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Microbial enhanced oil recovery, a critical review on worldwide implemented field trials in different countries

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ABSTRACT

In recent years that reaching oil price to its minimum amount has become a critical issue in petroleum industry, microbial enhanced oil recovery (MEOR) is a main topic of interest in energy researches as an environment-friendly and low operating cost treatment technology. Accordingly, it could be considered as an adequate alternative for conventional EOR techniques. The significant positive impact of MEOR technology in enhancement of oil recovery is established in both sandstone and carbonate reservoirs with different flow characteristics implemented all over the world. Unfortunately, in spite of its enormous benefits, MEOR is still not widely under investment due to lack of sufficient data. This paper presents the fully detailed update of MEOR field trials which exclusively investigates the field history performance of MEOR in different countries. This investigation includes 47 field trial cases in 21 countries in which the corresponded technologies, reservoir/formation names, microorganisms, nutrients and specific effects of each case are totally illustrated. Furthermore, microbial bioproducts and screening criteria parameters are widely demonstrated. A unique categorization of MEOR biosurfactants is also presented. In addition, different set of carried out experiments on biosurfactants along with their effects on IFT and residual oil recovery are examined. In fact, this review confirms the creditability of MEOR which creates strong perspectives to move toward more investment on this method.

1. Introduction

Typically, 35–55% of crude oil is left behind in the reservoir after primary and secondary recoveries [1] which should be extracted by different improved or enhanced oil recovery techniques such as miscible gas injection, polymer flooding and thermal EOR methods [2].

In recent years that the oil price has declined to its minimum value, selection of the optimal recovery method is significantly influenced by economical issues. Consequently, development of cost effective technologies which bring maximum oil reserves to production is a main topic of interest in today's energy researches [2]. Microbial enhanced oil recovery is potentially a low-priced technique in which different microorganisms and their metabolic products are convinced to exploit the remaining trapped oil in the reservoir [2]. MEOR is widely applicable in sandstone [3] and carbonate [4,5] reservoirs with light/heavy crude oil [6,7] and low/mid and high permeabilities [8,9]. Satisfactory results of implemented field trials lead to the fact to contemplate MEOR as an adequate alternative for other IOR/EOR technologies [10].

The concept of employing microorganisms to accomplish maximum oil recovery was first proposed by Beckham [11] who established the possibility of utilizing bacterial enzymes in oil recovery [12]. In 2007, Saikrishna Maudgalya et al. [13] investigated the success or failure of 407 reported MEOR field trials in sandstone and carbonate reservoirs where the tremendous positive results were a great establishment on applicability of this technique. In 2014, Biji Shibulal et al. [12] presented a review on thermophilic spore-forming bacteria as resistant microorganisms to very extreme oil reservoir conditions.

Development of sufficiently accurate models to simulate salinity, mobility control, temperature, produced bioproducts and other needed parameters is extremely vital to choose the best reservoir candidates for MEOR process which contributes to maximum ultimate recovery [14,15]. In fact, complexity of proposing a comprehensive model to interpret all aspects of MEOR is a critical issue [16]. In 2015, Jay Patel et al. [16] reviewed the twelve published models with different approaches to interpret MEOR processes.

In 2007, Lazar et al. [17] presented a review on world experience of MEOR field trials during the last 40 years. In his study, different technologies, microorganisms and nutrients utilized in each country as well as the corresponded positive or negative impact on the incre-

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Table 1
MEOR processes classification (adapted from [19]).

MEOR process	Production problem	Type of used microorganism
Well stimulation	• Formation damage • Low oil relative permeability	• Generally surfactant, gas, acid and alcohol producers
Waterflooding	• Trapped oil due to capillary forces	• Generally surfactant, gas, acid and alcohol producers
Permeability modification	• Poor sweep efficiency channeling	• Microorganisms that produce polymer and/or copious amounts of biomass
Wellbore cleanup	• Paraffin problems • Scaling	• Microorganisms that produce emulsifiers, surfactants and acids • Microorganisms that degrade hydrocarbons
Polymer flooding	• Unfavorable mobility ratio • Low sweep efficiency	• Microorganisms that produce polymers
Mitigation of coning	• Water or gas coning	• Microorganisms that produce polymer and/or copious amounts of biomass

Table 2
Advantages and disadvantages of MEOR technology (adapted from [2,10,17,20–25]).

Advantages	Disadvantages
• Economically efficient • Low injection cost of microbes and nutrients • Low expenses and complexity of facilities set up • Low energy consumption required for microbial metabolic activities • Considerably efficient in sandstone and carbonate reservoirs • Microbial metabolic activities enhancement along with time, as opposed to other EOR additives • Low environmental pollution • Obtaining better results due to occurrence of multiple mechanisms at the same time • Possibility of applying to both light and heavy crude oils	• Corrosion of equipment as a result of aerobic bacteria activities • Limited applications in offshore platforms in view of requirement of much sugar as anaerobic bacteria activities • Complexity of developing a comprehensive model to interpret all aspects of MEOR process • Toxicity of microbes due to existence of specific heavy metal ions • Microorganisms tolerance limitationsin in regard to reservoir conditions

mental oil production were introduced, but there was no information about reservoir/formation name and detailed effects of each case. Moreover, the related information of all cases of each country was presented together without any specification of each case. In the present study, the fully detailed updated MEOR field trial cases are presented which includes 47 field trial cases in 21 different countries. In this investigation, the technologies, reservoir/formation name, microorganisms, nutrients and fully detailed effects of each specific case carried out in each country are exclusively presented.

2. MEOR processes

MEOR processes are basically involved with two categories of in-situ and ex-situ mechanisms. In in-situ mechanism, generation of certain kinds of products such as gases, acids, biopolymers, etc. occurs by stimulation of different indigenous bacteria under appropriate reservoir conditions [2]. In contrary, ex-situ mechanism involves the selective removal of generated bioproducts from surface by microbial metabolic activities to be finally injected to the reservoir [2,18]. Table 1 presents different MEOR processes along with their production problems and type of utilized microorganisms.

It should be noted that MEOR has some advantageous over conventional EOR methods which make them to be contemplated as a remarkable option for investment in petroleum industry. On the other hand, some constrains such as process complexity and microorganism survival limitations could be regarded as the reasons for lack of investment on this technique. To illustrate different aspects of this issue, MEOR advantages and disadvantages are listed in Table 2.

3. Microbial bioproducts

3.1. Bioproducts full specifications

In MEOR, a variety of drastically beneficial metabolites are produced by microorganisms which finally increase the ultimate oil recovery [26]. There are specific approaches in which propagation of microbial bioproducts significantly affect the physical properties of reservoirs including porosity, permeability and wettability as well as fluid characteristics such as viscosity, IFT, etc. [10]. Generally, the bioproducts could be classified into seven major groups as biosurfactants, biopolymers, gases, acids, solvents, biomass and emulsifiers. Biosurfactants have a significant impact on wettability alteration as a result of their potential in lowering surface and interfacial tensions. Biopolymers could aid in enhanced oil recovery by permeability and viscosity reduction which leads to mobility ratio alteration. Gases are produced by some specific kinds of bacteria which contribute to re-pressurization of the reservoir and finally enhancement of oil recovery. Acids and solvents have an enormous potential to dissolve different parts of rock which results in porosity and permeability improvement and consequently reduction of the entrapped oil. Biomass could be much efficient in improvement of oil recovery by selectively plugging the porous media which finally channels the floodwater towards available oil. Oil emulsification could be achieved under production of emulsifiers by a wide variety of microorganisms where stable emulsions with hydrocarbon (commonly oil in water) are formed [16]. Table 3 shows a full list of generated bioproducts by different microorganisms along with their major effects, production problems and best reservoir candidates for MEOR process. It shall be noted that among all of the bioproducts, biosurfactants have been much more attracting to be investigated by many researchers as a consequence of their enormously beneficial properties including biodegradability, stability, low toxicity and specifically the considerable impact on wettability alteration which significantly enhances the ultimate oil recovery.

In this regard, the brief introduction and detailed classification of biosurfactants as well as the relevant conducted experiments are demonstrated in the next two following sections.

3.2. Biosurfactants

3.2.1. Biosurfactants classification

Biosurfactants are one of the metabolic products of microbial enhanced oil recovery which have potentially significant effects on surface and interfacial tensions, emulsification, solubility, etc. [29].

Table 3
Microbial bioproducts (adapted from [12,16,17,22,25–28]).

Microbial Product class	Sample products	Microorganisms	Production problem	Effect	Type of formation/ reservoir
Biosufactants	• Emulsan • Alasan • Surfactin, • Rhamnolipid • lichenysin • Rhamnolipid • Glycolipids • Viscosin • Trehaloselipids	• Bacillus sp. • Pseudomonads • Rhodococcus sp. • Acinetobacter • Bacillus sp. • Pseudomonas • Rhodococcus sp. • Arthrobacter	• Poor microscopic displacement efficiency	• Interfacial tension reduction • Emulsification • Pore scale displacementimprovement • Wettability alteration	• Sandstone or carbonate reservoirs with moderate temperatures (< 50 °C) and relatively light oil (API > 25)
Biopolymers	• Xanthan gum • Pullulan • Levan • Curdlan • Dextran • Scleroglucan	• Xanthomonas sp. • Aureobasidium sp. • Bacillus sp. • Alcaligeness sp. • Leuconostoc sp. • Sclerotium sp. • Brevibacterium	• Poor volumetric sweep efficiency	• permeability reduction inwater-swept regions • Injectivity profile and viscositymodification • Mobility control • Selective or nonselective plugging	• Stratified reservoirs with different permeable zones
Gases	• CO_2 • CH_4 • H_2 • N_2	• Fermentativebacteria • Methanogens • Clostridium • Enterobacter	• Heavy oil	• Reservoir repressurization • Oil swelling • Permeability improvement • IFT and viscosity reduction • Flow characteristics improvement	• Heavy oil-bearing Formations (API < 15)
Acids	• Propionic acid • Butyric acid	• Fermentative bacteria • Clostridium • Enterobacter • Mixed acidogens	• Low porosity • Poor drainage • Formation damage	• Dissolve carbonaceous minerals or deposits • Permeability and porosity improvement • Emulsification • CO_2 production due to reaction between acids and carbonate minerals • Oil viscosity reduction	• Carbonate or carbonaceous reservoirs
Solvents	• Alcohols and ketones that are typical cosurfactants • Acetone • Butanol • Propan-2-diol	• Fermentative bacteria • Clostridium • Zymomonas • Klebsiella	• Heavy oil • Poor microscopic displacement efficiency	• Oil viscosity reduction • Wettability alteration • Permeability improvement due to rock dissolution • Heavy, long chain hydrocarbons removal from pore throats • Emulsification • Interfacial tension reduction	• Heavy oil-bearing Formations (API < 15) • Strongly oil-wet, waterflooded reservoirs
Biomass	• Microbial Cells and EPS(mainlyExopolysaccharides)	• Bacillus • licheniformis • Leuconostocmesenteroides • Xanthomonas • Campestris	• Poor microscopic displacement efficiency	• Permeability reduction • Selective and nonselective plugging • Emulsification • Wettability alteration of mineral surfaces • Oil viscosity Reduction • Oil pourpoint Desulfurization reduction • Oil degradation	• Stratified reservoirs with different permeable zones
Emulsifiers	• Some kinds	• Acinetobacter sp. • Candida • Pseudomonas sp. • Bacillus sp.	• Paraffin and oilSludge deposition • Poor microscopic displacement efficiency	• Oil emulsification	• Waxy oil (> C_{22} alkanes); paraffinic oil and asphaltene-bearing formations
Hydrocarbon metabolism	• Some kinds	• Aerobichydrocarbondegraders	• Paraffindeposition • Poor microscopic displacement efficiency	• Paraffin deposits removal • Oil mobility improvement	• Wells with paraffin deposition • Mature waterflooded reservoirs

Correspondingly, they are extremely important as a consequence of their biodegradability [30], low toxicity [31], emulsification activity and their stability in different environments [31]. This fact differentiates biosurfactants from chemical surfactants due to these advantages. Based on the charge of the polar head group, biosurfactants are divided into four groups as cationic, anionic, nonionic and zwitterionic [32]. Five major types of biosurfactant produced by microorganisms are classified in detail in Table 4 which also represents the specific microbes along with each category.

3.2.2. Biosurfactant experiments

Different experiments establish the high applicability of biosurfactants in residual oil recovery from porous systems at elevated salinities and temperatures [27]. In particular, lipopeptides have lower effective concentration in comparison to other types of biosurfactants such as rhamnolipids [36]. In Das and Mukherjee [37] experiments on sand

Table 4
Biosurfactant classification (adapted from [20,27,31–35]).

Biosurfactant class	Subgroup class	Producing microorganism
Glycolipid	Rhamnolipids	• P. aeruginosa • Pseudomonas sp. • Pseudomonas chororaphis • Pseudomonas aeruginosa UW−1 • Pseudomonas aeruginosa GL−1
	Trehalolipid/Trehalose lipid	• R. erythropolis • Mycobacterium sp. • Norcardia SFC-D • Rhodococcus sp. H13 A • Rhodococcus sp. ST−5 • Norcadiaerithropolis • Arthobacter sp. • Pseudomonas sp.
	Sophorolipids	• Torulopsisbombicola • T. apicola • Arthrobacter sp. • Candida bombicola • Candida apicola • Candida antarctica • Torulopispetrophilum • Candida apicola IMET 43747
	Mannosylerythritol lipids (MEL)	• C. antarctica • Pseudozymaaphidis • Pseudozymarugulosa
Lipopeptides and lipoproteins	Peptide-lipid	• Bacillus licheniformis
	Serrawettin	• Serratiamarcenscens
	Viscosin	• Pseudomonas fluorescens
	Surfactin	• Bacillus subtilis • Bacillus pumilus A1 • Bacillus subtilis C 9 • Lactobacillus sp.
	Subtilisin	• Bacillus subtilis
	Gramicidin	• Bacillus subtilis
	Polymyxin	• Bacillus polymyxia
	Iturin/Fengycin	• B. subtilis
	Lichenysin	• Bacillus licheniformis • Bacillus licheniformis • Bacillus licheniformis JF−2
Fatty acids, neutral lipids, and phospholipids	Fatty acids	• Corynebacteriumlepus
	Neutral lipids	• Nocardiaerythropolis
	Phospholipids	• Thiobacillusthiooxidans • Acinetobacter sp. • Corynebacteriumlepus
Polymeric surfactants	Emulsan	• Acinetobacter calcoaceticus
	Biodispersan	• Acinetobacter calcoaceticus
	Mannan-lipid-protein	• Candida tropicalis
	Liposan	• Candida lipolytica
	Carbohydrate-protein-lipid	• Pseudomonas fluorescens • D. polymorphis
	Protein PA	• P. aeruginosa
	Alasan	• calcoaceticus • Acinetobacter radioresistens
Particulate biosurfactants	Vesicles and fimbriae	• Acinetobacter calcoaceticus • Cyanobacteria
	Whole cells	• Different bacteria

packed columns, 50–60% of residual oil recovery and a reduction in surface tension were confirmed where lipopeptide biosurfactants were produced by two thermophilic Bacillus subtilis strains with potato peels as nutrient support. Joshi et al. [38,39] carried out another experiment on sand packed columns which contributed to residual oil recovery of 25–33% and surface tension reduction by using Bacillus subtilis strains 20B, B. licheniformis K51, B. subtilis R1, and B. strain HS3. The positive result of this process was due to production of lipopeptide biosurfactants. Wang et al. [36] produced rhamnolipids by genetically engineering of Escherichia coli and Pseudomonas in sand packed columns. Sayyouh [40] executed a set of experiments by utilizing microorganisms isolated from Egyptian and Suadi Arabia oil fields which resulted in production of biosurfactants and enhancement of oil recovery as well as rock wettability alteration and IFT reduction. Peihui et al. [41] used facultative anaerobes of Daqing oil field in an anaerobic coreflood experiment which yielded to production of biosurfactants. As a result, IFT, PH and oil viscosity decreased and a notable increase was recorded in light alkane propagation. In this experiment, the residual oil recovery increased by 10%. Aerobic mesophilic hydrocarbon degrading bacteria were used in a core flood experiment by Kowalewski et al. [42] where the produced biosurfactant altered the wettability and lowered the IFT. Nourani et al. [43] experiment on glass micro models and carbonate rock with or without fracture resulted in IFT and wettability reduction where five microorganisms from Persian reservoirs were employed. Moreover, indigenous microorganisms from Persian reservoirs at 45 °C were tested in a core flood experiment which resulted in residual oil recovery of 14.3% due to production of lipopeptide biosurfactants [43]. The production of glycolipid and phospholipid surfactants by Pseudomonas strain was established in Okpokwasili and Ibiene [44] experiments on sand packed columns which finally increased the residual oil recovery by 52%. Johnson et al. [45] experiment was based on adsorption to carbonates by using B. subtilis microorganism which contributed to production of surfactin biosurfactant and consequently surfactin adsorption and wettability alteration. In fact, biosurfactants seem to have a tremendous potential in improving residual oil recovery, IFT reduction and wettability alteration which make them one of the most important topics of research in MEOR field.

4. Screening criteria

There are some factors that should be taken into account which drastically influence the final results of MEOR process such as reservoir properties including temperature, pressure, salinity, PH and economical aspects [10]. Temperature could be considered as the most substantially important factor among prerequisite situations in MEOR due to its significant influence on microorganisms survival, growth and their metabolic products [32]. For instance, too low temperatures may slow down the transport process. On the other hand, too high temperatures could potentially affect enzymes and proteins by disrupting vital cell activities [22,32].

Pressure is also recognized as an important parameter due to its essential role in MEOR. To illustrate its effect, high hydrostatic pressures have contradictory effects on bacterial growth. However, their impact on bacteria survival is negligible [46]. Furthermore, increasing pressure influences the redox potential of gases such as carbon dioxide and increases gas solubility which is the consequence of encountering deeper depths [25].

Salinity is still another crucial parameter which is dependent on both temperature and pressure and has a notable effect on viscosity reduction [47]. Brine concentration of reservoirs are in a range of 100 mg/L to over 300 g/L [48] according to the corresponded depth which dramatically affects the MEOR process due to microorganisms tolerance indifferent salt concentration conditions [22,47]. A good illustration of this fact could be considered as slowing down of the metabolic generation rate of biosurfactants, gases, alcohols and acids in high salinities [49]. Furthermore, less amount of produced ex-situ surfactants is required to reduce the surface tension due to CMC reduction as a positive effect of salinity [32].

There are also other effective parameters involved in success or failure of MEOR processes such as PH, permeability and pore size which substantially influence the efficiency of microbial enhanced oil recovery. For instance, PH affects surface charge and enzymatic activities [32]. Another example could be illustrated as the impact of pore size on permeability reduction which has a negative effect on transport process [32].

Table 5
MEOR screening criteria parameters (adapted from [10,16,21,50,51]).

Screening Criteria								
Parameter	**IRS, Ahmedabad** [16]	**US DOE** [16]	**CNPC** [10]	**Reviewed projects range** [50]	**Lazar (1990)** [50]	**Bryant & Burchfleld** [21]	**24 Norwegian Fields range** [50]	**Lake & Walsh** [51]
Formation temperature, °C	< 90	< 71	30–60	19–82	≤70	< 71	61–155	< 140
Crude oil viscosity, cp	< 20	–	30–150	3–50	5–50	–	0.1–4.83	–
Permeability, md	> 50	> 100	≥150	0.1–5770	≥150	> 100	1–20,000	> 150
Brine salinity, g/L	< 10	< 10	≥100	1.4–104	≤150	< 100,000	14–273	100,000
Water cut,%	30–90		60–85	–	–	–	–	–
°API gravity of crude oil	> 20	18–40	–	–	–	–	–	> 15
PH	6–9	–	–	–	–	–	–	–
Pressure, kg/cm2	< 300	–	–	–	–	–	–	< 3000
Residual oil saturation, %	> 25	> 25	–	–	–	> 25–30	–	Not critical
Depth, ft (m)	< 8000 (2400)	< 10,000 (3048)	–	122–2103	–	< 3048	1300–4208	< 8000 (2400)
Porosity,%	–	–	17–25	8–32	≥20	–	11–35	–
Wax content,%	–	–	≥7					–
Total bacterial concentration in produced fluid, number /ml	–	–	≥1000	–	–	–	–	–

Table 6
Microorganisms classification according to temperature and pressure (adapted from [32]).

Classification parameter	Microorganism class	Range
Temperature (°C)	Psychrophile	< 13
	mesophile	8–47
	Different classes of thermophiles	42–113
Pressure (MPa)	Piezotolerant	Up to 50 MPa
	Piezophiles	Up to 65 MPa
	Extreme piezophiles	Up to 100 MPa

Table 7
Microorganisms classification according to type of respiration (adapted from [32]).

Type of respiration	Microorganism family	Products
Aerobic	• Corynebacterium	• Surfactants
	• Psedomonas	• Surfactants and polymers
	• Xanthomonas	• Polymers
	• Clostridium	• Gases, acids, alcohols and surfactants
Anaerobic	• Desulfovibrio	• Gases and acids
	• Bacillus	• Acids and surfactants
	• Leuconostoc	• Polymers
Facultative	• Arthobacter	• Surfactants and alcohols
	• Enterobacter	• Gases and acids

Table 9
Control of hydrogen sulfide (H_2S) production in reservoirs by use of nitrates.

Injection species	Result	References
Continuous NH_4NO_3 injection	Sulfide levels reduction by 40–60%	[59]
Continuous injection of NO_3^-	H_2S reduction after breakthrough of treated water	[60,61]
NO_3^- and NO_2 Injection	Decrease of Sulfide levels dissolved in both production equipments and produced water	[62]
Continuous injection of NO_3^- and PO_4^{2-}	Decrease in sulfide levels; enhancement of nitrate reducer	[63]

Table 5 represents the reservoir screening criteria parameters which are substantially vital for survival, growth and metabolic activities of microorganisms. The appropriate ranges of screening criteria parameters are gathered from different papers which are based on investigations of various sources including Institute of Reservoir studies (IRS), US Department of Energy (DOE) and China National Petroleum Company (CNPC).

5. Classification of microorganisms and MEOR

In regard to engagement of microorganisms for recovery enhancement in different field trials, based on the reservoir characterization study, some specific mechanisms are needed to be activated to reach the desired results. Selection of the appropriate microorganisms is a

Table 8
MEOR classification according to type of microorganism and recovery mechanism (adapted from [49,54–56]).

Type of microorganism	Effect	Recovery mechanism	Effect
Bacillus	Production of gases, alcohols and biosurfactants	Permeability modification	Volumetric sweep efficiency improvement in waterflooding process
Clostridia	Production of acid and gases		
Pseudomonas	Production of biopolymer and biosurfactant along with permeability modification	Biopolymers, Biosurfactants Acids and alcohol production	Permeability reduction and capillary number enhancement
Sulfate reducing bacteria(SRB)	Oil biodegradability and viscosity reduction along with production of methane		
Nitrate reducing bacteria(NRB)	Souring control and permeability modification	Oil biodegradibility	Production of low viscosity molecules
Others	Oxidation and biodegradability of hydrocarbons along with permeability modification and methane production	Gas production	Oil viscosity reduction

Table 10
Number of MEOR field trials (adapted from [13]).

Property	Lithology	Range	Number of trials	Number of successful trials	Number of failed trials
Permeability (md)	Sandstone	1–10	0	0	1
		10–75	7	6	1
		75–1000	53	41	12
		1000–10,000	2	1	1
	Carbonates	1–10	2	2	0
		10–75	1	1	0
		75–1000	1	1	0
		1000–10,000	0	0	0
Temperature (°F)	Sandstone/Carbonates	50–200	66	48	18
		> 200	0	0	0
Salinity (ppm)	Sandstone/Carbonates	< 1000	0	0	0
		1000–10,000	14	13	1
		> 10000	12	6	6
Type of recovery mechanism	Sandstone/Carbonates	–	34	29	5
Type of field test	Sandstone	–	314	300	14
	Carbonates	–	89	88	1

critical issue that should be exactly investigated in order to accomplish this aim. Consequently, classification of microorganisms and the effects resulting from utilization of each group are the major issues that should be considered in implementation of MEOR projects.

5.1. Different classification approaches

Basically, in MEOR processes microorganisms are classified into two groups of indigenous and exogenous [2]. The future perspectives of MEOR technology seem to be based on injection and stimulation of indigenous microorganisms rather than exogenous ones due to being more adaptive to reservoir conditions. Furthermore, in-situ development of microorganism cultures along with accurate evaluation of their production process is comprehensively less sophisticated [52].

In another point of view, microorganisms could be categorized according to temperature and pressure ranges at which the situation is adequately appropriate for their survival, growth and production of the required products [32] as presented in Table 6. Type of respiration is still another aspect according to which microorganisms could be divided into three groups. Table 7 presents the microorganism categories and their products [53]. On the other hand, classification of microbial enhanced oil recovery could be established based on type of microorganisms and recovery mechanisms. This classification along with specific effects of each case is shown in Table 8. It shall be noted that sulfate and nitrate reducing bacteria aid in enhancement of oil recovery in a behavior different from other kinds of microorganisms. In fact, instead of generation of the seven major groups of bioproducts, NRBs are assumed to activate the mechanisms which aid in control of the souring phenomena and SRBs have the capability to reduce viscosity and interfacial tension by production of aliphatic and aromatic hydrocarbons. In this regard, the following section is exclusively focused on introduction of these bacteria.

5.2. Sulfate and nitrate reducing bacteria

Sulfate reducing bacteria (SRB) are a class of microorganisms that could potentially form a crude oil stabilized emulsion system as well as decreasing surface and interfacial tensions by generation of metabolic products such as aliphatic and aromatic hydrocarbons [57,58]. Desulfotomaculum nigrificans, Thermodesulfobacterium mobile, Archaeoglobus fulgidus, Desulfovibrio longus and Desulfobacterium cetonicum. are good examples of sulfate reducing bacteria [57]. SRB activities could lead to souring phenomenon [27].

Nitrate reducing bacteria (NRB) are another class of microorganisms which play a key role as souring control agents by different mechanisms including:

- performing as electron donors;
- sulfide oxidation;
- SRB inhibition by nitrite and increasing the redox potential [27].

Some examples of using nitrates to control hydrogen sulfide (H_2S) production in reservoirs are presented in Table 9.

6. Nutrient

Although utilization of the appropriate microorganisms is much important in successfully implementation of MEOR field trials, supplying the proper and sufficient amount of nutrients is considerably vital for living and growth of microorganisms which finally contributes to enhancement of oil recovery. As a result, introduction and classification of different kinds of nutrients for utilization in MEOR field trials seems to be beneficial. Growth rate and nutrient concentration are smoothly related to each other. In other words, availability of sufficient amount of nutrient along with appropriate composition is the key parameter to obtain required bioproducts and correspondingly a successful MEOR process. In 1981, Jenneman [18] employed in-situ oil as nutrient which decreased the production rate of bioproducts. In fact, these bacteria consume hydrocarbon as their food source by degrading long chains of alkyls which results in enhancement of precious, light crude oil [26,64]. Classification of nutrients for MEOR purposes is as the following:

- Molasses only;
- In-situ hydrocarbon (crude oil);
- Molasses and nitrogen and phosphorous salts;
- Miscellaneous nutrients [13].

7. Field trials

During last five decades, a notable number of microbial field trials have been implemented in different countries to evaluate the applicability of this dramatic technology. Successful and failed field trials presented by Maudgalya [13] are presented in Table 10. These field trials are based on reservoir permeability, temperature, salinity, type of recovery mechanism and type of field test in different sandstone and carbonate reservoirs. Microbial enhanced oil recovery field trials including 47 cases in 21 different countries are elaborately presented in Table 11 which includes the countries, technologies, reservoir/formation name, utilized microorganisms, nutrients and obtained effects relevant to each case. In 1954, the first field trial was conducted in Lisbon oil field, Union County, Arkansas, USA [16,17] where C. acetobutylicum microorganism along with injection of molasses as nutrient support were utilized [65]. The predominant mechanisms

Table 11
Microbial enhanced oil recovery field trials.

Country	Technology	Cases	Microbial system	Nutrient	Effects	Ref.
China	CMR,[a] MFR,[b] MSPR[c]	Shengli oil field (pilot tests)	Microorganisms in all cases: ● Slime-forming bacteria: Xanthomonas	Nutrientsin all cases: ● Molasses 4–6% ● Molasses 5% ● Residue sugar 4% ● Crude oil 5% ● Xanthan 3% in waterflooding	● Oil production increased in a range of 2001–122800 t in different cases ● Water cut reduction ● Natural decline rate alteration	[6,8–10,17,66–68,97–101]
		Dagangkongdian oil field	campestris, Brevibacteriumviscogenes, Corynebacteriumgumiform		● Oil viscosity reduction by 7.7% ● Production improvement ● Inter-well permeability profile modification ● Surface tension reduction	
		Xinjiang Liuzhongqu oil field	● Microbial products as biopolymers, biosurfactans ● Mixed enriched bacterial cultures of Bacillus,Pseudomonas, Eurobacterium, Fusobacterium, Bacteroides		● Oil emulsification ● Emulsion stability improvement ● Water cut reduction ● Oil production improvement	
		Jilin oil field			● Promotion of water injection profile	
		Huabe Baolige oil field			● Rate of kinetic viscosity reduction increased	
		Changing Jing'an Y9 oil field			● High permeability zone plugging ● Improvement of oil displacement coefficient ● Oil production improvement	
		Daqing oil field (post polymer flooding)	● Bacillus cereus ● Brevibacillusbrevis ● Hydrocarbon-degrading strains		● Polymer plugging removal ● Oil production increased by 165% ● Oil viscosity reduction ● Alkane profile alteration	
USA	CMR	Single well stimulation waterflooding case held in Tulsa, Oklahoma	● Mixed cultures of Clostridium sp., Bacillus sp.,B. licheniformis and a gram-negative rod	● Molasses 4%	● Oil production improved up to 79%	[3]
	CMR	Scale up of microbes in a single well stimulation case	● Anaerobic and facultative anaerobic bacteria high fermenting sucrose-molasses medium	● Sucrose ● Molasses ● Phosphate salts ● Nitrate salts ● Yeast extract	● Significant increase of oil production	[73]
USA	CMR	Univ. field (Oklahoma state)	● Clostridium SD.	● Molasses (4–8%) ● Dry milk solids(0.09%)	● Oil production increased by 100% for 30 days ● PH reduction ● Production of gases, acids and solvents	[71]
	CMR	Single well stimulation case	● Mixed anaerobic microbial cultures	● Molasses	● Oil production increased by 230% for 7 months	[72]
	CMR	Case 5	● Mixed cultures of Bacillus and Clostridium	● Molasses 4% with compatible mineral nutrients as $(NH4)_3PE_4$	● Oil production increased up to 350%	[102]
	CMR	Case 6	● Culture of Clostridium type	● Molasses 4–10% ● Salts: Urea; ammonium nitrate; glicolate acetate	● Considerable increase of oilproduction for 5 months	[17]
	MFR	Alpha environmental field test in Texas	● Mixed cultures of hydrocarbondegrading bacteria	● Inorganic nitrogen and phosphate nutrients ● Biocatalyst	● Oil recovery improvement due to surfactant and CO_2 production ● PH and paraffin reduction ● Increase of API gravity	[103]

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Table 11 *(continued)*

Country	Technology	Cases	Microbial system	Nutrient	Effects	Ref.
	MFR	Pilot test in the Loco Filed (a heavy oil reservoir with API of 21)	• Special adapted strain of Clostridium	• Water • Free corn syrup • Some mineral salts	• Oil viscosity Reduction caused by CO_2 production • Butanol and surfactant production • Improved mobility control and sweep efficiency	[104]
	MFR		Single well stimulation waterflooding case held in Tulsa, Oklahoma	• Mixed cultures of Clostridium z., Bacillus sp., B. licheniformis and a gram-negative rod	• Molasses 2–4%	• Oil production enhancement by 13% and water/oil ratio reduction by 30% after 10 months
	[3]					
MFR	Cretaceous Nacatoch formation in Arkansas	• Clostridium acetobutvlicum	• Molasses 2%	• Oil production Increased by 250%	[65]	
	MFR	Case 11	• unknown	• Molasses • Mineral salts	• An average increase of oil production by 42% for all wells	[105]
	MSPR	Case 12	• Surfactant and co-surfactant gas producing cultures • Polymer-polysaccharide gas producing cultures	• Injection medium (ingredients not mentioned)	• Oil production enhancement for a limited time	[105]
USA	Microbial fracturing fluids recovery	Case 13	• Desulfovibrio hydrocarbon-lastus	• Ca or Na lactate • Ascorbic acid • Yeast extract • K_2HPO_4 • NaCl • Agar gel agent	• Oil Production rate increased by 66%	[105]
	Paraffin removal treatment	Case 14	• A liquid culture of mixed marine source microorganisms	• Saline solution of nutrients to control paraffin deposition	• Oil production Increased by 166% for 3 months	[105]
Russia	MSPR	Bashkiria reservoir	• Aerobic and anaerobic activated sludge bacteria	• Waste waters with addition of some biostimulators and chemical additives	• Additional oil recovery of 1000–2000 t/year for each of 600 producing treated wells	[106]
	Nutritional flooding	Vyngapour oil field in west Siberia	• Indigenous bacteria • Lactobacteria	• Local industry wastes • Sources of nitrogen, phosphorus and potassium	• Production of 2268.6 extra tons of oil • Water extraction reduction	[76]
	MFR	Three pilot tests in Romashkino field	• Stratalmicroflora (aerobic and anaerobic) of flooded oil fields	• Aerated fresh water with added mineral salts	• 32.9% additional oil recovery • Production of organic acids, surfactants, polysaccharides, methane and carbonic acid	[74]
	MSPR	Case 4	• Anaerobic and aerobic bacteria as: sulfate reducing dentrifying, putrefactive and acid butyric fermenting, cellulose digesting	• Peat biomass and silt reach in hydrolysable substrates	• Increase in oil production from 180 to 200–300 t oil/day	[107]
	MFR	Case 5	• Mixed aerobic and anaerobic bacteria	• Molasses 4%	• Oil production increased by 8%for 4 months	[75]
Romania	CMR	Romanian oil fields	• Adapted mixed enrichment Clostridium, Bacillus and gram-negative rods	• Molasses 4%	• Oil production enhancement by 100–200% up to 5 months • Reduction of waterflooding injection pressure	[17,77–80,108,109]
Romania	CMR	Romanian oil fields	• Adapted mixed enrichment cultures predominated byClostridium, Bacillua and gram-negative rods	• Molasses 2–4%	• Oil production enhancement up to 200% in two wells for 1–4 years	[17,79,108,109]
Argentina	Batch, Squeeze	Six wells in Piedras Coloradas oil field	• Hydrocarbon degrading anaerobic facultative microorganisms	• Nourishment from linear hydrocarbon	• Oil production enhancement between 25.8% and 110% • Water cut reduction by 39.1%, 59.5%, 55.6%, 72.8%, 58.7% and	[82]

(continued on next page)

Table 11 *(continued)*

Country	Technology	Cases	Microbial system	Nutrient	Effects	Ref.
					40% in different wells ● Oil viscosity reduction	
	MSPR	Vizcacheras oil field (Papagayos formation)	● Hydrocarbon degrading anaerobic facultative microorganisms	● Inorganic nutrient (N, P, K and oligo elements)	● An increase in oil recovery ● Water retraction ● Fractional flow alteration	[83]
Malaysia	CMR	Three wells in Bokor offshore field	● Adaptive microorganisms	● Adaptable nutrients	● Water cut reduction ● An increase in oil production by 15%, 36% and 120% in different wells ● Permeability reduction ● Skin reduction in two wells	[84–87]
Brazil	CMR	An onshore oilfield located in the northeast of Brazil	● Reservoir native bacterium	● Adaptable nutrients	● Plugging of the high permeability zone ● Vertical sweep efficiency improvement ● Biopolymer production	[88]
India	CMR, MSPR	Indian oil fields	● Multi-bacterial Consortium: Clostridium type Thermo anaero bacterium sp. and Thermococcus sp.	● Molasses 3%	● An increase in oil production	[16]
Australia	BOS system[d]	Alton oil field in Queensland	● Microbial products as biopolymers, biosurfactans ● Ultra microbacteria with surface active properties	● Formulate suitable base media	● Positive effect	[89,110]
Bulgaria	CMR, ASMR[e]	All cases	● Indigenous oil-oxidizing bacteria from water injection and water formation	● Water containing air, ammonium and phosphate ions ● Molasses 2%	● Positive effect	[111]
Former Czechosl-ovakia	CMR, MFR, ASMR	Preliminary trialsin an oil deposit	● Mixed cultures Of sulfate reducing bacteria and Pseudomonas SD. hydrocarbon ● Oxidizing bacteria	● Molasses	● Microbial growth detection ● Oil viscosity reduction ● Stimulation of sulfate reducing bacteria	[90,112]
England	MHAF,[f] MSPR	Case 1	● Naturally occurring anaerobic strain (high acid generator) ● Special starved bacteria (good producers of exopolymers)	● Soluble carbohydrate sources ● Suitable growth media	● Positive/Negative effect	[113]
Former East Germany	MFR, ASMR	A carbonate reservoir case	● Mixed cultures of thermophilic: Bacillus and Clostridium ● Indigenous brine microflora	● Molasses 2–4% with addition of nitrogen and phosphorous sources	● Oil production enhancement ● Water/oil ratio reduction from 88% to 34%	[114]
Germany	_	A carbonate reservoir case	● Clostridium	● Molasses	● Water cut reduction from 80% to 60% ● An increase in oil production from 50 to 150 t per day	[91]
Hungary	MFR	Demjen field	● Mixed sewage-sludge cultures ● Anaerobic thermophilic mixed cultures (predominants:Clostridium, Desulfovibric and Pseudomonas)	● Molasses ● Sucrose ● KNO_3 ● Na_3PO_4	● Increase of oil production by 12–60% for a few weeks up to 18 months ● Gas production (CO_2) ● Decrease in PH, oil viscosity and oil/water ratio	[115,116]
Norway	_	North Sea MEOR field projects	● Nitrate-reducing bacteria naturally occuring in North Sea water	● Nitrate and 1% carbohydrates addition to injected sea water	● Negative effect	[50,92]
Poland	MFR	16 tests in Carpathian crude oil reservoir	● Mixed aerobic and anaerobic bacteria belonging to genera: Arthrobacter, Clostridium, Mycobacterium, Pseudomonas and Peptococcus	● Molasses 4%	● Significant increase of oilproduction up to 300–360% for 2–8 years ● Fluids characteristics alteration	[117]
Canada	MSPR	A heavy oil reservoir with high permeability zones	● Biopolymer producing bacteria (Leuconostocmesenteroides)	● Dry sucrose ● Sugar beet ● Molasses ● Fresh water	● Surface tension reduction from 66.5 to 59.6 ● Restoring good fluid flow ● PH reduction from 6.4 to 6 ● Bioproducts generation as: acetic	[118–122]

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Table 11 (*continued*)

Country	Technology	Cases	Microbial system	Nutrient	Effects	Ref.
					acid, lactic acids, ethanol and propanol	
The Netherlands	MSPR	Case 1	● Betacocusdextranicus (Slime-forming bacteria)	● Sucrose ● molasses 10%	● Significant increase of oil production ● The oil/water ratio changed from 1:20 to 1:50	[94,109]
Saudi Arabia	CMF, CMR, MFR, MSPR	Oil fields of 7 Arab countries	● Adequate bacterial inoculum according to requirements of each technology	● Adequate nutrients for each technology	● Negative effect	[16,20,123]
Trinidad-Tobago	CMF	Trinidadian oil wells	● Fac. anaerobic bacteria high producers of gases	● Molasses 2–4%	● Negative effect	[95]
Venezuela	MFR	Venezuelan oil wells	● Adapted mixed enrichment cultures	● Molasses	● Positive/Negative effect	[16,17]

[a] Cyclic microbial recovery.
[b] Microbial flooding recovery.
[c] Microbial selective plugging recovery.
[d] Biological stimulation of oil production.
[e] Activation of stratalmicroflora recovery.
[f] Microbial hydrocarbon anaerobic fermentation.

were gas, acid and surfactant production as well as viscosity reduction which finally contributed to tremendous increase of 250% oil recovery [16]. In 1991, Wang presented exclusive documented results which confirmed the application of MEOR in China oil fields [17]. In China, field trials administrated by China National Petroleum Company (CNPC) showed significant increase in oil production where microbial water flooding process was the most predominant approach [10,52,66]. Moreover, hundreds of single wells were investigated in Shengli oil field to enhance oil production and lower water cut which showed satisfactory results [10,17,66]. In Daqing oil field, microbial water flooding resulted in polymer plugging removal by cleaning polymer deposits [67]. Dagang Kongdian, Xinjiang Liuzhongqu, Jilin, Fuyu and Huabe Baolige are other examples of oil fields in China for which wonderful results were achieved by microbial enhanced oil recovery [10,68,69]. In Fact, China is one of the leaders in microbial field studies due to its remarkably successful field trials in recent years. In US, several MEOR field tests were conducted in the National Institute for Petroleum and Energy Research in Nowata county with minimum cost [17]. Field results established the significant increase in oil production by 13%, 42%, 79%, 230%, 250% and 350% in different cases as well as considerable water cut reduction [3,65,70–73]. In Russia, stimulation of indigenous microbiota was performed by using oxygen, some salts and molasses as nutrient which contributed to increase of oil recovery [74]. In 1960s, Soviet Union (now Russia) efforts were oriented toward MEOR technology. A single well treatment was conducted in Sernovodek oil field where mixed bacterial cultures and molasses solution were injected which resulted in a slight increase in oil production [74,75]. Following that, potential applicability of MEOR method was examined in Tataryia oil field based on Wagner's experience [16]. In 1993, another MEOR project was carried out in Vyngapour oil field in west Siberia by convincing the nutritional flooding technology [76]. In this project, reservoir indigenous bacteria were tested which showed positive results on oil production. In Romania, successful single well stimulations and microbial flooding recovery technologies were examined in different oil fields which established increase of oil production by an average of 100% and 200% in various cases [77–81]. In Argentina, six wells in Piedras Coloradas oil field were tested by using hydrocarbon degrading anaerobic facultative microorganisms [82]. An increase of oil production between 25.8% and 110% was recorded and the water cut decreased by 39.1%, 59.5%, 55.6%, 72.8%, 58.7% and 40% in different wells. Furthermore, oil viscosity was significantly decreased in all wells [82]. Another field trial in Argentina was done in the strong water drive Papagayos formation of Vizcacheras oil field by using hydrocarbon degrading anaerobic facultative microorganisms with adaptive nutrient support which finally led to oil recovery enhancement [83]. In Malaysia, three wells in Bokor offshore field were selected for microbial process which contributed to water cut reduction and an increase in oil production by 15%, 36% and 120% in different wells. Moreover, skin factor and permeability were decreased in two wells [84–87]. In 2010, microbial enhanced oil recovery was carried out in five wells in an onshore field in Brazil to plug high permeable zones in the reservoir by producing biomass and biopolymer [88]. The perspective of this trial was to engage indigenous bacteria which finally resulted in plugging of high permeable zones and improvement of vertical sweep efficiency. In India, some field trials were conducted by the Oil and Natural Gas Corporation (ONGC), The Energy and Resources Institute (TERI) and the Institute of Reservoir Studies (IRS). These field trials were based on cyclic microbial recovery and microbial selective plugging recovery which finally led to an increase in oil production [16]. In Australia, the oil production increased in Alton oil field by developing a new concept involving stimulation of indigenous microorganisms presented by Sheehy [89,90]. In Germany, the attempts towards implementation of MEOR projects were renewed from 1982 and in the following years a MEOR field trial was conducted in a carbonate reservoir with complex formation characteristics. In that trial, Clostridium species and mo-

Fig. 1. Extended map of countries involved in MEOR.

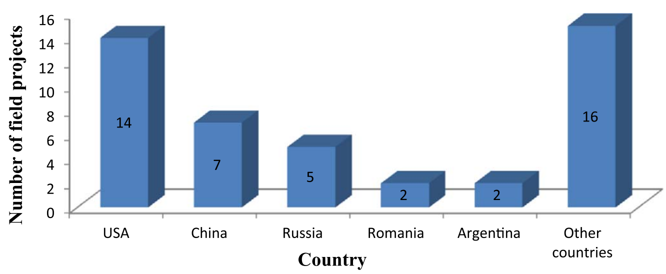

Fig. 2. Number of microbial field projects in different countries.

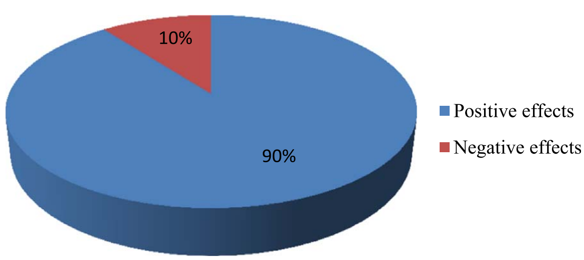

Fig. 3. Effect of MEOR in different fields.

lasses were used which consequently decreased water cut from 802% to 60% and increased oil production from 50 to 150 t per day [91]. In Norway, an offshore field trial was run under microbial process by using NRB bacteria with compatible nutrient support which finally showed negative results [50,92]. In Poland, 18 field trials were conducted by Karaskiewicz [93] between 1961 and 1969 by using mixed cultures of genera Arthrobacter, Clostridium, Mycobacterium,

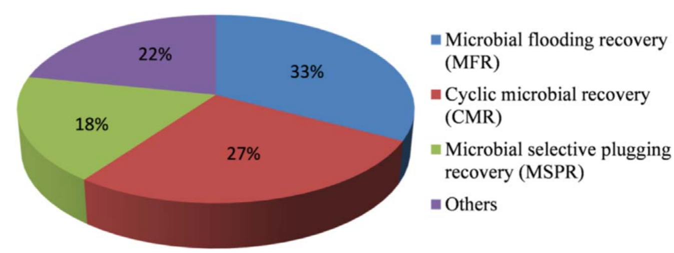

Fig. 5. Utilized technologies in different MEOR processes in all cases.

Peptococcus, and Pseudomonas [17]. In 1958, a selective plugging experiment was carried out in the Netherlands where the oil production increased significantly and the water/oil ratio reduction was detected as a result of injecting Betacoccus dextranicus microorganisms [94]. In a full study, MEOR applicability in Arab reservoirs was investigated by Sayyouh [40] where 300 formations from seven Arab countries (Saudi Arabia, Egypt, Kuwait, Qatar, UAE, Iraq and Syria) were selected for data analysis with the goal of enhancing oil recovery. The anticipation of these efforts was 30% recovery of residual oil under Arab reservoir conditions [40].

Field tests conducted in Trinidad and Tobago Oil Company (TRINTOC) showed negative results, but researches are still continuing to find an appropriate way to make MEOR practical in field scale [95]. In 2012, a coreflood experiment was done in Sultan Qaboos university in Oman to investigate MEOR applicability in fractured carbonate rocks by biomass selective plugging recovery mechanism [96]. In the experiment, Bacillus licheniformis strains were utilized with different nitrogen sources, yeast extract, peptone and urea as nutrient support. The final promising result of 27–30% oil recovery confirmed the MEOR

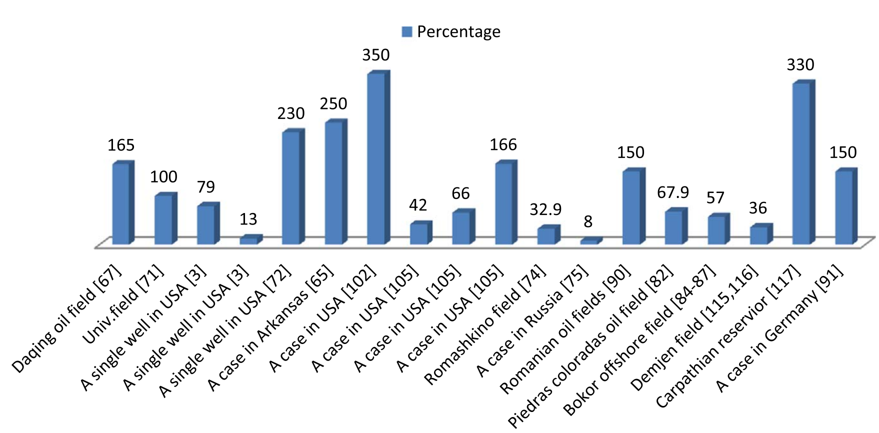

Fig. 4. Recovery factor improvement (%) in some microbial treated field.

potential in fractured reservoirs by using microbial biomass for selective plugging recovery [96].

In 2007, Saikrishna Maudgalya et al. [13] classified four hundreds and seven MEOR field trials which were reported in literature. This classification was based on seven categories as lithology, type of test, recovery mechanism, microorganism, nutrient, and reservoir properties. In this investigation 314 and 89 field trials were carried out in sandstone and carbonate reservoirs, respectively. Clostridium species were the most commonly used microorganisms in all tests. In addition, molasses were used in most of trials as nutrient support. Table 10 is a representation of Maudgalya's study which lists the number of successful and failed field trials based on reservoir permeability, temperature, salinity, type of recovery mechanism and type of field test in different sandstone and carbonate reservoirs [13].

The last historic survey of MEOR field trials was presented by Lazar [17] where he summarized various field trials in different countries with introducing the utilized technologies, microorganisms and nutrients. Table 11 presents the fully detailed updated history of different cases of MEOR field trials with corresponded qualitative and quantitative effects of microbial EOR on each specific case. Furthermore, the utilized technology, reservoir/formation name, microorganisms and nutrients are demonstrated separately for each case which extensively differentiates this table from all tables presented in different papers.

Fig. 1 presents the extended map of countries in which the countries possessing a background in implementation of MEOR projects are highlighted. To graphically illustrate different aspects of this technology, Fig. 2 presents the number of field projects implemented in different countries which are reported in this study. This figure establishes the fact that a great portion of attempts towards MEOR technology is made in USA. It should also be noted that China has had a remarkable development in microbial flooding recovery approach in recent years. The efficiency of MEOR technology in regard to having positive or negative impacts on the implemented fields is depicted in Fig. 3 which exclusively creates some insight for investing on this method due to the remarkable confirmed positive effects. To illustrate the positive impacts of this outstanding technology, some numerical recovery factor improvements which were recorded in different field trials are shown in Fig. 4. Fig. 5 shows the average abundance of utilized technologies in all microbial case studies presented in this paper which establishes the fact that Microbial Flooding Recovery (MFR), Cyclic Microbial Recovery (CMR), and Microbial Selective Plugging Recovery (MSPR) are the most effective technologies among others which creates strong perspectives for investment.

8. Conclusions

Microbial enhanced oil recovery is a low-priced and eco-friendly technology which could potentially increase the ultimate oil recovery. Unfortunately, despite drastic advantages of this technology, it is still not fully supported due to lack of field test data and the perceived process complexity. The tremendous positive results of MEOR carried out in different fields which are presented in this study are an establishment on the creditability of this technique. In fact, more collaborative efforts should be performed in order to specifically analyze phenomena in MEOR. This leads to representation of precise and reliable pre and post process interpretations which prepares the suitable situation for investment on this method in reservoirs which reasonably fit the needed screening criteria parameters. In this study, different microorganisms, bioproducts, nutrients, utilized technologies, screening criteria parameters and consequently the effects of MEOR projects in various fields in different countries were elaborately discussed, but all of these provided information are just an incentive for investment in this field and oil companies should investigate different aspects of this technology more comprehensively and finally more towards implementation of more MEOR projects in field scale. In conclusion, future perspectives of petroleum industry are perceived to be substantially relied on microbial enhanced oil recovery as a consequence of technical and economical aspects as well as environmental issues.

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