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# Microbial Enhanced Oil Recovery

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Aliya Yernazarova, Gulzhan Kayirmanova,  
Almagul Baubekova and Azhar Zhubanova

Additional information is available at the end of the chapter

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## Abstract

The ever-rising global demand for energy and the issue of large volumes of unrecovered oil after primary and secondary oil production operations are driving the development and/or advancement of enhanced oil recovery (EOR) techniques. Conventional EOR processes include thermal, immiscible and miscible gas injection, chemical, and microbial enhanced oil recovery (MEOR), among others. This chapter provides an overview of MEOR including its history, strata microflora, mechanisms of MEOR for oil recovery, and a brief recount of field MEOR applications.

**Keywords:** microbial enhanced oil recovery, MEOR, microorganisms, strata microflora, biosurfactants, oil reservoirs

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## 1. Introduction

The necessity of improving and/or advancing the current enhanced oil recovery (EOR) processes to make them more efficient has attracted the attention of researchers and oil field operators. Thus, over the last few decades, this problem has received constant attention resulting in slow but steady growth of the average oil recovery factors. For instance, at present the worldwide average recovery rate is about 30%, whereas in the USA, the average oil recovery factor is 39%. However, many experts believe that in the foreseeable future the recovery factor may well reach 50–60% and even 70–80% [1].

The development of an oilfield refers to the process of displacing the accumulated liquid and gas hydrocarbons in the reservoir towards production wells. Oil is produced initially using the natural driving energy of the reservoir (i.e., primary recovery operations), or by introduc-

ing energy into the reservoir during secondary oil recovery (i.e., waterflooding or gas flooding), as soon as the natural reservoir energy is depleted.

Particularly, in Kazakhstan most of the hydrocarbon deposits have already been discovered and commercially produced. Currently, fewer and fewer drilling sites in those mature reservoirs are of interest from the commercial standpoint. In this regard, the residual oil left behind in these mature hydrocarbon deposits after primary and secondary oil recovery offers an opportunity for the implementation of EOR processes, including the application of microbial enhanced oil recovery (MEOR) technology.

## 2. Review on MEOR

### 2.1. History of MEOR

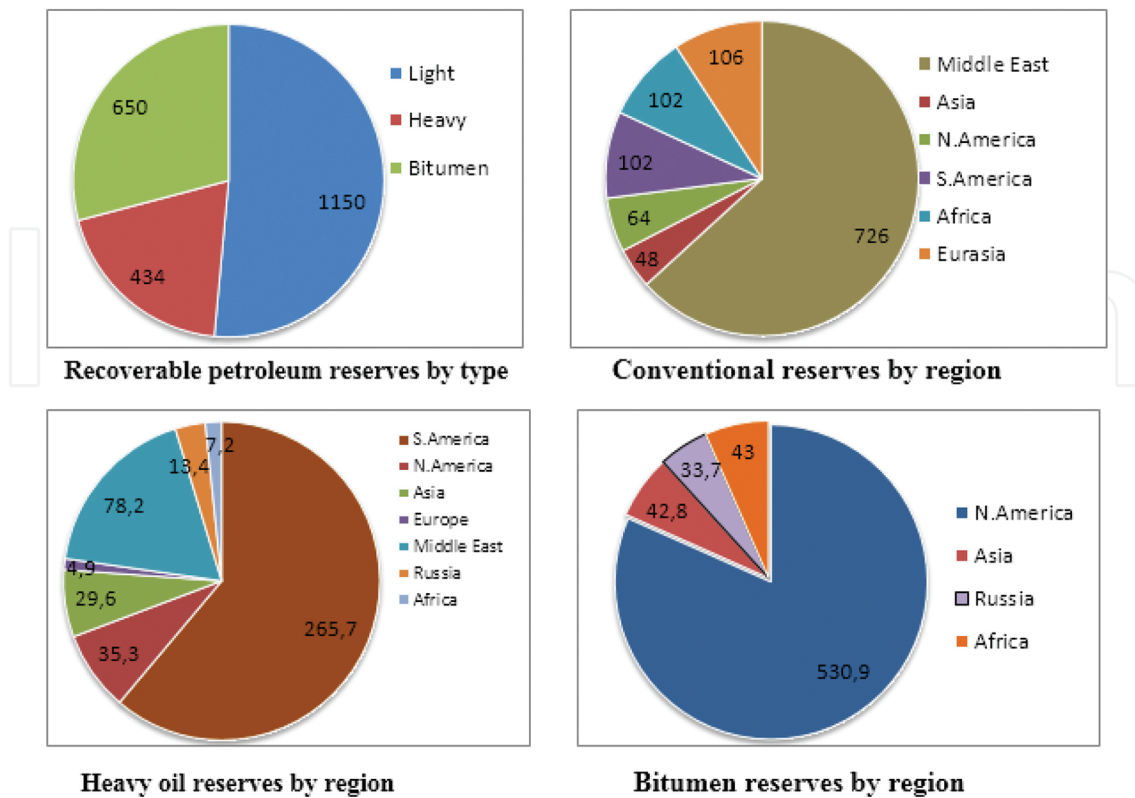
In 1926, J. W. Beckman [2] came to the conclusion that it was necessary to develop additional methods to augment oil recovery beyond primary and secondary oil recovery processes. Therefore, he proposed the utilization of microorganisms as one of the solutions to the oil recovery issue. Later on, the use of microorganisms for oil recovery enhancement was patented by C. E. ZoBell in 1946 [3], since then, the MEOR process has been validated by numerous studies and successful fields tests, the first of them carried out in Arkansas, USA, in 1954 [4].

Since the 1970s, intense research efforts on MEOR have been made in the USA, USSR, Czechoslovakia, Hungary, and Poland. The oil crisis in the 1970s further aroused the interest in MEOR research in more than 15 countries. For instance, in 1976, the Soviet Government enacted a special regulation "...concerning measures on achieving the most efficient oil recovery processes." This regulation defined the target volumes of additional oil recovery that were required using tertiary enhancement methods and provided economic incentives to encourage oil-production enterprises [5].

Since year 1970 until the 2000s, microbial ecology and deposit characterization were the focus of MEOR research. By 1990, MEOR reached interdisciplinary technological status. In 2007, a review of 322 MEOR projects in USA showed that 78% of the total number of projects were successful in enhancing oil recovery; while no cases of lowered oil recovery were revealed [6]. At present, there is a grown interest in the application of MEOR to enhance oil production from depleted reservoirs, because its low capital cost and environmental friendliness.

MEOR mechanisms are the same mechanisms obtained from other chemical enhanced oil recovery (EOR) methods; however, MEOR presents the advantage that microbial metabolites are directly produced in the reservoir rock formation, which makes them more effective. Furthermore, microorganisms metabolize different hydrocarbons at different rates [6].

**Figure 1** presents a breakdown of the worldwide recoverable petroleum reserves by type and region prepared by Meyer and Attanasi [7] and Schmitt [8].



**Figure 1.** World's current recoverable petroleum reserves by oil type and region in billions of barrels. From Meyer and Attanasi [7] and Schmitt [8].

Worldwide accumulations of heavy oil and bitumen are about five times higher than the reserves of light conventional oils. For instance, heavy oil resources are an essential part of the oil industry in Kazakhstan as well as in a number of other oil-producing countries.

The largest reserves of bitumen and heavy oil are located in Canada and Venezuela; while significant reserves are also found in Mexico, the United States, Russia, Kuwait, and China [9].

Kazakhstan is currently experiencing a period of late-stage development. Oil fields under waterflooding have reached a high water cut ranging from 80 to 90%, while a large volume of undeveloped oil reserves (up to 60–70%) are located in deep oil reservoir formations. In addition, most deposits of Kazakhstan are characterized by high viscosity oils and complex geological structures [10].

## 2.2. MEOR: Challenges and Opportunities

Primary and secondary oil recovery processes achieve on a worldwide basis an average recovery of 33% of the original oil in place (OOIP); while the unrecovered oil (67%) might be retained in the reservoir by viscous and/or capillary forces. Conventional chemicals, such as solvents and surface-active compounds (surfactants) are used during chemical EOR applications. Solvents reduce the oil viscosity to improve the oil mobility by overcoming viscous forces; while surfactants reduce the interfacial tension between oil and rock or oil and water

overcoming capillary forces. These chemicals are added to the injection water and transported within the reservoir during water flooding, however, the chemicals reach only the places where oil has already been displaced by water; furthermore, the chemicals could be partially consumed and/or retained within the rock formation before they reach the target area in the reservoir for their intended use [6].

The injection of solvents and surfactants into some reservoirs have yield unsatisfactory results because the chemicals failed to contact the residual oil for the required time period, which is needed to achieve a long-term effect. Another problem is the natural heterogeneity of the reservoirs; therefore, the injected chemicals inevitably flow along the paths of least resistance (i.e., high permeability zones, natural fractures, etc.) where the saturation of residual oil is usually the lowest.

It has been known for decades that specifically selected microorganisms are capable of metabolizing hydrocarbons producing organic solvents, such as alcohols, aldehydes, surface-active fatty acids, and other metabolites which can interact with the crude oil improving its fluidity. Other oil production issues such as the presence of paraffin, emulsions, and corrosion problems can also be controlled using microorganisms. For instance, extensive research has been conducted on the use of biosurfactants (BS) for enhanced oil recovery applications [11–14].

Prior to the application of MEOR technologies, the projects are assessed to determine the compatibility of the crude oil and reservoir properties with MEOR taking into account the physicochemical properties of the crude oil, reservoir production performance, and reservoir properties (i.e., temperature). At the preliminary stage, reservoir fluid samples are collected and tested for compatibility with the MEOR systems. The first stage is the identification of the indigenous hydrocarbon-consuming bacteria, which is already adapted to the in situ reservoir conditions; after which the best action strategy for each project is designed and developed [4, 6].

MEOR can be applied on individual wells as follows: (1) from the well being treated or (2) from the target well and adjacent wells of the same reservoir. The MEOR solution is injected into adjacent wells in the same way as water is injected into the reservoir. The volume of the MEOR biomaterial to be injected is calculated based on the pore volume of the target reservoir. The solution is mixed and pumped through the injection well followed by the injection of water to drive the biological solution into the oil saturated zones. Then, the treated well is shut in for the required period of time (normally 24 h to 7 days) after which oil production is resumed. This procedure is repeated every 3–6 months to enable microorganisms to move deeper into the deposit to oil saturated zones [6].

Some of the general advantages of MEOR are outlined as follows:

- Increase of the productivity of the oil fields [9];
- Increase in the total oil produced and more efficient operation of wells and oil fields;

- Increase of the viscosity of the formation water due to the upsurge of biomass concentration and the microorganisms' metabolic products, such as soluble biopolymers, which reduces the mobility of the formation water within the formation rock [9];
- The MEOR set up is less expensive, because the injected bacteria and nutrients are inexpensive [15, 16];
- Low energy input requirement for microbes to produce MEOR agents [16];
- Reduced of the operations downtime [9];
- MEOR is environmentally friendly, because microbial products are biodegradable [15, 16].

In terms of the quality of the oil produced, some benefits are [9]:

- An increase of light alkanes <C<sub>20</sub>;
- Reduction of the average content of C<sub>20</sub>–C<sub>40</sub> alkanes;
- Biodegradation of high molecular heavy hydrocarbon components;
- Splitting of aromatic ring structures;
- Splitting of phenolic ring chemical structures;
- Transformation of sulfur-containing organic compounds;
- Emulsification of crude oil that can be easily mobilized to the production well.

MEOR methods can be divided into two main groups:

1. *Ex-situ* production of the MEOR metabolites such as biosurfactants, biopolymers, and emulsifiers using exogenous or indigenous bacteria. In this case, microorganisms are grown using industrial fermenters or mobile plants and then injected into the oil formation as aqueous solutions.
2. *In-situ* production of the MEOR metabolites. In this case, the formation of metabolites is the result of the microbiological activity that takes place directly in the reservoir. The MEOR metabolites are produced by indigenous bacteria or by exogenous bacteria that are injected into the reservoir.

*In-situ* MEOR can be divided into two categories depending upon the method of injection of microorganisms and nutritional media (e.g., molasses, whey, and other waste food or chemical products) into the reservoir [17]. The first category consists in the *in-situ* stimulation of the natural indigenous microflora of the reservoir by means of injecting nutrients into the reservoir. The alternative (second category) is the injection of microbial cultures (exogenous or indigenous) along with nutrients; which is the preferred mode of application in the field. In any case, the development of these methods is impossible without the knowledge of the physicochemical and microbiological conditions in the oil bed. Oil recovery by water flooding is characterized at later stages by the formation of a mature biocenosis. The growth of this integrated microorganism community depends on the availability of nutrients.



The *in-situ* production of metabolites is carried out in two stages. First, water and oxygen are pumped into the formation as a water-air mixture containing mineral salts, nitrogen, and phosphorous to activate the indigenous microflora. In the presence of water and air, aerobic bacteria oxidize hydrocarbons producing low molecular weight organic acids (acetic, propionic, butyric, etc.), alcohols (methanol and ethanol), biosurfactants, and carbon dioxide, which increase the pressure in the reservoir [18–20].

In the second step, oxygen-free water is injected into the reservoir to activate anaerobic indigenous bacteria that metabolize crude oil to acids, and gas (i.e., methane, carbon dioxide). The accumulation of these biogases increases the reservoir pressure. If the pressure in the reservoir is high enough, methane could be dissolved into the liquid hydrocarbon phase reducing its viscosity. Similarly, carbon dioxide could also reduce the oil viscosity if the pressure in the formation allows the miscibility of CO<sub>2</sub> into the bulk oil phase. A reduction of the oil viscosity improves the oil-displacing properties through the reservoir increasing oil production [14]. Furthermore, CO<sub>2</sub> could react with the minerals in the rock and dissolve carbonate increasing the permeability of the formation rock.

In the oil industry, MEOR has been applied for several uses besides enhanced oil recovery, such as well stimulation; remediation of oil spills in soil and ground water; and to clean borehole, down hole equipment, and piping, among others.

### 2.3. MEOR process components

The MEOR process consists of two essential components: hydrocarbon-consuming microorganisms and a nutritional medium as the source of nitrogen and phosphorus. Hydrocarbon-consuming microorganisms can be exogenous or indigenous. Indigenous are isolated for characterization from the hydrocarbon deposit where they will be employed.

The use of industrial byproducts as nutritional media such as molasses [21–24], corn steep liquor [25], and cheese whey [24] has been documented. The injection of nitrate aqueous solution at a concentration of 1.5 g/l of injected water has been recommended to suppress the activity of sulfate-reducing bacteria [22]. Reduction of the cost of nutrients during the application of MEOR processes can be achieved by injecting only nitrogen and phosphorous sources. Nitrogen is an essential nutrient for bacterial growth. Likewise, phosphorous is another key nutrient. If phosphorous nutrients are lacking, microbial cells cannot synthesize enough ATP for their metabolic activity [26].

### 2.4. Reservoir microflora

Microbial communities in oil rock formations are dated as the Earth's most ancient biocenoses, which sank to great depths along with organic residues and biogenic sludge.

Numerous varieties of microorganisms have been isolated and detected from different oil reservoirs such as sulfate and sulfur reducers hydrogenotrophic and heterotrophic methanogens [27–30], fermentative bacteria [31, 32], hydrocarbon and oil-oxidizing bacteria [19, 33], iron and manganese reducing microbes [34].

The presence of indigenous microflora and exogenous microorganisms in water and oil-bearing deposits has been demonstrated [3]. Exogenous microorganisms have been introduced into the reservoirs during drilling and flooding (i.e., secondary and tertiary oil recovery) operations. In the absence of molecular oxygen (i.e., absence of a terminal electron acceptor), microbial hydrocarbon decomposition is possible through anaerobic respiration using nitrate, iron oxide, carbon dioxide, or sulfate. Interspecific electron transfer is also possible with methanogenic or sulfate reducing bacteria as biological acceptors. In oil strata with temperatures between 20 and 80°C, there are complex microbial communities made up by fermentative bacteria and methanogens that can oxidize hydrocarbons and reduce sulfur, sulfate, and iron. The microbial count in high temperature oil reservoirs is low.

The studies of microbial communities conducted on samples of formation water from the Zhetybay and Kulsary oil fields located in Western Kazakhstan gave total aerobic counts of  $1.8 \cdot 10^6$  and  $25.1 \cdot 10^6$  cells/ml, respectively. The number of aerobic microorganisms present in the water samples from the Zhetybay field is lower than the bacterial count from the Kulsary field by an order of magnitude. While the count of anaerobes is  $0.38 \cdot 10^5$  cells/ml for the Zhetybay field sample and  $0.5 \cdot 10^2$  cells/ml for the Kulsary field. These observations correlate well with the respective depth of each reservoir; the water samples from the Kulsary field were collected at a depth of 250 m; while the water samples of the Zhetybay field were collected at a depth of 1900 m, therefore it is expected that at deeper reservoirs conditions (i.e., Zhetybay field) anaerobic microorganism would adjust better. It has been reported that in deep water and oil-bearing strata the total bacterial count is as high as 10 million cells/ml [35].

The effect of microorganisms is significant if they are numerous and physiologically active. An arbitrary threshold for bacteria is estimated at 1 million/1 g substrate since it is only in such quantities that they can have significant ecological impact. For each ecological factor (temperature, amount of nutrients, concentration of microcells, and trace elements), there are optimum values which favor the growth of an organism and the extreme values at which growth is suppressed. At values close to the extremes of the preferred range for a given organism, its survival is still possible though its growth is limited because the organism is under physical stress conditions. Microbiological studies on bacteria obtained from the Zhetybay and Kulsary hydrocarbon deposits show that aerobes play an important ecological role since they are found in large numbers and in physiologically active states [35].

Exogenous bacteria such as allochthonic bacteria are present in oil reservoirs, which were introduced during water injection creating a mixture of exogenous and indigenous microflora. At reservoir depths of 1–3 km, thermophilic microbial communities are found. These microbial communities are made up of microorganisms commonly found in deep reservoirs and bacteria normally encountered in shallow areas of the reservoirs (i.e., <1 km) but in lower numbers.

For instance, the Zhetybay and Kulsary oil reservoirs contain several groups of microorganisms including spore-forming bacteria, *Micromycetes*, *Pseudomonas*, *Bacillus*, *Enterobacteriaceae*, with the most prevalent being the spore-forming bacteria whose counts reach  $0.12 \cdot 10^5$  cells/ml [35].



Total bacterial counts and the abundance of certain groups of aerobic and anaerobic bacteria are remarkably lower in oil reservoirs than the count of bacteria determined in the water used during waterflooding. The reason is that not all microorganisms survive extreme reservoir oil conditions. Some bacteria may be immobilized on the surface of the rocks lowering the number of bacteria in the liquid phase. Viable cells of methanogenic microorganisms have been found in reservoir fluids (i.e., formation brine) with salinity as high as 200 g/l, however, these and other microorganisms were also present in large numbers in substantially desalinated fluids [35].

Microbial community in oil reservoirs can be considered as closed and semiclosed systems, because they exist in an environment hindered from water exchange, which is characterized by a slow mass transfer at constant temperature in the absence of atmospheric air and sunlight. In this ecosystem, oil is the main source of energy for the microbial community. Molecular nitrogen and ammonium nitrogen are sufficient to meet the needs of the microflora. The phosphorus content is small, which limits the biogenic processes in this ecosystem. Therefore, microbiological processes proceed slowly due to low water exchange and lack of nutrients. The development of oil reservoirs by water injection introduces dissolved oxygen into the system that activates microbiological processes and as result oil biodegrades [36].

Aerobic microorganisms have been found in formations with temperatures ranging from 20 to 70°C and pH ranging from 6.0 to 8.4. Some of these aerobic bacteria have been identified as *Rhodococcus ruber*, *Arthrobacter oxydans*, *Kocuria rosea*, *Gordonia rubropertincta*, *Cellulomonas cellulans*, *Bacillus subtilis*, *B. cereus*, *Pseudomonas fluorescens* [14, 22, 37–40]. Thermophilic microorganisms can grow at oil reservoir temperatures ranging from 40 to 70°C, at pH ranging from 6.0 to 7.8, and salinity concentrations from 0 to 5% NaCl. In high temperature oil reservoirs, hydrocarbon-oxidizing bacteria are a common component of the biocenoses in the bottom-hole areas of the water injection wells through which dissolved oxygen enters the stratum. Hydrocarbon-oxidizing bacteria found in these locations are often spore-forming, which allows survival in extreme environmental conditions [35].

Wang et al. isolated three thermophilic hydrocarbon-degrading species, such as *Bacillus* sp., *Geobacillus* sp., and *Petrobacter* sp. that could tolerate 55°C of temperature [41].

Thermophilic bacteria were isolated from a reservoir, located at Maracaibo Lake, Venezuela, which has temperatures ranging from 60 to 80°C and pressures ranging from 1200 to 1500 psi [42]. Moderately, thermophilic spore-forming sulfate-reducing bacteria (*Desulfotomaculum* and *Bacillus*) have been identified in the Zhetybay high temperature oil field in Kazakhstan [35].

The anaerobic microflora present in oil reservoirs are commonly bacteria of the genera *Bacteroides*, *Clostridium*, *Thermoanaerobacter*, *Thermococcus*, *Thermotogales* [43], *Petrotoga* [44], *Thermotoga* [45], *Desulfotomaculum* [46], *Caminicella* [47], *Geosporobacter* [48]. Screening for microbial consortia from some Omani oil wells by Al-Bahry et al. [49] showed a total of 30 genera and 69 species of microorganisms. In this study, most of the detected genera were found to be anaerobic, thermophilic, and halophilic and some of them were documented to be suitable candidates for MEOR.

## 2.5. MEOR oil recovery mechanisms

During the MEOR process, the components are mixed at surface facilities and injected into the oil reservoir. Inside the reservoir, MEOR-bacteria are transported by the injected water and accumulate in porous zones at the oil/rock and oil/water interfaces. Bacteria utilize very small amounts of oil and produce metabolites such as solvents, surfactants, acids, and carbon dioxide. These bioproducts interact with the oil in the reservoir to reduce the oil viscosity, interface tension at the oil/rock and oil/water interfaces, improve rock permeability by removing paraffin, mud, and other debris that plug the porous media [15, 50]. Microbial cells are continuously generated as well as the *in-situ* production of metabolites. The prolong interaction of metabolites with the oil in the reservoir, changes the oil properties in such a way that immobile unrecoverable oil is converted into movable oil that can flow to the production wells increasing oil output accordingly.

Microbial degradation of oil, which is a complex chemical compound, is the result of cometabolism of microorganisms where the metabolism's products of the hydrocarbon-oxidizing bacteria serve as the substrate for other physiological groups in the reservoir. Hydrocarbons are decomposed to produce fatty acids that can be utilized by other microorganisms [51].

The main mechanisms acting on oil recovery by MEOR are summarized as follows:

- a. Formation of bioacids that could dissolve some of the minerals (i.e., clays, carbonates, etc.) contained in the formation rocks. Rock dissolution increases the porosity and permeability of the reservoir [52–54];
- b. Production of solvents and biogases, leading to lower oil viscosity that facilitates oil displacement through the porous media [55–58];
- c. Formation of biosurfactants, biopolymers and other compounds, that could interact with the crude oil by emulsifying the oil, reducing its viscosity, and reducing the interfacial tension at the oil-water interface [59–63];
- d. Production of microbial biomass that could change the wettability of the oil rock [55, 64].

One of the most important functionalities of oil-oxidizing microorganisms is their capability of using hydrocarbons to produce biosurfactants, which emulsify hydrocarbons. The hydrocarbon-oxidizing microorganism's strains that are very active in producing biosurfactants are: *Pseudomonas aeruginosa*, *Bacillus subtilis*, *Mycobacterium rhodochrous*, *Rhodococcus erythropolis*, *Candida lipolytica*, and *Torulopsis gropengiesseri*. Microorganisms belonging to different genera have the ability to metabolize hydrocarbons including more than 300 fungal, bacterial, yeast, and actinomycetes strains. The hydrocarbon-oxidizing ability is quite common in bacteria belonging to the genera *Mycobacterium*, *Rhodococcus*, *Pseudomonas*, *Micrococcus*, and *Bacillus*. In fungi and yeast-like organisms, this faculty is often found in nonsporogenic *Candida*, *Trichosporon*, and *Exophialia*. The vast majority of *Rhodotorula* species is also capable of oxidizing hydrocarbons [65–69].

The implementation of MEOR requires low capital investment; while it offers high efficiency, and environmental friendliness. The initial phase of the MEOR process is the partial oxidation

of residual oil in the bottom-hole area that yields bioproducts such as carbon dioxide, low-molecular-weight fatty acids, and other organic compounds. Further, when these bioproducts are transported by the injected water into the anaerobic zones of the reservoir, methanogenic microorganisms are activated. Production of methane is important because this is an easily extractible gas that can be dissolved into the oil phase (i.e., if the reservoir pressure is high enough) improving the oil mobility [70].

During waterflooding, dissolved oxygen in the water is delivered to the strata. This oxygen is rapidly consumed at the bottom-hole area during the microbial oxidation of residual oil, which causes the stimulation of anaerobic bacteria, particularly, methanogens, in the oxygen-free zone of the stratum [70]. The number of aerobic hydrocarbon-oxidizing and oligocarbophilic bacteria grows to a less extent, however, at the same time the content of anaerobic metabolism products in oil formation waters increases significantly. During this process, carbonate and sulfate content increases.

Foam-forming organic substances that reduce the interfacial tension at the oil/water interface by a factor of 100 have been identified to be caused by microbiological oil oxidation products in the bottom-hole area [71].

Oil recovery by waterflooding can be viewed as a natural fermenter, where continuous microbial cultures could be maintained. These microbial cultures could be activated by the injection of microorganisms and nutritional medium components. In this case, residual oil serves as the main substrate for microorganisms; while in the bottom-hole area, a specific microbial community is formed whose activity can be regulated [71].

The temperature of the oil reservoirs determines the types of microbial communities. In the bottom-hole areas of the injection wells, the temperature corresponds to the temperature of the injected water. In high temperature reservoirs, as is the case of the Zhetybay oil field, cold water is injected, therefore mesophilic bacteria prevail at these conditions compared to the thermophilic communities of the Uzen oil field in Kazakhstan, where hot water is injected [71].

The implementation of MEOR starts with the addition of biological materials to the injection water. Microorganisms enter the reservoir mixed with the injected water through the existing flooding system without affecting the injection rate or pressure. The implementation of MEOR process requires very small modifications, if any, to the existing water injection equipment, so that the flooding process is not interrupted [6].

After the implementation of the MEOR project, it is continuously monitored through bacteria population growth and the oil output rate within certain period of time. The hydrocarbon-oxidizing bacteria population is kept under continuous surveillance after the injection of MEOR fluids. The population size is compared to that of the indigenous hydrocarbon-oxidizing bacteria before the beginning of the process. Normally, such population starts to grow slowly. In addition, the fluids produced are also monitored for the presence of hydrocarbon-oxidizing bacteria in order to assess how far the microorganisms have moved into the reservoir after injection [6].

## 2.6. Field tests applications of MEOR

There is extensive MEOR published literature on laboratory research data and pilot field trials. Although at present widespread commercial use of the MEOR technology has not taken place yet.

Biotechnological methods for increasing oil recovery have to solve a number of practical problems [72], which are summarized as follows:

- a. The preparation of suitable microorganisms and microbial associations highly active at the specific conditions of the reservoir, including the composition and properties of the crude oil. Most of the microorganisms that adapt to the conditions of the field could have little effect on the composition and properties of the crude oils. Industrial applications require new strains of microorganisms with the following qualities: tolerant to high temperatures and salinities concentration, as well as capable of synthesizing surfactants and polysaccharides.
- b. The establishment of techniques to create appropriate reservoir conditions to favor the growth and activity of specific microorganisms. This requires further exploration of ways to introduce additional nutrients, primarily nitrogen and phosphorus compounds.
- c. The development of cost-effective methods for sulfate reduction. Reservoir conditions are ecological niches for sulfate-reducing bacteria. It is necessary to control the generation of hydrogen sulfide because it creates the problem of a toxic aggressive environment, corrosion, higher sulfur content in the crude oil, toxic products, and other undesirable consequences.

Maudgalya et al. [73] reviewed 407 MEOR field trials worldwide. The field trials were classified according to the following parameters: reservoirs' lithology and properties, microorganisms, nutrients, type of test, and type of recovery mechanism. From the total 407 field trials, 333 field trials were applied following the well stimulation method, 26 of the trials were conducted using the waterflooding and 44 field trials were conducted as single well (huff-puff scheme) applications; while details of the application method for the remaining four field trials were not provided. This survey indicated that the primary mechanisms for MEOR were permeability profile modification, increase of capillary number (i.e., biosurfactants, alcohols, biopolymers, and acids), biodegradation of heavy crude oil components making the oil less viscous, and the swelling of the oil due to the absorption of biogas (i.e., CO<sub>2</sub> and CH<sub>4</sub>) within the bulk oil phase.

Careful review of the common characteristics and results observed from these 407 MEOR field trials indicate that successful field trials were obtained at the following conditions:

- Minimum reservoir permeability of 75 md to ensure propagation of bacteria and nutrients deep into the reservoir;
- Reservoir temperature <200°F;
- Brine salinity <100,000 ppm;

- Bacteria species commonly used: anaerobic bacteria (i.e., *Clostridia*). The bacterium *Clostridium* showed to be effective in both sandstone and carbonate reservoirs. *Bacillus* (i.e., aerobic) species were also used or combination of them. The use of indigenous bacteria is strongly recommended because they only need the supply of nutrients and have a greater chance of growing at reservoir conditions, making the process less costly;
- Nutrient: the most common organic nutrient used was molasses; while phosphorus and nitrogen fertilizers were the most common inorganic nutrients;
- Oil saturation: ranging between 45 and 70%;
- Candidate fields most suitable for MEOR are waterflooded fields with relatively high oil saturations [73].

The Activated Environment for Recovery Optimization (AERO) technology has been developed for improving waterflood performance. The AERO system is a microbial process designed to increase oil recovery during waterflooding by the following mechanisms: improved sweep efficiency due to microdiversion of fluid pathways at the pore level, interfacial tension reduction, and residual oil mobilization (i.e., biosurfactants). This technology has been successfully implemented by Statoil offshore Norway and in the Stirrup field in southwest Kansas, USA. Highlights of this technology are minimum to none capital investment with very low risk for implementation and high performance efficiency at low operational costs [74].

Research conducted to establish the potential for MEOR application at the heavy oil Schrader Bluff formation on the North Slope of Alaska indicated that the viable mechanisms for driving incremental heavy oil recovery are:

- Wettability alteration;
- Permeability modification causing improvement of reservoir conformance;
- Some reduction of the interfacial tension between oil and water.

This study also demonstrated that the most important criteria for selecting a reservoir for MEOR applications are the reservoir temperature and formation brine salinity, which must favor bacterial growth. Furthermore, an effective MEOR application depends on the optimal use of the appropriate microbes and nutrients and their proper application in the reservoir [75].

DuPont possesses a solid expertise in MEOR and considers it a low-risk and low-cost technology to produce incremental oil from mature fields. DuPont has established a set of reservoir criteria for its successful application as follows:

- Reservoir temperatures <160°F;
- Moderate salinity levels up to 100,000 ppm;
- Reservoir permeability above 30 md to ensure the propagation of the microbes and nutrients deep into the reservoir;
- The reservoir must be under a waterflooding recovery.



According to DuPont's experience, the main mechanisms for oil recovery are permeability modification due to the formation of a biofilm on the rock surface and wettability modification. Successful field trials conducted by DuPont indicate that oil recovery from mature fields can be increased up to 25% with a cost of \$10 per incremental barrel of oil. Furthermore, DuPont considers the MEOR technique to be more cost effective compared to other EOR processes, such as CO<sub>2</sub> flooding or polymer flood [76].

A biopolymer, Schizophyllan, has been developed by Wintershall. The unique properties of this biopolymer are tolerance to high salinity (up to 19 wt%), tolerance to temperatures as high as 275°F, mechanical stability, and high viscosity. Therefore, the Schizophyllan biopolymer would make possible the application of polymer flooding in harsh reservoir environments. The main downside of this biopolymer is its susceptibility to bacterial degradation; however, this has been prevented by the addition of biocides. A pilot test has indicated that the performance of polymer flooding using this biopolymer has rendered oil recoveries ranging from 20 to 25 % higher than the oil recoveries expected from conventional waterflooding [77].

Successful MEOR application in a mature waterflooded reservoir in Saskatchewan, Canada has been reported [78]. This MEOR application consisted in the stimulation of indigenous bacteria through the injection of the appropriate nutrients. Production data obtained from this MEOR field application indicate higher oil production rates, incremental oil recovery, and decreased water cuts (up to 10%), which decreased operating costs due to reduced lifting and water treatment costs. In this field application, it was considered that the main MEOR mechanism was modification of the oil and water relative permeability driven by the interactions at the oil-water-microbes interface. Several benefits of this MEOR approach compare to other MEOR applications schemes and other EOR processes are as follows [78]:

- Low application costs;
- Low process cost per incremental oil production, on average it was US\$ 6 per barrel of oil produced;
- No capital outlay required to implement the MEOR project;
- Low risk to implement;
- Environmentally friendly.

Numerical modeling has been used to attempt the quantitative prediction of the performance of the MEOR process [73]. A study conducted by Eduarda et al. [79] in which a finite difference method was applied, indicated that appropriate bacterial growth within the reservoir is the determining variable affecting the oil recovery factor.

### 3. Conclusion

MEOR technology makes use of special indigenous or exogenous microbial strains and nutrients that are injected into the reservoir to enhance oil production. The metabolic action of



the injected exogenous microbial strains and the indigenous reservoir microflora produce metabolites such as gases, alcohols, and surface active compounds (biosurfactants) that interact with the crude oil. Biogases provide additional reservoir driving pressure; while bioalcohols and biosurfactants reduce oil viscosity and surface tension between oil-water and oil-rock, respectively. Under the effect of metabolites, the crude oil flowing properties are modified causing its release and mobilization toward the production wells enhancing the oil flow output.

The following metabolites interact with the crude oil changing its physicochemical properties:

- Organic acids (i.e., acetic, propionic, and butyric acids);
- Solvents (i.e., acetone, aldehydes, low-molecular-weight alcohols, ketones, etc.);
- Biomass (i.e., cell debris);
- Biopolymers (i.e., xanthan, scleroglucan, polysaccharides);
- Biosurfactants (i.e., rhamnolipid, surfactin);
- Biogases (i.e., methane, CO<sub>2</sub>, etc.).

MEOR is an easy-to-use process which requires minimum, if any, upgrade of the existing process equipment and facilities. This process has the potential to recover oil reserves that otherwise would remain immobile and unrecoverable. This process overcomes natural and chemical barriers in oil deposits that hinder microbial growth. MEOR is safe and environmentally friendly that does not cause any threat to plants, animals, and humans.

## Author details

Aliya Yernazarova<sup>1,2\*</sup>, Gulzhan Kayirmanova<sup>1</sup>, Almagul Baubekova<sup>1</sup> and Azhar Zhubanova<sup>1</sup>

\*Address all correspondence to: aliya.yernazarova@gmail.com

1 Department of Biotechnology, Al-Farabi Kazakh National University, Almaty, Kazakhstan

2 Institute of Ecology, Almaty, Kazakhstan

## References

- [1] Sandrea I, Sandrea R. Global oil reserves – recovery factors leave vast target for EOR technologies. *Oil and Gas Journal*. 2007;105(41):44–47.
- [2] Beckman JW. The action of bacteria on mineral oil. *Industrial and Engineering Chemistry, News Edition*. 1926;4:23–26.

- [3] Zobell CE. Bacterial release of oil from oil-bearing materials. *World Oil*. 1947; 26:36–47.
- [4] Yarbrough HF, Coty VE. Microbially enhanced oil recovery from the Upper Cretaceous Nacatoch formation, Union County Arkansas. In: *Proceeding of International Conference on Microbial Enhancement of Oil Recovery, USA*; 1983. p. 149–153.
- [5] Kryanev D, Zhdanov S. Use of advanced reservoir recovery methods in Russia and abroad. *Drilling and Oil*. 2011;2:22–26 (in Russian).
- [6] Portwood JT. (Company Alpha Environmental Midcontinent, Inc.). A commercial microbial enhanced oil recovery technology: Evaluation of 322 projects. In: *Proceedings of the SPE Production Operations Symposium*; 2–4 April, Oklahoma City, Oklahoma: SPE; 2007. p. 693–709.
- [7] Meyer RF, Attanasi E. Heavy oil and bitumen – strategic petroleum resources. U.S. Geological Survey Fact Sheet 2003-70-03. <http://pubs.usgs.gov/fs/fs070-03/fs070-03.html>.
- [8] Schmitt DR. Heavy and Bituminous Oils: Can Alberta Save the World/ Australian SEG Preview magazine. 2005;118:22–29.
- [9] Guseva UZ, Ovsyannikova VS, Svarovskaya LI, Altunina LK. Role of microorganisms during EOR. <http://www.ipc.tsc.ru/proekts/1/10/index.htm> (in Russian).
- [10] Miroshnikov V, Kurbanbayev MI, Tolokonskyi S. EOR at fields in Kazakhstan. In: *Proceeding of International Symposium on Theory and Practice of Application of Enhanced Oil Recovery Methods, Moscow*; 2011. p. 34–41 (in Russian).
- [11] Abdolhamid HR, Sadiq Al-Baghdadi MAR, El Hinshiri AK. Evaluation of biosurfactants enhancement on bioremediation process efficiency for crude oil at oilfield: strategic study. *Ovidus University Annals of Chemistry*. 2009;20:25–30.
- [12] Feng Z, Feng M, Rongjiu S, Jie Z, Siqin H, Ying Z. Production of rhamnolipids by *Pseudomonas aeruginosa* is inhibited by H<sub>2</sub>S but resumes in a co-culture with *P. stutzeri*: applications for microbial enhanced oil recovery. *Biotechnology Letters*. 2015;37(9): 1803–1808. DOI: 10.1007/s10529-015-1859-4.
- [13] Gudina EJ, Rodrigues LR, Teixeira JA, Pereira JFB, Coutinho JAP, Soares LP. Biosurfactant producing microorganisms and its application to enhance oil recovery at lab scale. In: *Proceedings of the SPE EOR Conference at Oil and GasWest Asia 2012 (OGWA)*. Muscat, Oman; 2012. V.1, p. 363–370.
- [14] Al-Bahry SN, Al-Wahaibi YM, Elshafie AE, Al-Bemani AS, Joshi SJ, Al-Makhmari HS, Al-Sulaimani HS. Biosurfactant production by *Bacillus subtilis* B20 using date molasses and its possible application in enhanced oil recovery. *International Biodeterioration and Biodegradation*. 2013;81:141–146.
- [15] Lazar I, Petrisor IG, Yen TF. Microbial enhanced oil recovery. *Petroleum Science and Technology*. 2007;25:1353–1366.

- [16] Chai LuJun, Zhang Fan, She YueHui, Banat Ibrahim M, Hou DuJie. Impact of a microbial-enhanced oil recovery field trial on microbial communities in a low-temperature heavy oil reservoir. *Nature Environment and Pollution Technology*. 2015;14(3): 455–462.
- [17] Fatkullina AS, Sadchikov AV. Use of biogas installation products for oil recovery. *Electronic Scientific Journal "Modern Problems of Science and Education"*. 2014;3.
- [18] Jimoh IA. Microbial enhanced oil recovery. PhD thesis. Luma Print; 2012. 6700 Esbjerg.
- [19] Belyaev SS, Borzenkov IA, Nazina TN, Rozanova EP, Glumov IF, Ibatullin RR. Use of microorganisms in the biotechnology for the enhancement of oil recovery. *Microbiology. (Maik Nauka Interperiodica)*. 2004;73:590–598 (in Russian).
- [20] Van H, Singh A, Ward O. Recent advances in petroleum microbiology. *Microbiology and Molecular Biology Review*. 2003;67(4):503–549.
- [21] Wang X, Li D, Hendry P, Volk H, Rashid A, et al. Effect of nutrient addition on an oil reservoir microbial population: implications for enhanced oil recovery. *Journal of Petroleum & Environmental Biotechnology*. 2012;3:118. DOI: 10.4172/2157-7463.1000118.
- [22] Nazina TN, Pavlov NK, Tatarkin Y, Shestakov NM, Babich TL, Sokolov DS, Ivoylov VS, Turov TP, Hisametdinov MR, Ibatullin RR, Belyaev SS, Ivanov MV. The development of biotechnology increase the degree of oil recovery from carbonate oil reservoirs on the territory of the Republic of Tatarstan. *Electronic Scientific Journal Georesources. Geoenergetika. Geopolitics*. 2012;2(6):1–6 (in Russian).
- [23] Wagner M, Lungershausen D, Murtada H, Rosenthal G. Development and application of a new biotechnology of the molasses in-situ method; detailed evaluation for selected wells in the Romashkino carbonate reservoir. In: *Proceeding of Fifth International Conference on Microbial Enhanced Oil Recovery and Related Biotechnology for Solving Environmental Problems*, BDM-Oklahoma, Tulsa; 1995. p. 153–173.
- [24] Joshi S, Bharucha C, Jha S, Yadav S, Nerurkar A, Desai AJ. Biosurfactant production using molasses and whey under thermophilic conditions. *Bioresource Technology*. 2008;99(1):195–199.
- [25] Eduardo J, Gudiña E, Fernandes C, Rodrigues AI, Teixeira JA, Rodrigues LR. Biosurfactant production by *Bacillus subtilis* using corn steep liquor as culture medium. *Frontiers in Microbiology*. 2015;6:59.
- [26] Tech Fu Yen, editor. *Microbial Enhanced Oil Recovery: Principle & Practice*. Boca Raton, FL: CRC Press Inc.; 1990. 257 p.
- [27] Stetter KO, Huber R, Blochl E, Kurr M, Eden RD, Fielder M, Cash H, Vance I. Hyperthermophilic archaea are thriving in deep North Sea and Alaskan oil reservoirs. *Nature*. 1993;365(6448):743–745.

- [28] Tardy-Jacquenod C, Caumette P, Matheron R, Lanau C, Arnauld O, Magot M. Characterization of sulfate-reducing bacteria isolated from oil-field waters. *Canadian Journal of Microbiology*. 1996;42(3):259–266.
- [29] Ng TK, Weimer PJ, Gawel LJ. Possible nonanthropogenic origin of two methanogenic isolates from oil producing wells in the San Miguelito field, Ventura County, California. *Geomicrobiology Journal*. 1989;7(3):185–192.
- [30] Birkeland NK. Chapter 14: The microbial diversity of deep subsurface oil reservoirs. In: Duhalt RV, Ramirez RQ, editors *Petroleum Biotechnology, Volume 151: Developments and Perspectives (Studies in Surface Science and Catalysis)* 1st ed. Elsevier Science: Amsterdam; 2004. 545 p. DOI: 10.1016/j.fuel.2006.10.012.
- [31] Davey ME, Wood WA, Key R, Nakamura K, Stahl DA. Isolation of three species of *Geotoga* and *Petrotoga*: two new genera, representing a new lineage in the bacterial line of descent distantly related to the *Thermotogales*. *Systematic and Applied Microbiology*. 1993;16(2):191–200.
- [32] Grassia GS, McLean KM, Glenat P, Bauld J, Sheehy AJ. A systematic survey for thermophilic fermentative bacteria and archaea in high temperature petroleum reservoirs. *FEMS Microbiology Ecology*. 1996;21(1):47–58.
- [33] Brown F, Maure A, Warren A. Microbial-induced controllable cracking of normal and branched alkanes in oils. United States Patent 6905870; 2005.
- [34] Bahrami A, Shojaosadati SA, Mohebbi G. Biodegradation of dibenzothiophene by thermophilic bacteria. *Biotechnology Letters*. 2001;23(11):899–901.
- [35] Annual Report of Project 4933/GF. The effective microbial consortium with high target activities; 2015. 45 p.
- [36] Grigoryan A.A. Physiology and ecology of aerobic organotrophic bacteria oil reservoirs. PhD dissertation, Moscow; 2004. Pp. 154.
- [37] Jenneman GE, McInerney MJ, Knapp RM, Clark JB, Feero JM, Revus DE, Menzie DE. A halotolerant, biosurfactant producing *Bacillus* species potentially useful for enhanced oil recovery. *Developments in Industrial Microbiology*. 1983;24:485–492.
- [38] Fan Zhang, Yue-Hui She, Hua-Min Li, Xiao-Tao Zhang, Fu-Chang Shu, Zheng-Liang Wang, Long-Jiang Yu, Du-Jie Hou. Impact of an indigenous microbial enhanced oil recovery field trial on microbial community structure in a high pour-point oil reservoir. *Applied Microbiology and Biotechnology*. 2012;95:811–821. DOI: 10.1007/s00253-011-3717-140.
- [39] Al-Sulaimani H, Al-Wahaibi Y, Al-Bahry SN, Elshafie A, Al-Bemani AS, Joshi SJ, Zargari S. Experimental investigation of biosurfactants produced by *Bacillus* species and their potential for MEOR in Omani oil field. In: *Proceedings of*

- the SPE EOR Conference at Oil and GasWest Asia 2010 (OGWA'10), Muscat, Oman; 2010. p. 378–386.
- [40] Al-Sulaimani H, Al-Wahaibi Y, Al-Bahry SN, Elshafie A, Al-Bemani AS, Joshi SJ, Zargari S. Optimization and partial characterization of biosurfactants produced by *Bacillus* species and their potential for ex-situ enhanced oil recovery. SPE Journal. 2011;16(3): 672–682.
  - [41] Wang T, Ma J, Liu QK, Zhao LX, Liang FL, Liu RL. Isolation of functional bacteria guided by PCR-DGGE technology from high temperature petroleum reservoirs. Huan Jing Ke Xue. 2008;29(2):462–468.
  - [42] Sanchez G, Marin A, Vierma L. Isolation of thermophilic bacteria from a Venezuelan Oil Field. Developments in Petroleum Science. 1993;39:383–389.
  - [43] Lien T, Madsen M, Rainey FA, Birkeland NK. *Petrotoga mobilis* sp. nov., from a North Sea oil production well. International Journal of Systematic Bacteriology. 1998;48:1007–1013.
  - [44] Magot M, Olliver B, Patel BKC. Microbiology of petroleum reservoirs. Antonie Van Leeuwenhoek. 2000;77:103–116.
  - [45] Ollivier B, Cayol JL. Fermentative, iron-reducing and nitrate-reducing microorganisms. In: Ollivier B, Magot M, editors. Petroleum Microbiology. Washington, DC: ASM Press; 2005. p. 71–88.
  - [46] Eden B, Laycock P, Fielder M. Oilfield Reservoir Souring. HSE Books; 1993. 90 p.
  - [47] Alain K, Pignet P, Zbinden M, Quillevere M, Duchiron F, Donval JP, Lesongeur F, Raguenes G, Crassous P, Querellou J, Cambon-Bonavita MA. *Caminicella sporogenes* gen. nov., sp. nov., a novel thermophilic spore-forming bacterium isolated from an East-Pacific Rise hydrothermal vent. International Journal of Systematic and Evolutionary Microbiology. 2002;52:1621–1628.
  - [48] Klouche N, Fardeau ML, Lascourrigues JF, Cayol JL, Hacene H, Thomas P, Magot M. *Geosporobacter subterraneus* gen. nov., a spore-forming bacterium isolated from a deep subsurface aquifer. International Journal of Systematic and Evolutionary Microbiology. 2007;57:1757–1761.
  - [49] Al-Bahry SN, Elshafie AE, Al-Wahaibi YM, Al-Bemani AS, Joshi SJ, Al-Maaini RA, Al-Alawi WJ, Sugai Y, Al-Mandhari M. Microbial consortia in Oman oil fields: a possible use in enhanced oil recovery. Journal of Microbiology and Biotechnology. 2013;23(1): 106–117.
  - [50] Youssef N, Elshahed MS, McInerney MJ. Microbial processes in oil fields: culprits, problems, and opportunities. In: Laskin AI, Sariaslani S, Gadd GM, editors. Advances in Applied Microbiology. Burlington: Academic Press; 2009. Vol. 66. p. 141–251.



- [51] Omoniyi OA, Abdulmalik FA. Review of microbial enhanced oil recovery: current development and future prospects. *International Journal of Scientific & Engineering Research*. 2015;6(1):1378–1389.
- [52] Al-Sulaimani H, Joshi S, Al-Wahaibi Y, Al-Bahry S, Elshafie A, Al-Bemani A. Microbial biotechnology for enhancing oil recovery: current developments and future prospects. *Biotechnology, Bioinformatics and Bioengineering*. 2011;1(2):147–158.
- [53] Adkins JP, Cornell LA, Tanner RS. Microbial composition of carbonate petroleum reservoir fluids. *Geomicrobiology Journal*. 1992;10:87–97.
- [54] Gray M, Yeung A, Foght J, Yarranton HW. Potential microbial enhanced oil recovery processes: a critical analysis. In: *Proceeding of the SPE Annual Technical Conference and Exhibition*; 21–24 September 2008; Denver. Colorado. USA; 2008. V.1. p. 303–327.
- [55] Research Priorities in Microbially Enhanced Hydrocarbon Recovery (MEHR) [Internet]. 2007. Available from: <http://www.energybiosciencesinstitute.org/media/MEHR%20White%20Paper%20Final.pdf> [Accessed: 2007-10-24] .
- [56] Bryant RS, Stepp AK, Bertus KM, Burchfield TE, Dennis M. Microbial enhanced water flooding field pilots. *Developments in Petroleum Science*. 1993;39:289–306.
- [57] Nielsen SM, Shapiro A, Stenby EH, Michelsen ML. *Microbial Enhanced Oil Recovery – Advanced Reservoir Simulation*. Kgs. Lyngby, Denmark: Technical University of Denmark (DTU); 2010. 145 p.
- [58] Youssef NH, Duncan KE, McInerney MJ. Importance of 3-hydroxy fatty acid composition of lipopeptides for biosurfactant activity. *Applied and Environmental Microbiology*. 2005;71:7690–7695.
- [59] Pommerville J. *Alcamo's Laboratory Fundamentals of Microbiology*. 8th ed. Massachusetts: Jones and Bartlett Publishers; 2007. 352 p.
- [60] Pruthi V, Cameotra SS. Production of a biosurfactant exhibiting excellent emulsification and surface active properties by *Serratia marcescens*. Short communication. *World Journal of Microbiology and Biotechnology*. 1997;13(1):133–135.
- [61] Youssef N, Simpson DR, Duncan KE, McInerney M, Folmsbee M, Fincher T, Knapp RM. In situ biosurfactant production by *Bacillus* strains injected into a limestone petroleum reservoir. *Applied and Environmental Microbiology*. 2007;73(4): 1239–1247.
- [62] Singh A, Van Hamme JD, Ward OP. Surfactants in microbiology and biotechnology: Part 2. Application aspects. *Biotechnology Advances*. 2007;25(1):99–121.
- [63] Cooper DG, Macdonald CR, Duff SJB, Cosaric N. Enhanced production of surfactin from *Bacillus subtilis* by continuous product removal and metal cation additions. *Applied and Environmental Microbiology*. 1981;42(3):408–412.



- [64] Desai J, Banat IM. Microbial production of surfactants and their commercial potential. *Microbiology and Molecular Biology Reviews*. 1997;61:47–64.
- [65] Chrzanowski Ł, Kaczorek E, Olszanowski A. The ability of *Candida Maltosa maltosa* for hydrocarbon and emulsified hydrocarbon degradation. *Polish Journal of Environmental Studies*. 2006;15(1):47–51.
- [66] Prenafe ta-Boldu FX, Summerbell R, Sybren de Hoog G. Fungi growing on aromatic hydrocarbons: biotechnology's unexpected encounter with biohazard? *FEMS Microbiology Reviews*. 2006;30:109–130.
- [67] Cheng Q, Kinney KA, Whitman CP, Szaniszló PJ. Characterization of two polyketide synthase genes in *Exophiala lecanii-corni*, a melanized fungus with bioremediation potential. *Bioorganic Chemistry*. 2004;32:92–108.
- [68] Qi B, Moe WM, Kinney KA. Biodegradation of volatile organic compounds by five fungal species. *Applied Microbiology and Biotechnology*. 2002;58(5):684–689.
- [69] Dallinger A, Duldhardt I, Kabisch J, Schauer F. Biotransformation of cyclohexane and related alicyclic hydrocarbons by *Candida maltosa* and *Trichosporon* species. *International Biodeterioration & Biodegradation*. 2016;107:132–139.
- [70] Nazina TN. Microorganisms oil reservoirs and their use in biotechnology enhanced oil recovery. PhD thesis; 2000. p. 67 (in Russian).
- [71] Nazina TN, Ivanova AE, Blagov AV. Microbiological characterization of oil reservoirs peninsula Mangyshlak. *Microbiology*. 1992;61(2):316–322 (in Russian).
- [72] Bekker RH, Gutorov UA, Gareev AM. Prospects of microbiological methods for enhanced oil recovery in the conditions of productive reservoirs of the Volga-Ural. *Oil and Gas Business*. 2012;10(3):34–39.
- [73] Maudgalya S, Knapp RM, McInerney MJ. Microbial enhanced-oil-recovery technologies: a review of the past, present, and future. In: *SPE Production and Operations Symposium*; March 31–April 3 2007. p. 1–11. SPE 106978.
- [74] Bauer BG, O'Dell RJ, Marinello SA, et al. Field experience from a biotechnology approach to waterflood improvement. In: *Presented at the SPE Enhanced Oil Recovery Conference, Kuala Lumpur, Malaysia; 19–21 July 2011*. SPE-144205-MS. DOI: 10.2118/144205-MS.
- [75] Jackson SC, Alsop AW, Choban ER, et al. Microbial EOR: critical aspects learned from the Lab. In: *SPE Improved Oil Recovery Symposium, Tulsa; 24–28 April 2010*. SPE-129657-MS. DOI: 10.2118/129657-MS.
- [76] Trent Jacobs T. DuPont touts MEOR technology. *Journal of Petroleum Technology*. 2014;66(06):34–36.
- [77] Jacobs T. Wintershall sees EOR promise in new biopolymer. *Journal of Petroleum Technology*. 2014;66(06):36–37.

- [78] Town K, Sheehy AJ, Govreau BR. MEOR Success success in Southern southern Saskatchewan. SPE Reservoir Evaluation & Engineering. 2010. ;13 (5): 773–781. SPE-124319-PA. DOI: <http://dx.doi.org/10.2118/124319-PA>.
- [79] Lacerda E, Priimenko VI, Pires AP. Microbial EOR: A a Quantitative quantitative Prediction prediction of Recovery recovery Factorfactor. In: SPE Improved Oil Recovery Symposium held in Tulsa,, 14–18 April, 2012. SPE 153866.

