-reservoir" visualization experiments with transparent cores. They applied the IFT radius-of-curvature, level-set method (Liu et al., 2011) to record changes to wettability in space and time in their visualization experiments. In this radius-of-curvature method, water-wet characteristics are taken as positive (concave oil surfaces), and oil-wet characteristics are taken as negative (convex oil surfaces). Observed changes in the radius-of-curvature distributions, consequently, reveal wettability changes in the synthetic reservoirs as the flow experiments progress. The visualization experiments indicated that MIEOR processes tended to breakdown larger residual oil blobs into smaller ones that were more easily mobilized, depending upon pore size distributions and the pores' propensity for connectivity or clogging in a specific reservoir.

Afripoli et al. (2010) studied mechanisms of pore-clogging, IFT changes and wettability alterations recording the emulsification effects of the alkane-oxidizing bacterium *Rhodococus sp*. 094. This bacterium can be either surfactant-producing or non-surfactant-producing depending on the carbon source used for growth. MIEOR was found to be optimal when pore-clogging and the formation of biosurfactants occurred simultaneously in a reservoir.

In terms of the IOR applications of MIEOR, microbes can be used to alleviate problems such as polymer plugging and poor mobility of heavy oils. These offer potentially valuable, environmentally-friendly and low-cost solutions to these problems that are widely experienced.

Wang and Zhuge (2014) demonstrated with laboratory and field tests that polymer plugs in the wellbore perforations and surrounding reservoir pore space in the Daqing oil field (China) could be successfully removed by introducing certain bacteria into the wellbores. The technique, applied at different reservoir temperatures and to polymers of different molecular weights, reduced polymer injection pressure by 25% and significantly increased oil production in the field test. It also avoided the need to use environmentally-unfriendly oxidants to remediate such polymer plugging problems.

High viscosity and low mobility is a common problem for heavy and waxy oil reservoirs that inhibits production rates. The potential exists to modify heavy oils by introducing spore-forming bacterial consortia to perform biodegradation transformations that improve its flow characteristics (Al-Bahry et al., 2016). Biodegradation of crude oil by strains of Bacillus bacteria and its applications in breaking down spilled oil are widely reported (Ijah and Ukpe, 1992). More recently, Shibulal et al. (2018) showed that heavy oils from various fields in Oman, when treated with the in-situ spore-forming bacteria Bacillus firmus and Bacillus halodurans, could be transformed into lighter oils. Laboratory tests indicated that these bacteria were specifically converting aromatic molecules into aliphatic molecules in the heavy oils treated. Core-flooding tests indicated that such transformations could result in 8% to 10% improvements in the recovery of the heavy oils treated with these bacteria.

2. MIEOR components

Microorganisms, frequently referred to as microbes, are ubiquitous at the Earth's surface and near-sub-surface. The oil and gas industries have used microbes for decades in applications varying from exploration, MIEOR and spill clean-ups. Many MIEOR processes focus on two specific enhanced recovery objectives: 1) the mobilization of stranded, residual oil after secondary recovery processes are completed (Fig. 2); 2) the enhancement of reservoir sweep to access stranded zones of, as yet, unproduced oil (Fig. 3) with the aid of biofilms by either redirecting flow to unswept reservoir zones or inhibiting water flow through preferential flow channels (Fig. 4).

These objectives are attained by stimulating useful metabolic activities that are either induced by the introduction of external microbes into a reservoir, or by exploiting microbes already present in the reservoir. In either case, the microbes need to thrive in reservoir conditions and form effective biochemicals.

The left-side diagram in Fig. 2 illustrates, schematically, residual oil (solid tone) remaining in a reservoir after primary and secondary recovery, both surrounding the mineral grains (stippled symbol) and as isolated globules in the formation/injected water (wavy symbol). The middle diagram in Fig. 2 illustrates that the introduction of biosurfactants into that reservoir tend to initially alter the interfacial tension (IFT) between the residual oil and the formation/injected water. This leads to the formation of emulsions in the pore fluids (i.e., water in oil in bound fluids around the mineral grains; oil in water in the more-freely-flowing fluids within the pore space). The right-side diagram in Fig. 2 illustrates, that over time the introduction of biosurfactants can significantly alter the wettability state of the rock formation; the change from an oil-wet to a water-wet state shown typically transfers more oil

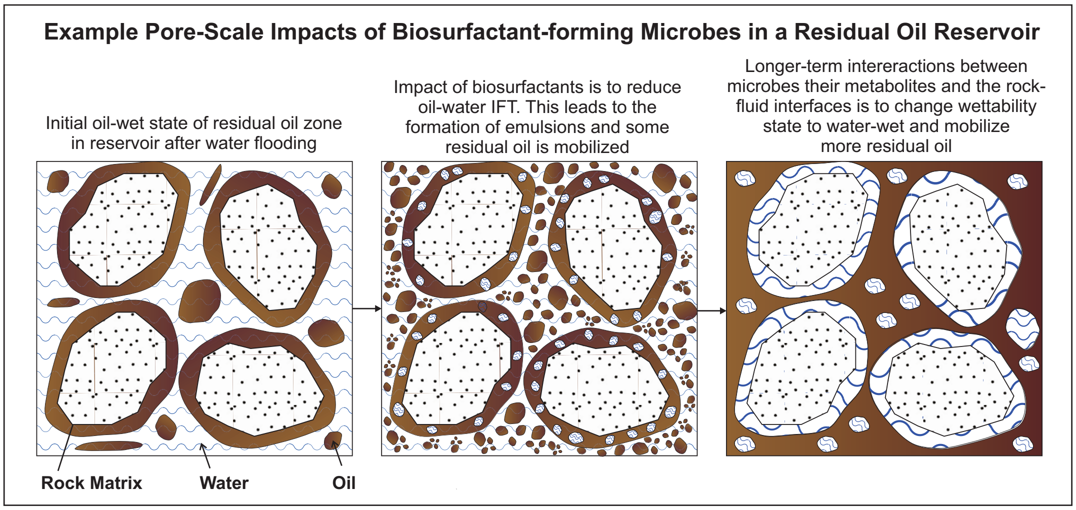

Fig. 2. Schematic of biosurfactants produced by some MIEOR processes in a residual oil reservoir, leading to changes in oil-water interfacial tension, the formation of emulsions as part of the breakdown of larger globules of oil, and changes to the wettability of the reservoir to more favourable states for oil to be recovered.

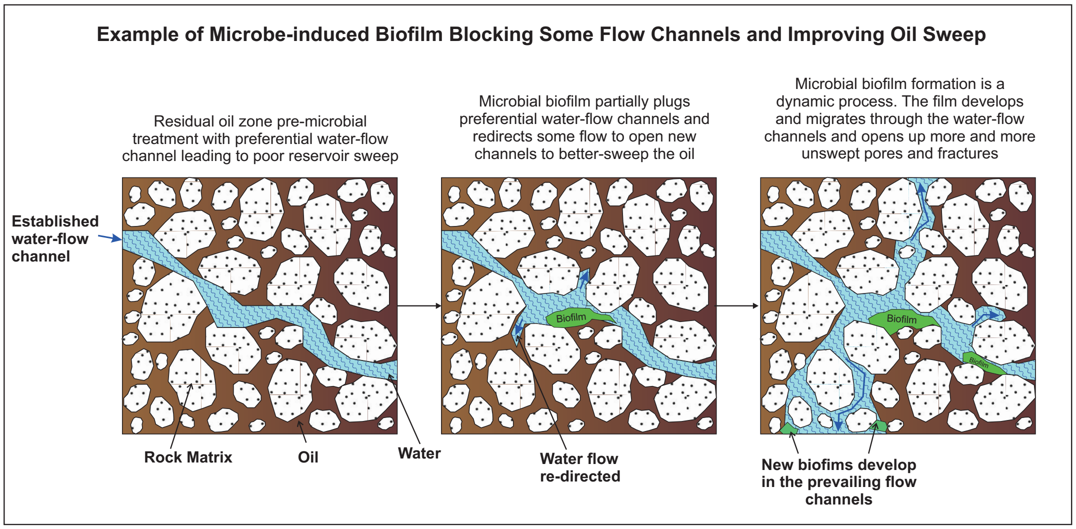

Fig. 3. Schematic of MIEOR induced biofilms within a reservoir causing the plugging of some pores and flow channels and promoting the formation of new flow channels and improved sweep of the residual/stranded oil zones.

into the more-freely-flowing fluids within the pore space, a process that is likely to enhance oil recovery.

The left-side diagram in Fig. 3 illustrates, schematically, the formation of preferential flow channels (light tone) related to higher permeability zones that develop during primary and secondary oil recovery. This leads to poor reservoir sweep and leaves much of the residual oil (dark tone) isolated from flow towards producing well bores in poorly-drained pore spaces between the mineral grains (stippled symbol) over much of the reservoir. The middle diagram in Fig. 3 illustrates that the formation of biofilms within the preferential flow channels leads to some pore plugging (and partial pore plugging) that disrupts flow though those channels. Such disruption forces fluids to move laterally from those channels thereby sweeping more of the reservoir. The right-side diagram in Fig. 3 illustrates that, over time, such activities cause new flow channels to be developed in the reservoir, thereby potentially improving oil recovery. Moreover, the continual development and movement of biofilms through the reservoir results in the stimulation of new flow channels to be a dynamic and evolving process.

MIEOR potentially has several advantages over conventional or non-microbial enhanced oil recovery (EOR) techniques. Its lower cost and its low environmental footprint are key benefits (Youssef et al., 2009, 2013; Safdel et al., 2017) highlighted that the injection cost of microbes and nutrients tends to be low, requiring low capital to build and low operating costs (e.g., energy input) to run relatively simple surface facilities to sustain microbial metabolism. MIEOR processes can be designed to work effectively in sandstone or carbonate reservoirs. Moreover, microbial metabolic activities tend to enhance over time, in contrast to the injected chemical additives of other EOR processes. MIEOR can be to both light and heavy crude oils. It is these multiple benefits working

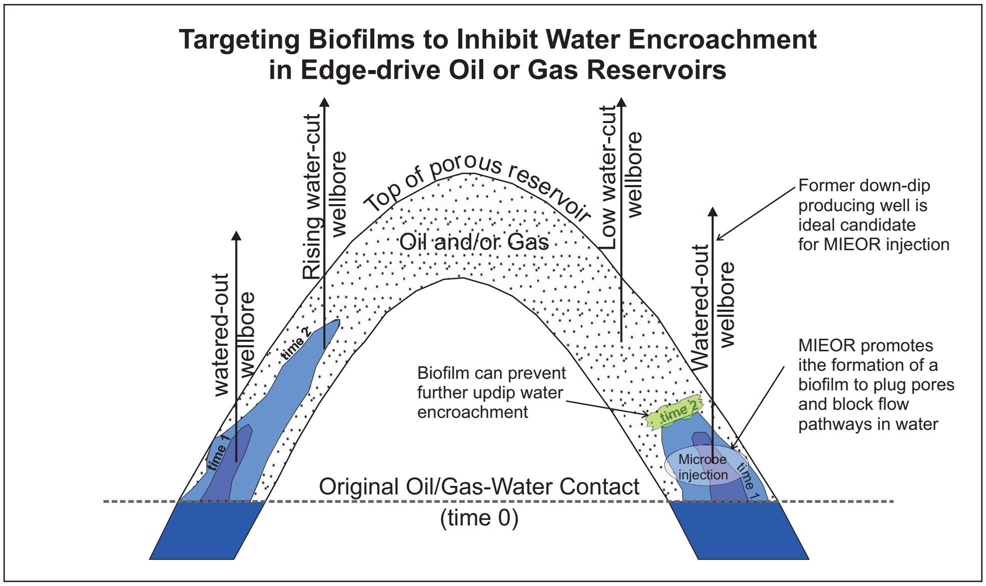

Fig. 4. Exploiting more extensive biofilms developments in targeted reservoir zones to inhibit water fingering and coning.

together that MIEOR processes have the potential to exploit.

2.1 Microbe classifications

There are a wide range of microbes deployed in MIEOR, but they can be grouped into two distinct types (Youssef et al., 2009): 1) autochthonous or indigenous microorganisms already living in oil reservoirs; and, 2) allochthonous or exogenous microorganisms that are developed specifically to be injected into reservoirs.

Microbes types are also distinguished by their oxygen requirements: 1) aerobes (O-) need oxygen because they cannot respire anaerobically or ferment; 2) anaerobes (A_o-) are mostly poisoned by oxygen and depend upon either anaerobic respiration or fermentation to metabolize; and 3) facultative anaerobes (A_n-) are more versatile and can metabolize with or without oxygen. Since oxygen levels are typically very low in oil reservoirs, autochthonous microbes tend to be anaerobic and/or facultative. The facultative anaerobes are able to exploit either dissolved oxygen or, in some cases, oxygen extracted by the reduction of sulphate or nitrate ions. On the other hand, true anaerobic respiration involves an electron transport chain, that does not use oxygen as the terminal electron acceptor. Rather, ions, such as sulphate ($SO_4{}^{2-}$), nitrate (NO^{3-}), or sulfur molecules (S) are the effective electron acceptors. In either case cellular respiration involves metabolic reactions that transform the biochemical energy contained in nutrients into adenosine triphosphate (ATP) that breaks down to provide the cell with energy. The formation of ATP also involves associated waste products being produced.

Nitrate-enhanced MIEOR has shown promising outcomes in stimulating the growth of biosurfactant-producing bacteria in reservoir conditions (Da Silva et al., 2014; Gassara et al., 2017). The microbial communities generated in the reservoir tend to vary through the various MIEOR stages. Zhan et al. (2017) showed that using wheat bran to stimulate indigenous microbial growth, that the microbe community *Pseudomonas sp.*, *Citrobacter sp.*, and uncultured *Burkholderia sp.* dominated through to the later A_o-stage, at which point *Bacillus sp.*, *Achromobacter sp.*, *Rhizobiales sp.*, *Alcaligenes sp.* and *Clostridium sp.* dominated.

Monitoring production wells for microbial community diversity is a useful way of identifying suitable well and field targets for MIEOR (Youssef et al., 2004; Xiao et al., 2013; Chai et al., 2015). The microbial consortia of typical producing oil fields are complex and diverse. For example, Al-Bahry et al. (2013) identified 33 genera and 58 species in the Wafra oil wells and Suwaihat production water (Al-Wusta region, Oman). Those microbial consortia were dominated by anaerobic, thermophilic, and halophilic microbes capable of generating biogases, biosolvents, and biosurfactants.

Microbes can also be usefully categorized according to other requirements, e.g., nutrients, pH required for growth, temperature range required for growth, salinity tolerance (halophilic), gaseous requirement. For example, using a classification based on optimal pH for growth, microbes are divided into three subdivisions: 1) Acidophiles; 2) Alkaliphiles; and, 3) Neutriphiles; those terms refer to microbes that grow best at acidic pH, alkaline pH and neutral pH (6.5-7.5), respectively.

The appendix describes a selection of microbe species that are the focus of recent research and field applications, identifying the biochemical products that they generate and citing the recent studies that have exploited them.

2.2 Microbial nutrients

Microbes require nutrients for growth, sustaining their metabolism and contribution to MIEOR. Nutrients tend to be the largest expense for most MIEOR processes (Rodrigues et al., 2006) contributing up to a third of fermentation costs. Carbon, nitrogen, and phosphorous all need to be available for microbes to grow. Optimizing the composition of nutrients has a considerable effect on the resulting bioproducts and helps to avoid unwanted contaminants.

Two sources of carbon are typically harnessed: 1) subsurface crude oil; and, additives to the injected fluids (e.g., molasses). Nutrients used in MIEOR processes are classified (Maudgalya et al., 2007; Safdel et al., 2017) as:

- Pure molasses
- Reservoir crude oil
- Molasses plus added salts of nitrogen and phosphorous
- Other

2.3 Microbial bioproducts

Bryant and Lockhart (2002) distinguished the most common by-products of MIEOR to be biomass including biogases, acids, alcohols, bio-polymers, bio-solvents and biosurfactants. These are the active components that change: 1) reservoir formations' physical properties including, porosity, permeability and wettability; and, 2) reservoir fluids' properties (e.g., viscosity, IFT, etc.). It is the beneficial changes in these properties that stimulate more effective residual oil displacement.

2.3.1 Biomass

Bacteria, yeasts, fungi and protozoa are all microorganisms that are able to grow fast and form substantial biomass within a sub-surface reservoir. Such biomass accumulations enhance residual oil mobilization in different ways, such as selective and nonselective plugging of high-permeability channels in the reservoir. They can also alter flow dynamics, IFT, wettability and initiate reductions in viscosity and sulfur content of crude oil.

2.3.2 Biosurfactants

Biosurfactants (and all surfactants) are surface-active materials that act to cause a reduction in the interfacial tension (IFT) between fluids and fluids and solids. They do this by changing the physio-chemical properties of the fluid (and fluid/solid) mixtures they come into contact with. They achieve this by inducing various actions, including: Cleansing (as a detergent), dispersing, emulsifying, foaming and wetting. Such actions are useful for MIEOR purposes (Banat, 1995) and for bioremediation of oil spills or oil contaminated surface sites (Shulga et al., 1999). Several microorganisms, including bacteria and yeasts, are known to stimulate growth of biosurfactants (Desai and Banat, 1997), such as glycolipids, phospholipids and rhamnolipid growth when added to oil in reservoir conditions (e.g., *Pseudomonas* aeruginosa).

Biosurfactants are molecules that contain organic compounds that are amphiphilic, i.e., they have two distinct components: 1) hydrophilic (typically the heads of the molecules); and 2) hydrophobic (typically the tails of the molecules). Soaps and sulfonates are the most common manufactured surfactants. Each component is formed by one or more microorganism. They have the same properties and applications as chemical surface-active agents that are extensively used as surfactants in chemical (but not microbial) enhanced oil recovery (CEOR) techniques. Typical surfactants deployed in EOR are various petroleum sulfonates, alkyl benzene sulfonate, carboxylate, and chrome lignin (Sheng, 2015), plus biosurfactant (e.g., Surfactin) and cationic Gemini surfactant (Jin et al., 2016). Reduction in IFT and increased mobility of the insoluble organic compounds contained within residual oil are the mechanisms they stimulate. Surfactants are among the most expensive chemicals used in EOR processes (Negin et al., 2017). Biosurfactants are valuable because they are more environmentally friendly (i.e., low toxicity and biodegradable) and potentially much cheaper to produce than the chemicals typically exploited for their surfactant properties in chemical EOR. Biosurfactants are easy to use, stable and sustainable under a variable pH, salinity and temperatures (Denger and Schink, 1995).

2.3.3 Biopolymers

Biopolymers include a wide range of chemical structures containing monomeric molecules combined by covalent bonding into larger molecular units. They include: Polynucleotides consisting of RNA and DNA components made up by combining multiple nucleotide monomers; polypetides made up of amino acid components; and polysaccharides made up of linearly-bonded carbohydrates. Examples of naturally occurring biopolymers, produced and used by many macro-organisms are cellulose, lignin, melanin and rubber. The biopolymers used in MIEOR processes are typically polysaccharides (Elshafie et al., 2017) that enhance oil recovery when introduced into reservoirs by promoting permeability modification (Sen, 2008).

As with other polymers used in chemical EOR processes, biopolymers control reservoir fluid mobility and sweep efficiency through injection/formation water viscosity increases (Ramsay et al., 1989). Polymeric surfactants (surfmers) consisting of a hydrophobic tail, a hydrophilic head and polymerizable vinyl double bonds, offer valuable properties that combining the attributes of surfactants and polymers (El-Hoshoudy et al., 2017). Some surfmers can copolymerize with acrylamide forming hydrophobically associative polyacrylamide (PAM) with valuable EOR properties and promote nano-scale reactions in the reservoir. The viscosity of polymer solutions tends to decline as temperature increases, whereas polyacrylamides tend to be more resistant to high temperatures and bacterial degradation, they can dissolve in water yet still decrease the mobility ratio of injected fluids (Mahdavi et al., 2017). The potential to generate a range of bio-surfmers is yet to be exploited. As with biosurfactants, biopolymers are more environmentally friendly than the chemicals typically exploited for their polymeric properties in chemical EOR.

2.3.4 Biosolvents

Ethanol, acetone, and butanol are solvents which can be produced as metabolites during the metabolic processes of some microbes. They increase solubility of the less soluble organic compounds in residual oil. This helps to reduce oil viscosity and oil-water IFT, acting together with biosurfactants

(Youssef et al., 2004, 2005, 2007). As with biosurfactants and biopolymers, biosolvents are more environmentally friendly than the chemicals typically exploited for their solvent properties in chemical EOR.

2.3.5 Bioacids (and alkalis)

Certain acids, such as lactic acids, acetic acid and butyric acid can be produced by microbial actions on specific nutrients (McInerney et al., 2005). These acids can enhance oil recovery by improve porosity and permeability by dissolving carbonate rocks and/or carbonate minerals in the reservoir formations matrix (McInerney et al., 1990). Kryachko (2018) recommends an initial dose of biosurfactant followed by a low dose of a biosurfactant with alkali (which could involve combined MIEOR plus chemical, but non-microbial enhanced oil recovery (CEOR)) to maximize immiscible gas-driven oil recovery. Combined surfactant-based processes, especially Alkali-Surfactant-Polymer (ASP) combinations, are considered to among the most effective CEOR techniques with the potential to yield high recovery rates (Olajire, 2017). MIEOR processes that can generate a combination of biosurfactants, biopolymers and bioalkalis are therefore likely to have similar reservoir performances.

2.3.6 Biogas

CH_4, CO_2 and H_2 are the gases produced when microbes ferment carbohydrate (sugar). They contribute to enhancing oil recovery by re-pressurizing pressure-depleted reservoirs and reducing viscosity of heavy oil by dissolving gases and gas liquids present in crude oil (Brown, 1992). Methanogens are microbes that produce about 60% CH_4 and 40% CO_2 as their metabolic biproducts. The CH_4 tends to integrate with oil and gas in the reservoir, whereas the CO_2 can either enter the formation water or act to boost oil mobility by viscosity reduction (Gray et al., 2008).

3. MIEOR reservoir and fluid mechanisms

MIEOR processes act on IFT, viscosity, wettability, etc., in a similar way non-microbial CEOR processes and face the same technical challenges. MIEOR and CEOR processes can be compared in terms of their risks and rewards (Bryant and Lockhart, 2002). Quantifying the performance of microbial processes in the reservoir (e.g., optimum product combinations and stoichiometric concentrations, reaction rates) is difficult and is typically not fully understood. Nonetheless, Bryant and Lockhart (2002) concluded that produced biogases (CO_2 and CH_4) were unlikely to have a significant positive impact on oil recovery, and that although biopolymers can increase the viscosity of formation water, they were typically not stable (at that time) under reservoir conditions, particular in heterogeneous reservoirs. They, therefore, considered that biomass activity was the most attractive MIEOR process likely to increase reservoir productivity and volumetric sweep through permeability decrease.

3.1 Plugging and biofilm production

Since a large number of reservoirs are naturally heterogeneous, fluid flow characteristics through them are typically defined based on the permeability of several distinct layers and/or sub-zones. As the mobility of reservoir brine (formation water) is greater than oil, during waterflooding, water is more likely to flow more easily and faster than oil through the high-permeability layers. This causes water breakthrough to happen much earlier and the volumetric sweep of oil is low as the flowing fluids are preferentially channelled through the highest permeability layers. Some specific microbes (e.g., biopolymers) are able to plug, or at least reduce flow through, the high-permeability channels (Fig. 3). This reduces porosity and permeability of at least some of the existing flow channels the reservoir (Fig. 4). Plugging is known to occur due to the actions of two distinct types of microbes: 1) viable cells; and, 2) non-viable cells (Zekri et al., 1999). A biofilm can be formed as a result of growth and adhesion of the viable microbes on the rock surface and its evolution modelled (Ebigbo et al., 2010). It is constituted by a semi-static phase made up of consortia of bacteria together with various biopolymer products that are heterogeneously distributed inside the reservoir pores. On the other hand, non-viable bacteria can act beneficially as particulates that clog the pore throats and reduce fluid flow and porosity.

Nitrogen-reducing bacteria (NRB) have the potential to precipitate iron minerals by combining soluble ferrous iron (Fe^{2+}) with nitrate reduction (Zhu et al., 2013). Plugging pore throats with Fe-based minerals in addition to biomass plugs makes them less prone to pressure-or temperature-related degradation.

3.2 Interfacial tension (IFT) reduction

In the waterflooding process, the oil-water IFT influences oil mobility and its production from a reservoir. Several EOR processes are designed to reduce IFT and thereby improve oil mobility. Surfactants and biosurfactants, as surface active agents with their hydrophilic (lipophobic) heads and a hydrophobic (lipophilic) tails, act effectively to reduce IFT. They also act as oil emulsifiers, which also helps to mobilize some of the trapped residual oil into the flowing fluid. Biosurfactants can be produced in a reservoir by injecting the appropriate nutrients (Wei et al., 2013). Alternatively, they can be injected through a wellbore following manufacture and separation in a controlled culture above ground (Al-Sulaimani et al., 2012).

3.3 Increase in water viscosity by biopolymer production

During waterflooding, the viscosity of displaced water plays the main role in increasing sweep efficiency and improving oil recovery. Biopolymers are able to increase viscosity in some of the displaced fluids. In turn, this can increase the mobility ratio of the residual oil leading to improved recovery.

3.4 Wettability alteration

Wettability alteration and oil-water IFT reduction typically occur simultaneously during EOR. In MIEOR different microbes can cause different rock wettability alterations in different reservoir lithologies, perhaps with positive and/or negative oil recovery impacts. Wettability alteration can be determined by measuring contact angle (Kowalewski et al., 2006) and the wettability index (Al-Sulaimani et al., 2012). In some laboratory tests, bacteria have prompted wettability to become less water-wet in some sandstone cores (Kowalewski et al., 2006) but to become more oil wet in some carbonates cores (Zekri and El-Mehaideb, 2002; Rabiei et al., 2013). On the other hand, some oil-wet carbonate cores were rendered more water-wet by biosurfactants derived from agricultural waste streams (Salehi et al., 2006; Johnson et al., 2007). Zekri and El-Mehaideb (2002) suggested that complex interactions of reservoir conditions determine wettability alterations induced by MIEOR (e.g., asphaltenes, microbe type and concentration, mineralogy, pH, pressure, salinity, sulfur, temperature, etc.)

3.5 Biodegradation of heavy hydrocarbons

Crude oils with greater concentrations of the longer-chain, higher-molecular weight hydrocarbons molecules are typically more viscous. Some biodegradation mechanisms, harnessing aerobic and/or anaerobic metabolites, are able to convert molecules with long-chain hydrocarbon structures into short-chains (Youssef et al., 2009). Singer and Finnerty (1984) suggested a range of possible interactions between microbes and hydrocarbons were likely involved in crude oil's physical and chemical degradation. Some of these occur within the water phase, others associated with large-oil droplets, and others within small oil-water-emulsion droplets.

3.6 Repressurization and dissolution of gas

The presence of the biogenic gases generated by a range of microbial processes tends over time to increase or help to maintain reservoir pressure, which is typically beneficial for oil production rates and ultimate oil recovery. Additionally, some biogenic gas generated within the reservoir is absorbed by the residual oil, causing its dynamic viscosity to reduce. Thus, in contrast to the conclusions of Bryant and Lockhart (2002), biogases are considered to make tangible contributions to MIEOR processes.

4. Experimental versus field performance

Various MIEOR technologies have been evaluated using laboratory tests and field trials. It is important that performances obtained by laboratory tests are confirmed by pilot-scale and field-scale trials, as some proposed MEOR methods have failed historically, for a variety of reasons, to perform as predicted in the laboratory when scaled up to be applied to real reservoirs at commercial scales. The results are mixed with some showing agreement, but others have demonstrated field performances which are not consistent with laboratory test results. Illias et al. (1999) carried out several experiments using bacterial strains extracted from oil-well-production samples (Malaysia). These bacterial strains were cultured with carbon-rich nutrients (including, sucrose, yeast extract) plus N-and P-bearing salts. During the exponential growth phase, some of the bacterial strains produced biosurfactants capable of reducing IFT by 20 dynes/cm (or, 20 mN/m, as 1 milliNewton/metre is equal to 1 dyne/centimetre). Other strains produced biopolymers capable of rapidly increasing viscosity of the supernatant from 1 to 4 cP. Once the stationary phase of bacterial development was established biopolymer production was inhibited and fluid viscosity stabilized.

MIEOR experiments with $Clostridium\ sp.\ TU-15A$ derived from formation water produced at Jilin (an oil field in China) (Sugai et al., 2007) yielded a biopolymer when cultured with a molasses-containing nutrient formulation (pH = 8.2). The cultures viscosity increased linearly with its molasses content rising to 70 cP over a 10-day cultivation period. Core flooding tests with this biopolymer, performed on two different sand packs, resulted in incremental oil recovery of 12% and 15%, respectively, after water flooding. These results were consistent with their MIEOR simulation studies of polymer producing microbes.

Purwasena et al. (2010) performed a laboratory test to evaluate the effect of the bacterium $Petrotoga\ sp.\ AR80$ in biodegrading the Yabase 33°-API-crude oil (Japan). During the bacterium's exponential growth phase reduction in oil viscosity reduction resulted from the breakdown of long-chain hydrocarbon molecules. They also reported that as salinity decreased, and temperature increased, higher degrees of viscosity reduction were achieved.

Armstrong and Wildenschild (2012b) injected active and inactive (non-viable) $Bacillus\ mojavensis\ JF-2$ and nutrients into cores together with a residual oil. They identified that IFT reduced from 54.3 mN/m to 8.7 mN/m as a consequence of biosurfactant mechanisms. Al-Sulaimani et al. (2012) investigated the biosurfactant impacts caused by direct injection of *Bacillus subtilis*. Compared with 23% oil recovery by waterflooding an optimal ratio of 50% biosurfactant and 50% chemical surfactant resulted in oil recovery increasing to 50%. Gudia et al. (2015) used *Bacillus subtilis* cultured in corn-steep liquor to produce a biosurfactant. They found out that the best microbial strain could reduce IFT to around 30 mN/m versus 66.4 mN/m as a result of water flooding alone. Such an IFT change was interpreted to suggest that oil recovery could be improved from 19.8% to 35%.

A number of MIEOR pilot field tests (microbial water flooding, heavy oil degradation, well stimulation to remove formation damage) were conducted in China in the 2000's, and these are summarized by Sheng (2013). Several MIEOR field tests during that period also focused on oil viscosity reduction and oil mobilization (e.g., Karim et al., 2001; Tingshan et al., 2005; Hou et al., 2011).

Karim et al. (2001) conducted laboratory experiments and field pilot tests on the heavy (20° API) and viscous (4 to 10 cP) oil in the Bokor field (Sarawak, Malaysia). One test showed that in-reservoir biodegradation the crude oil sample had resulted in the destruction of all normal and branched alkane molecules and the destruction of some aromatic molecules. MIEOR tests reduced viscosity and changed other characteristics of the heavy oil without signs of formation damage. A pilot field test was performed on 3 wells which were monitored for up to 6 months, resulting in higher oil and lower water production rates. Oil flow rate increased incrementally by about 270 barrels/day during the pilot test, representing a 47% increase in the oil contribution.

Tingshan et al. (2005) performed an experiment on Qinghai and Xingjiang crude oils (China). Injecting consortia of bacteria including *Bacillus brevis* and *Bacillus pseudomonas* together with nutrients, they demonstrated significant reductions in asphaltenes and gum components. In addition, they performed field tests in which average viscosity reduced by about 15% and oil recovery increased from 8.53% (pre-treatment) to 35.72% (post-treatment) for the Qinghai oil field (3 wells), while daily oil production rose six-fold for the Xingjiang oil field (6 wells).

Hou et al. (2011) performed MIEOR field tests in the Daqing Chaoyanggou oil field (Block Chao 50, China) involving 9 injectors and 24 producers. They injected into the producing zone, *Brevibacillus brevis* and *Bacillus cereus* extracted from formation water mixed with nutrients. The biosurfactants produced in-situ caused oil-water IFT to reduce from 46.3 mN/m (pre-injection) to 39.8 mN/m (post-injection). Nazina et al. (2017) described MIEOR-field-trail results at the high-temperature, heavy-oil zones in the Dagang field (China). They reported a total of 46,152 t of additional oil was recovered at three experimental sites (North block and block no. 1 of the Kongdian bed and the Gangxi bed) and an 11% reduction in viscosity in the Kongdian bed combined with a reduction of IFT of the formation water. Previously, Jimenez et al. (2012) had demonstrated the potential for the aromatic oil fractions in the Dagang reservoir to be biodegraded to form methane.

Wang et al. (2016) reported the results of a single-well field test (i.e., P6-P48 well) in the Chunfeng Oilfield (China). This well was producing extra-heavy oil from the oil-water transition zones in thin, shallow reservoirs via huff-n-puff (HnP) steam injection. High water cut had previously caused that well to be shut-in. In 2014, some 865 m^3 of a prepared solution (microbes plus nutrient plus activator) was injected into that well. The well then remained shut-in for a further 166 days. Subsequently, over a 405-day production period it produced 3,464 t of oil (applyng a conversion factor of approximately 7 barrels/tonne that equates to approximately 24,000 barrels). The produced crude oil viscosity had decreased by 58% and the production outperformed the 16 adjacent wells undergoing conventional huff-n-puff production. Alkan et al. (2016) described their design and risk management strategy for a MIEOR HnP one-well pilot project for a high-salinity-(160,000 ppm)-heavy-oil field in Germany oil field. Their focus was on optimizing nutrient compositions and dosage to stimulate growth and metabolite production whilst preventing the activation of sulphate-reducing bacteria (SRB) growth on the metabolites generated.

Ibrahimov et al. (2017) describe the results of long term MIEOR field test extending from the 1980s at 19 onshore sites in 15 fields of the Absheron Peninsula, Azerbaijan. The nutrient substrates deployed include molasses, milk whey and waste water sludge. They describe the detailed MIEOR production results for two fields, Bibiheybat and Pirallahi, for the period 1998 to 2009. Significantly, they used the production performance records from multiple wells to identify the hydrodynamic reservoir factors influencing enhanced oil production. They also and used these to successfully plan further MIEOR developments and forecast the related production increments from specific wells.

Ke et al. (2018) reported results from a long-term and large-scale pilot test on the Baolige oil field (China). This test recovered 210,000 tons of MEOR-related crude oil during 43 months from 169 production wells. Based on laboratory tests a mixture of species was injected into the reservoir: *Bacillus subtilis, Arthrobacter, G. subterraneus, Pseudomonas aeruginosa, Bacillus licheniformis and Rhodococcus sp.* Following the test some uncertainties still need to be resolved: 1) the nature of interactions between exogenous with indigenous bacteria; 2) role of reservoir heterogeneities in controlling bacterial flow through the reservoir; and, 3) long-term stability and sustainability of bacterial actions in the reservoir.

5. Modelling and simulation of MIEOR processes

The numerical models developed to explain MIEOR mechanisms, their impacts under the reservoir conditions and to predict their performance in terms of incremental oil recovery are diverse and have evolved significantly in recent years. This is highlighted by the different types and objectives of the models mentioned in this section.

Chang et al. (1991) described a comprehensive model for MIEOR processes incorporating three-dimensional analysis, three fluid phases and multiple microbial components. Their model was able to accurately predict the movements of injected microbes and nutrients, and the produced metabolites during core-flooding experiments. That model was used to successfully replicate a wide variety of MIEOR processes such as bio-clogging, the consumption of nutrients and their dispersion (Bryant et al., 1992; Bryant and Lindsay, 1996).

Li et al. (2011) developed a functional relationship between residual oil saturation and capillary number using a finite element model to couple biological and hydrogeological components. This enabled them to simulate modifications to IFT. By applying this to a homogeneous reservoir, testing showed that MEOR could enhance the oil recovery in conditions where capillary numbers between 10 and 5 are established. Skiftestad (2015) evaluated a two-phase flow regime applied to homogeneous porous media, in the presence of microbial activity. The model developed considered dynamic capillary pressure, calculated assuming Darcy's law, the principle of mass conservation and the diffusion/dispersion-advection equation. Dynamic capillary pressure modelling provided insight to the effect of microbes on fluid flow, oil production and oil recovery.

Van Noorden et al. (2010) highlighted the benefits of deriving upscaled (effective) models from initial micro-scale models by applying an asymptotic expansion method that involved limited computational effort. They developed a pore-scale model for biofilm growth in a porous medium and applied their upscaling algorithm to derive an effective model that was able to explain deposition or detachment of biomass along the pore walls of the porous media. That upscaled model was able to predict the development of biofilm layers of various thicknesses distributed over space and time. Kumar et al. (2014) applied a formal asymptotic techniques to derive upscaled equations for reactive flows in domains mimicking biofilm growth with oscillating flat and rough boundaries in channels over substrates with complex geometry.

Cheng et al. (2014) developed an oil production prediction model to simulate multi-slug MIEOR in heterogeneous reservoirs. Their model was built to explain experimental results and involved combining Buckley-Leverett theory and exponential production decline. They demonstrated that the model could meaningfully predict oil production rates, time to water breakthrough time, water cut and water saturation at the water-flood front.

Amundsen (2015) further developed the one-dimension MIEOR models proposed by Nielsen (2010) that focused on the impact of surfactant production, and of Lacerda et al. (2012) that focused on polymer production, to address biofilm formation applying the MATLAB Reservoir Simulation Toolbox (MSRT). Further MIEOR modelling using MSRT applied to biosurfactants are provided by Akindipe (2016). The simulation results obtained were able to qualitatively explain the effects of interfacial tension decrease and water viscosity increase on oil displacement. The results support the expectation that biopolymers have a profound effect on oil recovery for heterogeneous reservoir systems involving a high permeability channel. Lacerda et al. (2012) observed from the results of their simulation that maximum specific growth rate of the biopolymer was the parameter with the greatest impact on oil recovery factor.

Peszynska et al. (2016) combined information from direct imaging, experiments, numerical simulations and visualization. By upscaling their computational flow model and coupling it with a biomass-nutrient growth model, they were able to reproduce experimentally produced morphologies in a qualitative manner.

Landa-Marban (2016) and Landa-Marban et al. (2017) developed a 2-D porous medium simulation to evaluate the spatial distribution and the evolution over time of the average reservoir pressure, water saturation, oil-water interfacial area, capillary pressure, porosity, permeability ratio, residual oil water saturation and bacterial, nutrient and biosurfactant concentrations. This led to the conclusion that the metric interfacial area had a significant impact on oil recovery, but to quantify that impact experimental studies are required. More recently, upscaled models have been deployed to study the microfluidic effects of flowrate and nutrient concentration on biofilm accumulation and adhesive strength in a microchannel (Liu et al., 2018). They have also been applied to further develop pore-scale models for permeable biofilms (Landa-Marban et al., 2018).

Hosseininoosheri et al. (2016) developed a kinetic model for biosurfactant reactions as a function of pH, salinity and temperature to model the controlling factors in the biodegradation process and the related growth rates of microbes in the reservoir. The model was run using UTCHEM reservoir simulator and involved four-phases of chemical flooding. The results were history-matched to core-flood experimental data. Results indicated that nutrient concentration, salinity and temperature were the most significant variables effecting oil recovery.

Artificial neural networks coupled with a genetic algorithm were used by Dhanarajan et al. (2017) to optimize biosurfactant incubation and biopolymer flooding and maximize oil recovery based on laboratory tests.

Anash et al. (2018) developed a MIEOR simulator to evaluate oil recovery enhancement resulting from oil-viscosity-reduction effects of temperature, salinity, pH and nutrient concentration. Results suggested that oil recovery was directly proportional to reductions in salinity reduction and increases in nutrient concentrations.

Wang et al. (2018) developed a reservoir-flooding simulation model with biopolymers. It was one-dimensional but involved two phases and five components and was validated with core-flooding experiments. A novel variable incorporated in this model is the microbial-death rate with and without nutrients present. The model's reaction kinetics are dependent on the microbial-death-rate variable. They found that models involving two death rates were better able to match water-cut behaviour. Simulation results suggested a 7%-8% increase in oil recovery from basic water flooding by the injection of biopolymer-producing microbes. The field of MIEOR modelling is evolving rapidly and there is significant scope to further develop and combine most of the models described. Also, it is anticipated that new and more comprehensive MIEOR reservoir models applying recently-developed optimization and machine learning algorithms are likely to be developed in the coming years.

6. Benefits, risks and environmental issues for MIEOR

Modern biologically produced polymers, solvents and surfactants have demonstrated their ability to typically outperform their chemical counterparts in a wide range of characteristics (Geetha et al., 2018). This is particularly so for their favourable environmental footprint, production based on cheaper, renewable waste raw materials, surviving in harsh reservoir conditions, and possessing lower toxicity (Al-Sulaimani et al., 2011; Patel et al., 2015).

Despite MIEOR's environmentally-friendly attributes, some environmental risks do exist. As with most other EOR techniques the risks of inducing unwanted formation damage (Wood and Yuan, 2018), such as pore plugging, reservoir souring, and corrosion need to be recognised and mitigated. Laboratory tests, simulations and field monitoring are necessary to identify these risks and, where possible, prevent or mitigate their impacts. MIEOR products (metabolites) leading to positive and negative reservoir formation damage outcomes are summarized in Fig. 5.

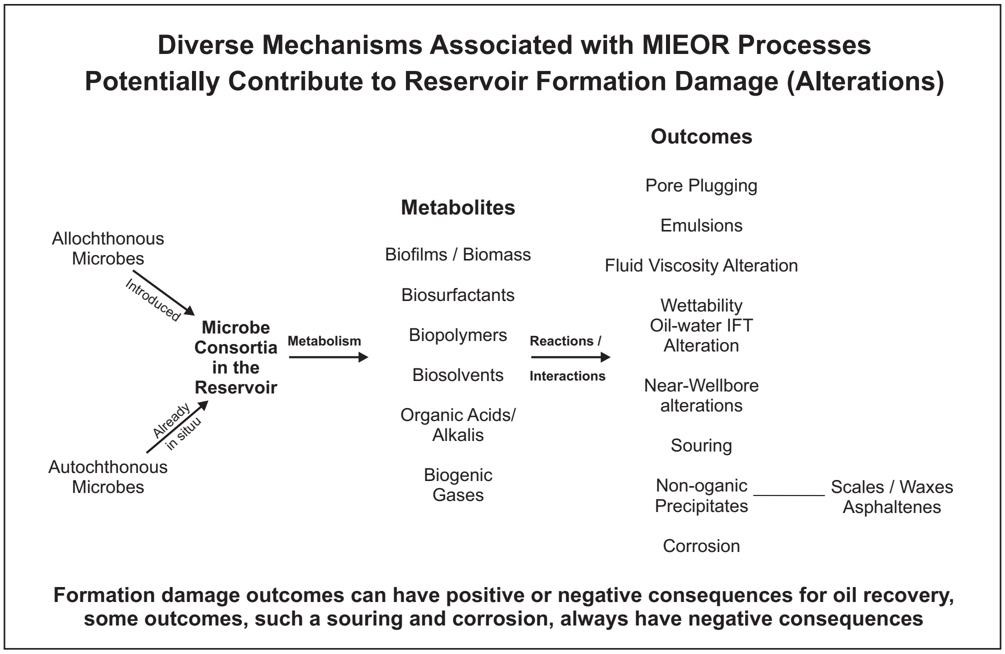

Fig. 5. A summary of potential reservoir formation damage outcomes caused by MIEOR metabolites.

6.1 Reservoir souring

One of these is the risk of reservoir souring if nutrients or sulphate-containing water are injected into reservoir. Depending upon the temperature, they may stimulate indigenous sulphate-reducing bacteria (SRB) to outgrow the injected microbes. SRBs obtain their energy anaerobically from organic compounds available in the wellbore and reservoir by the reaction depicted in Eq. (3) and produce hydrogen sulphide (H_2S):

$$4\,H_2 + SO_4{}^{2-} + 2\,H^+ \rightarrow 4\,H_2O + H_2S + \text{Energy} \qquad (3)$$

H_2S production in a reservoir causes its crude oil to become sour making oil processing more expensive and time consuming. In addition, the presence of hydrogen sulphide will increase the potential for corrosion of wellbore tubulars, production vessels and pipelines. In addition, liberating hydrogen sulphide can plug rock pores in the reservoir due to the precipitation of iron sulphide reducing permeability (Gregory, 1984; Bass, 1997; Brown, 2010). Nitrate is often injected into reservoirs to inhibit souring (Gieg et al., 2011) and is also injected for some nitrate reduction MEOR processes.

SRBs play a key role in reservoir souring, but their impact in MIEOR can often be inhibited (Sugai et al., 2014), e.g., by controlling the temperature (i.e., ensuring that it is not too low in the reservoir zones surrounding an injection well) and ethanol content of injected sea water. Zhang et al. (2012) analysed consortia of microbes extracted from injected and formation fluids sampled from four oil fields subjected to water injection in which reservoir temperatures varied from 25 to 70 °C. They found that the injected microbes had less impact on the formation water microbes in the higher-temperature reservoirs. This suggests that there is a delicate temperature balance when injecting microbes into a reservoir: if the temperature is too low, souring is likely to be promoted; if the temperature is too high, injected microbial communities are unlikely to survive and grow.

In certain conditions nitrate reducing bacteria may be able to catalyse corrosion at metal-biofilm surfaces where nutrients are limited by the microbes utilizing iron as an electron donor (Kryachko and Hemmingsen, 2017). Although nitrate is often injected into reservoirs to inhibit SRB and control corrosion, some nitrate-reducing bacteria (NRB) may undermine this. Microbial growth through fermentation processes in the reservoir may also produce weak organic acids close to metal surfaces contributing to corrosion, but these are likely to be of less concern than those of NRB.

Plugging of pore throats by biofilms and authigenic iron minerals could in certain conditions be unintended consequences of MIEOR (Kryachko, 2018). Laboratory tests such as those to identify clumping and sorption tendencies of cells (Klueglein et al., 2016) simulation and reservoir monitoring, including a rigorous produced fluids and solids sampling strategy (Kruger et al., 2016), is required to identify formation damage of this type.

6.2 Sustainability of MIEOR

6.2.1 At the micro-reservoir level

The ability to achieve and sustain desired in-situ metabolic activity depends upon the MIEOR processes applied being carefully designed to consider reservoir and fluid properties including: pH, pore geometry (porosity/permeability), pressure, salinity and temperature.

(A) Pore-size distribution

The existence and survival of microbes in underground reservoir is now well established (Frederickson and Phelps, 1996; Marshall, 2008). The size distribution of a reservoir formation's pores relative to the size of the desired microbes to be exploited is a key consideration. Surprisingly, the lower limit of the mean formation's pore sizes can be less than that of certain bacteria. For example, Frederickson et al. (1997) reported phospholipid fatty acid assays and C_{14} acetate mineralization measurements to assess microbe consortia in shale and sandstone cores (New Mexico, USA). No metabolic activity was identified in formations with pore throats smaller than 0.2 μm. However, microbial activity could be induced in some such rocks after extended incubation periods. On the other hand, they detected high levels of microbial activity in the formations displaying higher permeability. They concluded that sustainable metabolic activity required formations with pore-sized distributions with individual-pore diameters ≥ 0.2 μm and for those pores to be in some way interconnected. This limit severely restricts the potential application of MIEOR in many tight reservoirs.

(B) Acidity/alkalinity (pH)

The pH of the aqueous formation fluids carrying the microbes has an impact on their surface charge and enzyme function (Marshall, 2008). The degree to which proteins in a microbe's cell wall are ionized depends significantly on the carrying fluid's pH. Consequently, cell surfaces of microbes are typically charged and, as with other charged particles possess diffuse double layers with thicknesses that vary according to electrolyte concentrations. Enzymic processes involved in microbe respiration tend to be dependent on the formation fluid's pH. The optimal pH for specific microbes can vary significantly (2 to 9.5, Marshall, 2008) and the acids generated by microbe metabolism can influence the sustainability of the fluid's pH to support their long-term survival.

(C) Temperature

It is possible to group microbes based on the temperature ranges in which they are able to thrive and survive sustainably: Psychrophiles can survive in temperatures up to 25 °C; mesophiles can survive at temperatures between 25 and 45 °C; and, thermophiles can survive at temperatures between 45 and 60 °C. It is the thermophiles that are required to survive in most commercial sub-surface reservoirs. However, more exotic microbes are known to thrive in water temperatures > 100 °C (e.g., sub-sea thermal vents up to 121 °C, Miroshnichenko and Osmolovskaya, 2006) which suggests that some MIEOR processes have potential to be deployed even in very high temperature reservoirs (Blöchl et al., 1995). Microbes continue to be developed that can survive in extreme ranges of temperature, pH and salinity (Elazzazy et al., 2015).

(D) Survival at extreme pressures, salinities and temperatures

Pressure tolerances of microbes are typically related to their optimum temperature preferences. In terrestrial environments, the pressure grows incrementally at about 30 atmospheres per km depth, compared to the average geothermal gradient of 25 °C per km (Marshall, 2008). Sub-surface oil reservoirs exist across a wide spectrum of pressures, salinities, temperatures and other conditions. Formation water salinities are often greater than seawater salinities; pressures can sometimes exceed 200 atmospheres; and, temperatures can exceed 80 °C. Although such conditions are all within the survival range of bacteria (Jimoh, 2012), as their upper limits are approached the number of microbes that can tolerate them reduces significantly. Guo et al. (2015) based on MIEOR laboratory and field experience in China, suggest that MIEOR can be realistically conducted in reservoirs of 120 °C, salinity $> 350,000$ ppm and permeability of as little as 10 mD. For survival in extreme reservoir conditions it typically makes sense to extract and develop indigenous microbial consortia, as demonstrated by Gaytan et al. (2015) for the Chicontepec oil reservoir, Mexico.

6.2.2 At the macro level of petroleum resource life expectancy

There are a huge number of mature oil fields, large and small, at various stages of development (primary, secondary and/or tertiary) with the vast majority still retaining more than 50% of their original oil in place within the reservoir. Moreover, many of these reservoirs contain extensively damaged zones with substantial stranded residual oil that is difficult, if not impossible, to recover by primary and secondary field development technologies. Hence, the opportunity for EOR techniques in general is huge, particularly as the world's demand for energy and oil continues to grow and it becomes more-costly to explore for and develop new discoveries.

Although there are many opportunities to exploit residual oil in mature fields, MIEOR must compete effectively with other EOR techniques, specifically the chemical (CEOR) techniques. To date the commercial appetite for CEOR and MIEOR has been limited. This is partly due to the high cost of chemicals in the case of CEOR. In the case of MIEOR and CEOR a significant limiting factor historically has been the inability to reliably understand and control the complex reactions occurring in the reservoir, and the recognition that different reservoirs (and zones of the same reservoir) respond quite differently to the stimulations and diverse reactions involved. The advances of recent field tests, associated with laboratory experiments and simulations, as described here, have explained and resolved many of the earlier uncertainties, demonstrating the potential reliability and sustainability of MIEOR techniques in certain conditions.

Going forward, the better understanding of MIEOR techniques that is emerging should enable it to out-compete most CEOR techniques in terms of consistency, lower cost of biochemicals versus non-organically-produced chemicals, and more acceptable environmental footprints of the materials consumed. In certain applications hybrid MIEOR/CEOR techniques may provide the most effective solutions. Consequently, larger-scale commercially-attractive MIEOR deployments should be achievable in the near future.

7. Advantages and disadvantages in applying MIEOR

7.1 Positive attributes

- Limited requirements and easy setup requirements for specialist surface facilities.

- Low costs associated with producing and injecting microbes and nutrients compared with many non-organic chemicals used for reservoir stimulation.
- Low energy consumption associated with sustaining microbial metabolic activities.
- Applicable and effective in both carbonate and sandstone reservoirs.
- Microbes can be customized to metabolize in a wide range of specific and extreme sub-surface conditions.
- Small environmental footprints.
- Impacts have the potential to increase over time as microbial communities grow within the reservoir and multiple MIEOR mechanisms come into play.
- Suitable and effective with light and heavy crude oil reservoirs.
- Can be exploited for wellbore and pipeline clean-up (dewaxing and descaling) in addition to reservoir stimulation.
- Extensive research and development of microbial consortia with positive MIEOR attributes continues to provide improved knowledge and understanding that has yet to be fully exploited commercially.

7.2 Negative attributes

- Equipment oxidation and corrosion (wellbore and surface facilities) caused by the actions of some microbes.
- Reservoir souring caused by some microbes in certain subsurface conditions.
- Limited tolerances of many microbes to extreme and varying reservoir conditions.
- Potential to cause formation damage (particularly unwanted pore plugging) in certain conditions.
- The complexity of microbial activities makes it difficult to develop reliable holistic simulation models for the multi-dimensional impacts of MIEOR processes in specific reservoirs.
- Many microbial consortia include some metabolites that are beneficial for oil recovery and others that are detrimental. Often understanding the complete impacts of the microbial consortia requires medium to long-term field tests.
- Extensive laboratory and pilot-testing is typically required to customize MIEOR to suit a specific reservoir.
- Ongoing nutrient requirements of some microbes represent a long-term operational burden for deployments in remote areas.
- Many microbes have toxicity sensitivities to the heavy metal ions and other chemicals present in some reservoirs/crude oils, additives and nutrients.

8. Summary

Knowledge and understanding of the complexities of the metabolic activities of microbial consortia and their impacts on reservoir properties, fluids and facilities is rapidly improving. Multiple beneficial products can be exploited that demonstrably improve oil field performance (e.g., biofilms, biosurfactants, biopolymers). Despite the slow commercial uptake of MIEOR techniques and mixed results from field trials historically, better laboratory testing, simulation modelling and field performance monitoring has lead to numerous successful field trials in recent years. However, MIEOR does have some potential downsides (e.g., reservoir souring, facilities corrosion, formation damage) that require mitigation. Nevertheless, the ability to isolate from reservoir fluids, customize and engineer microbial species capable of thriving in extreme reservoir conditions continues to expand the range of reservoirs suitable for MIEOR deployments. To be successful, recent field studies highlight that detailed laboratory testing to carefully tailor the microbial consortia to suit a specific reservoir, followed by extensive field-pilot testing, are essential before field-wide deployment. Going forward MIEOR should be able to outperform traditional CEOR by generating biochemicals in the subsurface that are cheaper, more environmentally acceptable and sustainable.

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Appendix: Microbe species with promising potential for MIEOR applications

Previous reviews (Sheng, 2013; Badruddin et al., 2017) provide a summary of the main microbe species used in historical MIEOR studies and field tests together with their microbial products and reservoir applications. A selection of the microbe species that are the focus of recent research and field applications are listed here.

Bacillus firmus and *Bacillus halodurans* for lightening heavy oils (Shibulal et al., 2018).

Bacillus mycoides for biosurfactant production (Najafi et al., 2015).

Bacillus licheniformis (thermophilic) to produce biopolymer (Dhanarajan et al., 2017; Halim et al., 2017).

Bacillus subtilis for producing Lipopetide-type biosurfactants (Pereira et al., 2013; Al-Wahaibi et al., 2014; Chen et al., 2015; Gudina et al., 2015a; Dhanarajan et al., 2017), *Bacillus subtilis RI*4914 for biosurfactant, solvent and biopolymer production with NH_4NO_3 treatment in high salinity and high temperature conditions (Fernandes et al., 2016).

Bacillus stearothermophilus for biosurfactant production in carbonate reservoirs (Sarafzadeh et al., 2014).

Clostridium sp. for biosurfactant production in high-temperature reservoirs (91+°C) (Arora et al., 2014).

Enterobacter cloacae for biosurfactant production capable of withstanding extreme reservoir conditions (Darvishi et al., 2011; Rabiei et al., 2013; Khajepour et al., 2014; Sarafzadeh et al., 2014).

Fusarium sp. BS − 8 for biosurfactant production (Qazi et al., 2013).

Luteimonas huabeiensis sp. nov indigeneous facultive microbe for generating biosurfactants and heavy oil degradation (Ke et al., 2018b).

Paenibacillus alvei for biosurfactant production (Najafi et al., 2015).

*Paenibacillus ehimensis BS*1 for biotransforming heavy oil to light oil (Shibulal et al., 2017).

Pseudomonas aeruginosa (thermo-and halo-tolerant) for producing biosurfactant from waste kitchen oil and other low-cost sources (Kryachko et al., 2013; Amani, 2015; Dobler et al., 2016; Varjani and Upasani, 2016; Chen et al., 2018) and without air injection (Zhao et al., 2018). It can grow and metabolise in aerobic and anaerobic environments (Arai, 2011).

Pseudomonas pultida for producing rhamnolipid-type biosurfactants, surface-active compounds of glycolipid-type (Kanna et al., 2014; Chai et al., 2015; Gudina et al., 2015b; Sajna et al., 2015; Sivasankar and Kumar, 2017).

Pseudomonas sp. 2*B* for producing biosurfactant (Aparna et al., 2012).

Pseudomonasstutzeri Rhl used to anaerobically produce rhamnolipid (Zhao et al., 2014) and to simultaneously inhibit sulphate-reduction and H_2S removal (Zhao et al., 2016).

Rhizobium radiobacter heterotrophic nitrate-reducing bacteria (hNRB) (Da Silva et al., 2014; Gassara et al., 2017).

Thalassolituus oleivorans for low-temperature heavy oil degradation (Chai et al., 2015).

*Thauera sp. TK*001 for nitrate-mediated MIEOR to breakdown heavy oils (Fida et al., 2017).

Virgibacillus salarius for use as a biosurfactant under extreme conditions (Elazzazy et al., 2015).

The denitrifying bacteria *Arcobacter sp.*, *Desulfuromonas michiganensis*, *Comamonas denitrificans*, and the sulphur-oxidizing *Thioalkalivibrio sulfidophilus* have also received some attention (Chai et al., 2015).