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Review Paper

Strategy for Optimum Chemical Enhanced Oil Recovery Field Operation

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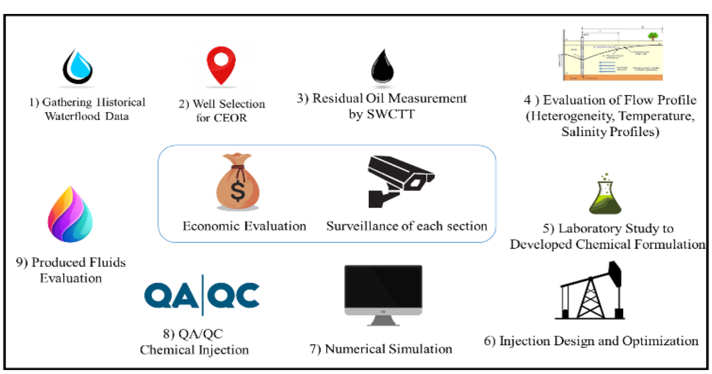
ABSTRACT

The main objective of this review paper is to present practical considerations for field implementation of chemical enhanced oil recovery (CEOR) methods which are complex and require a tailored study for a given reservoir. Researchers have examined several CEOR methods and screening standards. To the best of our knowledge, however, there is no thorough review paper to provide a detailed workflow for transitioning laboratory studies into best practices to field project execution and operations. We analyze and highlight more than thirty publications published between 2018 and 2021 in order to give the readers the latest information about different CEOR methods. We also present a summary of both conventional and cutting-edge CEOR technologies. This provides the readers, researcher, and chemical suppliers with a better understanding of the novel hybrid techniques that are currently being developed. We present several tools for ranking and selecting the CEOR methods, such as techniques for selecting chemicals, screening guidelines, laboratory workflow, injection parameters, chemical formulations, and economic parameters. Our survey's findings indicate that scaling up from laboratory scale to field deployment has many challenges and barriers. These barriers include; project cost, history match and forecast simulations, surveillance, facilities, hybrid method considerations, standardization of performance metrics, the onset of CEOR projects, chemical manufacturing, and the environmental impacts of CEOR operations. Finally, based on these findings, we have proposed a new workflow for practical implementation of CEOR projects. In summary, this paper provides a practical strategy for developing, implementing, and assessing CEOR field operations.

KEYWORDS: CEOR; Surfactant; Polymer; Modeling and Simulation; Ranking and Screening Criteria; Pilot Design

GRAPHICAL ABSTRACT



HIGHLIGHTS

- A comprehensive review of traditional and novel hybrid CEOR methods.
- Provide different methodologies to screen and rank CEOR methods.
- Review of experimental workflow for CEOR and scale up methodologies from lab scale to field pilot.

1. Introduction

The primary source of energy is still fossil fuels which need to be managed properly. Energy consumption is the main motivation behind various hydrocarbon recovery techniques. In general, primary, and secondary techniques of production can result in 20–40% of conventional oil production in place (Nwidee et al. 2016, Thomas 2008, and Muggeridge et al. 2014). As a result, the residual oil will be extracted using various technologies known as Enhanced or Improved Oil Recovery (EOR, or IOR). EOR technologies are classified into three types: thermal, chemical, and gas/solvent injection. Because of the physics of porous media, the trapping and mobilization of crude oil can be difficult to grasp. The underlying physics includes factors, such as high interfacial tension, temperature, oil viscosity, capillary pressure, and complex rock-fluid and fluid-fluid interactions. Injecting chemicals into the reservoir will change the initial equilibrium state of the hydrocarbon fluids, potentially resulting in the mobilization of trapped oil. According to (Machale

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et al., 2019), interest in CEOR operations has increased by approximately a factor of five during the previous few decades. Several review papers (Pal et al. 2018, Gbadamosi et al. 2019, Tackie-Otoo et al. 2020, Druetta et al. 2019, and Ahmadi and Chen 2012) have been written about CEOR technologies.

EOR are referred to the technologies that recover oil by injecting gas or chemicals originally not native to the reservoir. Gas and thermal methods are currently producing a large fraction of EOR oil from light and heavy oil of conventional reservoirs worldwide. However, chemical EOR projects are also active in Canada, South America, China, India, Oman, Kuwait, and India. The injection of chemicals such as polymers, surfactants, and alkali and their combinations into oil reservoirs are referred to chemical enhanced oil recovery (CEOR) and can significantly increase the recovery of oil. Polymer increases water viscosity, yielding better mobility control to reduce the amount of oil bypassed in the unswept volume of reservoir after waterflood. Surfactants reduce capillary forces by lowering the interfacial tension to ultralow values on the order of 10-3 -10-2 mN/m, allowing the mobilization and recovery of trapped oil that is normally left behind in conventional waterflooding. The injection of an alkali agent with surfactant and/or polymer increases the pH of formation water and promotes a reaction with the acidic components of crude oil and generates insitu surfactant to make this process more efficient in oil recovery and cost compared to surfactant/polymer flooding.

Reservoirs with induced fractures or high-permeability channels are quite common in mature oil fields. Resin, foam, polymer/gel treatments, and/or polymer flooding are among enhanced oil recovery (EOR) techniques typically used to correct the reservoir heterogeneity and improve oil production. Chemical EOR (CEOR), involving alkali, surfactant, and polymer chemicals can mobilize and recover large amounts of both upswept and residual oil from mature oil fields. CEOR includes the injection of a mixture of chemicals to both improve volumetric sweep efficiency to produce oil from upswept zones after the water flood and produce residual oil saturation left behind in the swept volume.

The information presented above demonstrates that, when used in conjunction with other EOR techniques like thermal and gas methods, chemical EOR techniques have a high capacity for resource recovery. However, the transition from laboratory studies to field operations requires a careful consideration of many variables and challenges. Two essential factors are economic analysis tools and the capabilities of numerical reservoir simulators to design and accurately forecast the field responses. Additionally, from an environmental standpoint, combining chemical and gas EOR techniques such as CO2 injection can lead to the generation of foam floods, which can be used for both carbon storage and enhanced oil recovery.

Although some researchers have studied several classes of CEOR technologies and their screening criteria, there is no technical paper that addresses practical aspects for field deployments to the best of our knowledge. As a result, rather than analyzing fundamental features of CEOR technologies, we focused on 35 review papers that covered chemicals for EOR application between 2018 and 2021, and based on that, we presented a new approach for successful operations planning and decision making. The specifics of chemical characterization, manufacture, formulation, and optimization are outside the purpose of this study. The major goal here is to examine the published CEOR operations and propose an integrated framework for the deployment of field projects based on the available experiences. Our technique can be utilized as an operational template for the implementation of industrial initiatives, as well as to launch research inquiries by the oil and gas industry and academics.

2. Scope and potential applications of CEOR

The range of chemical materials and processes used in EOR applications is extensive. CEOR technologies are being used more widely in industries for a variety of reasons, including increased demand for oil extraction, technological developments, hybrid methods, and economics. As a result, several review papers on chemical materials and methodologies have lately been published. The following is a summary of a selection of recent review papers on CEOR techniques published between 2018 and 2021.

2.1. 2021

Liu et al. 2021 recently evaluated different aspects of surfactant adsorption behavior, including mechanisms, isotherms, kinetics, and thermodynamics. The key parameters influencing surfactant adsorption are reported to be surfactant properties, solution chemistry, rock mineralogy, and reservoir temperature. Other synergetic chemical formulations, such as alkalis, polymers, nanoparticles, co-solvents, and ionic liquids, are reported as materials that can lower surfactant adsorption in addition to forthcoming trends and future problems. The paper also discusses the salinity gradient and low salinity water flooding.

The methods, measurements, and factors influencing surfactant retention on rocks were detailed by Kalam et al. 2021. The paper of Kalam and his colleagues includes reservoir types, surfactant kinds, surfactant adsorption, phase trapping and precipitation, several approaches of surfactant retention measurements, retention minimizing procedures for both ionic and nonionic surfactants, and future prospects.

Yao et al. 2021 conducted a review of surfactant flooding for carbonate reservoirs while taking wettability alteration into account. The electrical charge on carbonate rock surfaces, the water film between crude oil and rock surface, crude oil/brine/rock interactions for oil-wetness, factors affecting wettability, conventional wettability measurement methods, surfactant characterization, and wettability alteration by anionic, cationic, zwitterionic, nonionic, and Gemini surfactants and their blends are all discussed. The authors also supplied wettability change data from spontaneous imbibition testing. Because of their low cost, anionic and nonionic surfactants have also been reported as field usage for surfactant EOR in carbonate reservoirs.

Dordzie and Degam 2021 published experimental and modeling analyses of various CEOR approaches for fractured carbonate reservoirs, including nanoparticles, low salinity water flooding, surfactant flooding, and the combination of low salinity nano surfactant. The mixing of different nanoparticles has not been adequately examined in the literature, according to their review. Sagbana and Abushaikha 2021 investigated chemical-based conformance control techniques in oil fields. The authors cover the methods, applications, classification, and factors impacting polymer gels, emulsions, and foam for conformance control application, as well as current breakthroughs in chemical-based conformance control agents.

Wang and Seright 2021 gave a comprehensive review of the colloidal dispersion gels (CDGs) publications as the alternatives of polymer flooding. The viability of CDGs for oil recovery, laboratory evaluation, field data, and simulation experiences were presented. The use of natural surfactants in EOR was reviewed by Atta et al. 2021.

2.2. 2020

Organic alkalis, biosurfactants, ionic liquids, and biopolymers were reported as alternative chemical agents for traditional alkalis, surfactants, and polymers employed in EOR by Tackie-Otoo et al.2020 The role of chemical additives and their rheological qualities in EOR was debated by Machale et al. 2020. Delamaide 2020 reported on polymer and ASP flooding field experiences in Canada, including Bodo, Moonet, and Suffield (2). There was also information about laboratory, pilot, and full-field testing.

Bera et al. 2020 reported on developments in ionic liquids as a chemical alternative. Ionic liquids can be employed for four purposes, according to their classification: drilling, EOR, unconventional heavy oil recovery-stimulations, and flow assurance. The status of surfactants for EOR application was described by Massarweh and Abushaikha 2020. Mechanisms of surfactant in EOR are explained, as well as surfactant adsorption on the rock and experiences with various types of surfactants, considering the fundamentals of surfactant flooding, such as Kraft point, CMC, Solarization ratio, and so on. The field name, location, formation properties, oil properties, surfactant characteristic, additional chemicals, and performance of each case were all documented by the authors. Surfactant flooding for carbonate reservoirs under hard conditions was described by Adila et al. 2020 Surfactant flooding's underlying mechanisms have been discussed. Amphoteric surfactants have been mentioned as candidates for HTHS Carbonate reservoirs, and numerical models, low-salinity surfactants, foams, and field applications have been described. More fundamental information regarding microemulsion, phase behavior, and effects of temperature and salinity are reported by Tartaro et al. 2020.

Fundamentals, experimental, and computational aspects of polymer flooding for CEOR applications were presented by Firozjaii and Saghafi 2020. The report also discusses the problem of polymer flooding in the HTHS situation. The organic chromium-based polymer gels were studied by Zhang et al. 2020. The article examines eight different types of organic chromium gels and discusses the conformity control agent's development process. A report by Scott et al. (2020) examined a broader range of polymeric materials and their use in the EOR process.

2.3. Prior to 2019

Belhaj et al. 2019 reviewed the effects of salinity, temperature, and pH on surfactant flooding and adsorption, focusing on the high-temperature and high-salinity (HTHS) conditions. A complete review of ASP was published by Yang et al. 2019. Each chemical's mechanism was highlighted, and the current state of ASP flooding in China was presented, with a focus on the Daqing oil field. There were also reports regarding ASP flooding in other oil fields and countries outside of China, including as the United States and Canada. The key notes as the obstacles of the ASP floods are operational issues, scaling and precipitation, difficulties in processing produced emulsions, and water disposal. Even though Nanotechnology is considered a subset of CEOR, Medina et al. 2019 reported using it for Thermal EOR. Agi et al. 2018 examined the disadvantages of Xanten and polyacrylamide in porous media and analyzed the natural polymer flow behavior in porous media. Natural polymers (polymers derived from agriculture and forest produce) were offered as alternatives since Xanten and polyacrylamide were not tolerant of high salinity, high temperature, and were detrimental to the environment. The writers also looked at the natural polymers that are available, as well as the mechanisms that govern retention and rheology in porous environments. Reservoir conformance issues, the background of in situ gel treatment, forms of cross-linked polymer gels, factors affecting gelation kinetics, and field application of cross-linked polymers were all discussed by Amir et al. 2019. Over 1000 field treatments or applications have been reported to have been carried out with crosslinked polymer gel systems around the world. The effect of polymer retention in porous media was studied by Al-Hajari et al. 2018.

The article by Al-Hajari et al. covers the mechanisms of polymer flooding, factors affecting polymer retention, polymer retention measurement, and modeling of polymer retention in porous media. Perazzo et al.2018 discussed several aspects of emulsion applications in porous media, such as fluid distribution in porous media, emulsions, microemulsions, Nano emulsions, microfluidics, and emulsion rheology for EOR. Pal et al. 2018 discussed the most recent advances in surfactant based CEOR for carbonate reservoirs. Surfactant flooding, foams, wettability alteration and interfacial tension reduction, microemulsion phase behavior, surfactant adsorption, hybrid methods, and field applications in Carbonate reservoirs, as well as future perspectives, are all covered. Ali et al. 2018 presented the most recent reports on diverse nanoparticle uses in the surfactant, polymer, surfactant-polymer, alkaline-surfactant-polymer, and low salinity waterflooding industries. There is a list of several classes and types of nanoparticles, as well as their research topics, such as FT reduction, wettability modification, emulsion stability, mobility ratio modification, and viscosity modification. The challenges and future of chemical heavy oil recovery techniques were highlighted by Ahmadi and Chen 2012.

A summary of the above survey is provided in Table 1.

Table 1
Summary of the recent publication regarding CEOR methods.

Author *	Year	Chemicals	Main Contribution
Liu *et al.*	2021	Surfactant	• Different aspect of surfactant adsorption • Mechanism, isotherms, kinetic and thermodynamic are reported
Kalam *et al.*	2021	Surfactant	• Surfactant retention on rocks • Methods, measurements and influencing factor are reported
Han *et al.*	2021	Surfactant	• Surfactant behavior from molecular standpoint • Effect of co-solvent and blend of nonionic and ionic surfactant are reported
Yao *et al.*	2021	Surfactant	• Surfactant flooding for Carbonate reservoir • Factors affecting wettability, conventional wettability measurement methods, surfactant characterization, and wettability alteration are discussed
Dordzie and Degam	2021	Nano, LSWF, Surfactant, Low Salinity Nano Surfactant	• Experimental and modeling analyses of various CEOR approaches are highlighted
Sagbana and Abushaikha	2021	Polymer Gels, Emulsions, and Foam	• Methods, applications, classification, and factors impacting polymer gels, emulsions, and foam for conformance control application are covered.
Wang and Seright	2021	Colloidal Dispersion Gels	• Review of CDGs publications as the alternatives of polymer flooding
Atta *et al*.	2020	Natural Surfactants	• The sources, synthesis, and classification of natural surfactants were reviewed
Tackie-Otoo *et al*.	2020	Organic alkalis, bio surfactants, ionic liquids, and biopolymers	• Alternative chemical agents for traditional alkalis, surfactants, and polymers are reported
Machale *et al*.	2020	Chemical additives	• The rheological qualities of chemical additives in EOR discussed
Delamaide	2020	Polymer and ASP flooding (field experiences)	• Information of laboratory, pilot, and full-field testing polymer and ASP flooding field experiences in Canada, including Bodo, Moonet, and Suffield (2) were provided
Bera *et al*.	2020	Ionic Liquids	• Drilling, EOR, unconventional heavy oil recovery-stimulations, and flow assurance are four type of activities that Ionic liquid can be used.
Massarweh and Abushaikha	2020	Surfactant	• Mechanisms of surfactant in EOR, surfactant adsorption on the rock and experiences with various types of surfactants were discussed
Adila *et al*.	2020	Surfactant	• Surfactant flooding for carbonate reservoirs under hard conditions was described
Tartaro *et al*.	2020	Microemulsion	• Phase behavior, and effects of temperature and salinity are reported.
Belhaj *et al*.	2020	Surfactant	• The effects of salinity, temperature, and pH on surfactant flooding and adsorption were reviewed.
Firozjaii and Saghafi	2019	Polymer flooding	• Fundamentals, experimental, and computational aspects of polymer flooding for CEOR applications were presented.
Zhang *et al*.	2020	Organic chromium-based polymer gels	• Eight different types of organic chromium gels were examined, and the conformity control agent's development process were discussed.

Continued …

Scott *et al*.	2020	Polymeric materials	• Advantages and disadvantages of biopolymers are provided.
Yang *et al*.	2019	ASP	• Each chemical's mechanism was highlighted, • The current state of ASP flooding in China was presented, with a focus on the Daqing oil field
Medina *et al*.	2019	Nanotechnology (in Thermal EOR)	• The interaction of nanoparticles with heavy fractions and variables that can influence the adsorptive phenomenon were presented.
Agi *et al*.	2018	Natural polymer	• The disadvantages of Xanten and polyacrylamide in porous media were examined • The natural polymer flow behavior in porous media were analyzed
Amir *et al*.	2019	Polymer	• Reservoir conformance issues, the background of in situ gel treatment, forms of cross-linked polymer gels, factors affecting gelation kinetics, and field application of cross-linked polymers were all discussed
Al-Hajari *et al*.	2018	Polymer	• Mechanisms of polymer flooding, factors affecting polymer retention, polymer retention measurement, and modeling of polymer retention in porous media
Perazzo *et al*.	2018	Emulsion	• Several aspects of emulsion applications in porous media, such as fluid distribution in porous media, emulsions, microemulsions, Nano emulsions, microfluidics, and emulsion rheology for EOR were highlighted.
Pal *et al*.	2018	Surfactant	• The most recent advances in surfactant based CEOR for carbonate reservoirs were discussed. • Surfactant flooding, foams, wettability alteration and interfacial tension reduction, microemulsion phase behavior, surfactant adsorption, hybrid methods, and field applications in Carbonate reservoirs are covered.
Ali *et al*.	2018	Nanotechnology	• Nanoparticle uses in the surfactant, polymer, surfactant-polymer, alkaline-surfactant-polymer, and low salinity waterflooding were provided.
Ahmadi and Chen,	2012	Surfactant	• Newly formulated chemicals for coupling with thermal oil recovery techniques are reported.

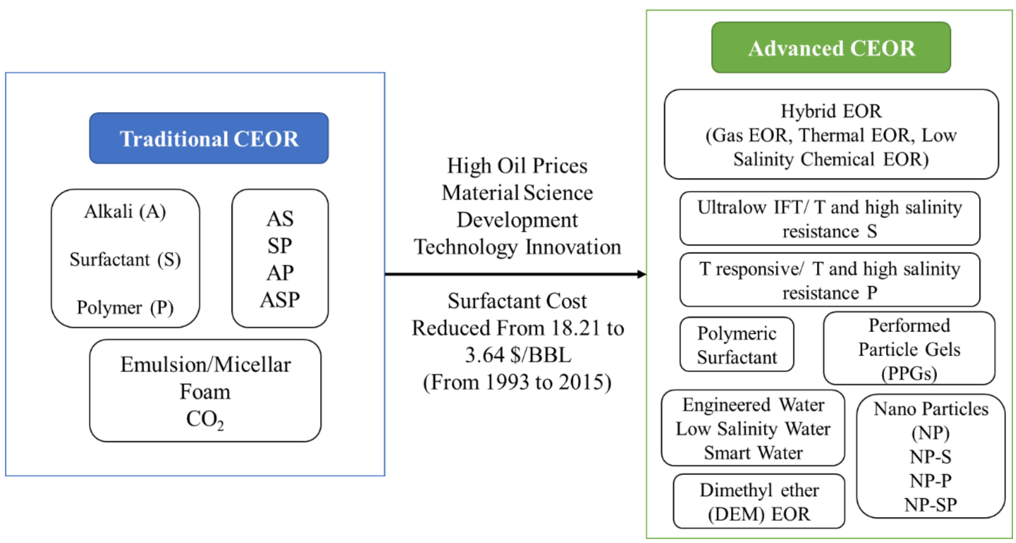

Figure 1. An updated classification of traditional and advanced CEOR methods. Redrawn and modified From Raffa 2021.

The conventional classification of CEOR approaches appears to be out of date, based on what has been mentioned above. Thus, according to Raffa 2021 Figure 1 shows a more advanced update classification.

Although the recent materials implemented for CEOR projects can be known by examining the above articles, several operational questions remain unsolved. They are summarized below:

• Where should someone begin a CEOR project if they wish to get started?
• What are the risks or costs for chemical suppliers or operators?
• How many screen tables and comparison tools are there for different CEOR methods, aside from simulation studies?
• Is there any material-process selection and optimization guidelines for different CEOR procedures that include different static and dynamic laboratory evaluation?
• How long does a CEOR project last? What is the best way to start a CEOR project?
• Is there a flow diagram for the surface injection facilities or monitoring equipment that CEOR projects require?
• Is there a report on the final cost and economic evaluation of CEOR projects? (This is the most significant question)
• Is there a cost-benefit analysis technique that can be used to assess the performance of CEOR projects?
• Is there a data bank or a standardization of performance metrics for CEOR projects? • What aspects of the CEOR methods should be considered before scaling them up?

In the following this paper tried to answer the above questions.

3. Phase behaviour and formulation design

Water composition is one of the most critical factors for assessing the profitability of designed chemical formulations. Water flooding, surfactant flooding, polymer flooding, ASP flooding, microemulsion flooding, and foam flooding are examples of CEOR technologies that are intensively dependent on water composition. The magnitude of ionic strength is affected by many variables, such as monovalent ions, divalent ions, ion exchange, reaction kinetics, neutrality, and total dissolved solids (Henthorne et al. 2014). Consequently, there should be a deep understanding of salinity profile design during the production of conventional reservoirs. Incompatibility of injection and reservoir brines may cause salt precipitation (Yuan and Wood 2018). The hardness scale (R+), which is derived as a ratio of total divalent ions divided by total cations (monovalent and divalent), is a useful tool for analyzing the properties of reservoir or injection brines, according to Tabary et al. 2013. Mathematically, Equation (1) illustrates the hardness scale (g/l):

$$R+=\frac{\left[Ca^{2+}\right]+\left[Mg^{2+}\right]}{\left[Na^{+}\right]+\left[K^{+}\right]+\left[Ca^{2+}\right]+\left[Mg^{2+}\right]} \quad (1)$$

The ideal salinity profile of surfactant phase behaviour, for example, is inversely proportional to water hardness. In addition to hardness scale, the salinity and composition of brine can have a significant impact on water flooding operations, and it leads to the generation of a new class of EOR methods, commonly known as low salinity water flooding, smart water flooding, or designer water injection Al-Shalabi and Sepehrnoori 2016. Low salinity waterflooding might be thought of as a form of CEOR methods. Also, the knowledge gained from LSWF can easily be transferred to other CEOR processes since salinity is a key factor in these processes. The following reviewing publications provide additional information on the current state of LSWF (Al-Shalabi and Sepehrnoori 2016, Afekare and Radpnjic 2017, Olayiwola and Dejam 2018, Bartels et al, 2019, Katende and Sagala 2019, Tetth et. al. 2020). Aside from engineering aspects, water sources and their salinity/composition manipulation have an impact on project economics. Most hydrocarbon accumulations are supported by aquifers. Hence, based on its unique characterizations, an optimum salinity profile should be determined for each chemical formulation. The optimum salinity profile refers to a certain salinity level in which the chemical composition is manipulated for technologies, such as surfactant or polymer flooding. In this regard, hybrid methods and chemical blends technologies are becoming a popular approach to reduce the cost and increase recovery efficiency. Activation of multiple recovery mechanisms, tackle operational challenges, reduces environmental impact, and lowers the costs of production are some advantages of hybrid martials that depends on salinity profile. Surfactant-Nano, Polymer-Nano or their combination Surfactant-Polymer-Nano are examples of such hybrid methods Corredor et al. 2019. Although there is a major effort to introduce the optimum formulation for hybrid materials, these materials have challenges with extreme conditions of high temperature, high salinity, and high pressure in addition to requirements for injection/production facilities. Further information about the literature review of the hybrid materials can be found in Hamza et al. 2017. Also, the Winsor-based graphs was used as suggested for surfactant-based formulation development presented by (Al-Murayri et. al.2019a, Al-Murayri et al. 2018a). Figure 2 shows an example of them. These graphs are used to investigate the effects of chemical formulations, concentrations, bine hardness, water-oil ratio, oil EACN, and temperature on phase behavior of surfactant formulations. General Winsor sensitivity and Winsor visualizations graphs are illustrated in Figures.

In addition to optimum phase behavior evaluation, the implementation of CEOR projects has substantial financial risks and requires overcoming technical challenges (Jürgenson et al. 2017). Project implementation in oil fields with harsh conditions, such as high temperature, high salinity, high pressure, low permeability, complex rock mineralogy, and offshore environments require additional planning with cautions. This indicates that oil and gas operators are dealing with more risks than chemical suppliers. Moreover, regardless of operational challenges, the unique characterization of materials in CEOR operations also needs additional effort and attention. Different rheological behaviour of polymers, special blends of surfactants, and chemical adsorption on the reservoir rocks are examples indicating an integrated and multi-disciplinary effort that is required for successful CEOR projects. The size of the reservoirs, chemical volumes, manufacturing, required logistic facilities and delivery of chemicals make the projects more complex than waterflooding. Thus, currently, most oil and gas operators consider using water flooding and polymer flooding due to several successful full-field projects, technology maturity, and favourable economics.

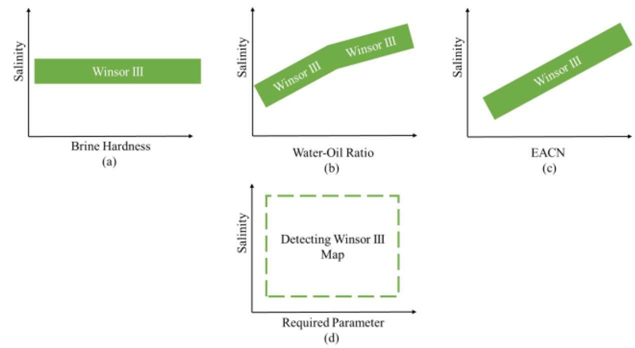

Figure 2. Winsor sensitivity graph used for designing various parameters for salinity ranges. Adapted from (Al-Murayri et. al.2019a, Al-Murayri et al. 2018a).

As an example, the plot of different phases of the project, the risk, and uncertainty illustrated by Karovic-Maricic et al. 2014 can be useful for the operators. EOR selection, pilot test, and implementation are three steps that have to be addressed carefully for successful operations. Figure 3 illustrates the uncertainty and risk associated with each phase of the operation.

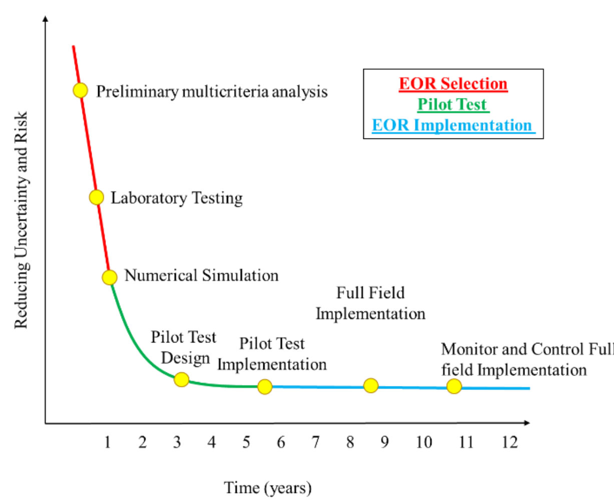

Figure 3. The plot of Risk and Uncertainty Analysis for different operational scales. Redrawn From (Karovic-Maricic et al. 2014).

Another advantage of using Fig. 3 is an estimate of the time for each phase of the project. According to the graph of (Karovic-Maricic et al. 2014), 12 years seem to be a reasonable period for CEOR operations. Project economics can be reported based on this time interval (12 years). We will later elaborate on the EOR project life.

4. Screening Criteria, and Laboratory Workflow

4.1 Screen and methodology selection

Screening and ranking oil reservoirs for CEOR implementation is a tricky task to conduct. Albeit some other researchers reported on screening and ranking of reservoirs for these methods, many of them have relied on in-house reports. Hence, in the next section, we will discuss the steps and methodology for the ranking and selection of CEOR methods.

It is critical to select the most reliable EOR methods and chemicals to produce the oil reservoirs. Proper selection of CEOR agents can reduce the cost and risk of implementation. Screening, material selection, and laboratory evaluation are crucial steps for CEOR operations compared to other EOR/IOR processes, such as water or solvent injection. It is mainly due to the interactions of injected chemicals with reservoir rocks and fluids. As the first screening tool, we are discussing a methodology based on the report by Dean et al. 2018. In that work, authors considered different EOR technologies for Rocky Mountain Reservoirs including carbon dioxide, surfactant, polymer, alkali, etc. Their methodology consisted of four fundamental steps: understanding project objectives, determining the agent volume requirement, determining sourcing option, pricing, logistics, and comparing EOR agents. The report gives examples that demonstrate how significant chemicals are required for a commercial field project. Thus, chemical suppliers and oil companies can use the information as an initial estimate for the required volume of the chemicals for their projects.

From the industry's point of view, the screening of different EOR technology is a debatable topic. Each reservoir requires its own and unique screening guidelines. Taber's tables were based on earlier work designed for this purpose (Tabar et al. 1997a, 1997b). Sheng provided updated tables for various CEOR technologies, such as the polymer, surfactant, and ASP flooding (Sheng 2014, Sheng 2015a, Sheng 2015b). Dickson et al. (2010) also presented a framework for identifying the most appropriate improved hydrocarbon recovery and predicting key reservoir performance.

Mohan et al. 2011 reported different screening tables for various EOR technologies including polymer, ASP, and micellar polymer flooding. Pogaku et al. (2018) also reviewed recent advances in chemical flooding. This report discussed polymer, alkaline-polymer, micellar-polymer, nanoparticles with polymer, and ASP methodologies. The screening parameters were cost, expected oil recovery efficiency, sensitivity, and resistance (of the materials), effectiveness, and field application. Moreover, there is another chart that belongs to the University of Texas at Austin, in which a more advanced table was presented (University of Texas at Austin's Webinar, 2015). It was the first time that a screening table for ACP (Alkali, Co-solvent, Polymer) and LTG (Low Tension Gas) flooding was presented. The latter is more up to date compared to earlier charts.

Moreover, to illustrate an industry example, readers can refer to the work of Al-Murayri et al. 2017a who presented a table for Sabriyah Lower Burgan reservoir in Kuwait; in which various EOR technologies, such as aqueous, gaseous, and thermal flooding were considered. Their screening table also included low salinity water flooding.

Chen et al. 2018 provided an integrated workflow to screen, rank, and evaluate different EOR and IOR scenarios for a candidate reservoir. They reported an algorithm to rank reservoirs based on the recovery factor and GOR. Also, six parameters were mentioned for reservoir rock and fluid properties. The screening parameters were depth, reservoir thickness, permeability, temperature, oil API gravity, and oil viscosity. Furthermore, Chen and his co-workers presented an advanced reservoir screening technique for EOR and IOR selection. This advanced approach is coupled with geological and geophysical characterizations to assess the EOR methods considering ten parameters as mobility ratio, minimum miscibility pressure, bubble point pressure, oil rate, active oil producers vs. cumulative oil production, WOR vs. cumulative oil production, water injection, and production rate history, initial and current GOR, initial and current reservoir pressures, reservoir pressure history, and commercial worldwide EOR projects. Both initial and advanced reservoir ranking algorithms can be found in Chen et al. (2018).

Adepoju et al. 2017 provided information about chemical performance uncertainties, and the uncertainty parameters for surfactant-polymer flooding were: residual oil saturation, endpoint water relative permeability, polymer viscosity, polymer adsorption, polymer permeability reduction, polymer inaccessible pore volume, polymer shear thinning, surfactant adsorption, micro emulsion viscosity, and residual oil saturation at high capillary number. Based on the above discussion, screening guideline tables and reservoir ranking are two essential tools to study the project before large-scale deployment.

4.2. Laboratory Workflows

Designing profitable chemical flooding projects require a comprehensive understanding of the injection parameters. Bai et. al.2017 reviewed different EOR technologies, such as CEOR and air injection for carbonate reservoirs followed by optimization of injection parameters by numerical simulation for a limestone carbonate reservoir. Different optimization studies were carried out for surfactant flooding, polymer flooding, and surfactant-polymer flooding. The injection parameters studied were polymer molecular weight and concentration, surfactant mass fraction, injection rate, and surfactant slug size. These values can provide a template for projects that are at the design stage. The report also considered the effect of wettability, interfacial tension, capillary forces, fracture, and matrix permeabilities. However, the authors did not consider the economics of CEOR operations.

CEOR projects require a series of laboratory tests to obtain the fluid properties, phase behavior tests for surfactant floods. The surfactant phase behavior and optimum design are obtained by a series of tube tests and tuning of the chemical formulation for given reservoir conditions. Conducting laboratory tests can help the researchers to better understand the complexity of the project. For sake of having a standard and unique protocol, four fundamental tasks should be carried out for each project reported by Al-Murayri et al. 2018a. 1) rock samples and fluid characterization, 2) chemical selection and design, 3) process evaluation and design, 4) process optimization and robustness assessment. Steps 2 and 3 (chemical selection and process evaluation) may be different for different chemical agents. Also, the economics of the project and the budget of the phase behavior tests are other determining factors. Al-Murayri et al. 2019a also reported a summary of conditions for dynamic core floods for two different chemical formulations. The report discusses core and brine characteristics, chemical slug properties (such as components of the main slug, post flush, and chase water), and results. Using this workflow with previous tools enables the industries and academia to have more integrated analyzing tools.

Ferreira and Moreno 2018 provided project workflow for polymer flooding consisted of screening, laboratory tests, simulations, and field execution. Figure 4 gives a general workflow, and some details are, however, missing from their flow chart.

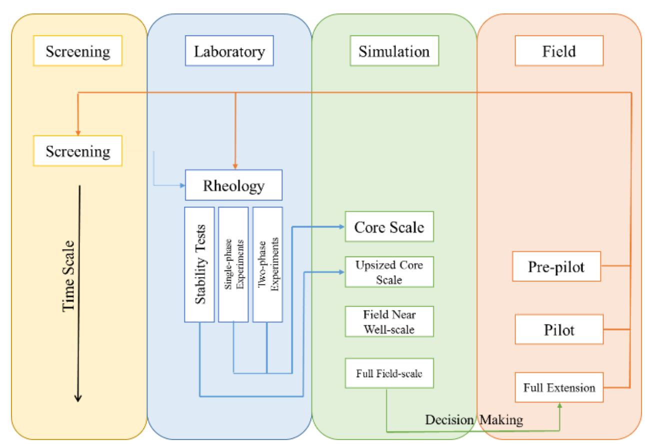

Figure 4. General Workflow of polymer flood implementation. The flowchart and its steps (screening, laboratory, simulation, and field) can be used as a template for the output of polymer flooding. Redrawn from Ferreira and Moreno 2018.

Itriago and Fresky 2019 reported the laboratory workflow for screening and evaluation of polymers. The workflow consisted of five steps: quality control of selected polymer, polymer solution properties evaluation, rock, and fluid characterizations, initial core flood conditions, and polymer performance evaluation. Details of each step are described in Figure. 5. A combination of this flowchart with general polymer flooding workflow (Figure. 4) is considered as the overall workflow for polymer flooding. This workflow can also be applied to SP or ASP tests.

For surfactant flooding, five types of performance criteria have been reported by Zhao et. al. (2010) optimal salinity, optimal solubilization ratio, equilibration time into fluid middle phases, microemulsion viscosity, core flood evaluation for oil recovery. Surfactant selection, phase behavior compatibility with reservoir minerology, stability at reservoir temperature and pressure, IFT studies, adsorption studies, and core flooding were stated as criteria for surfactant flooding by Chowdhury et al. 2022.

Flooding with surfactant-polymer is also possible. EOR screening, process development, results scaleup, single-well validation, and multi-well pilots were reported by Alsofi et al. 2021. Authors offered more details at the process development stage, where they evaluated solubility, phase behavior, IFT, and adsorption for surfactant design, and viscosity, filtration, and thermal stability for polymer selection. The process development also included tests for compatibility, injectivity, separation, water quality, and core flooding. For more information, see the report by Alsofi et al.

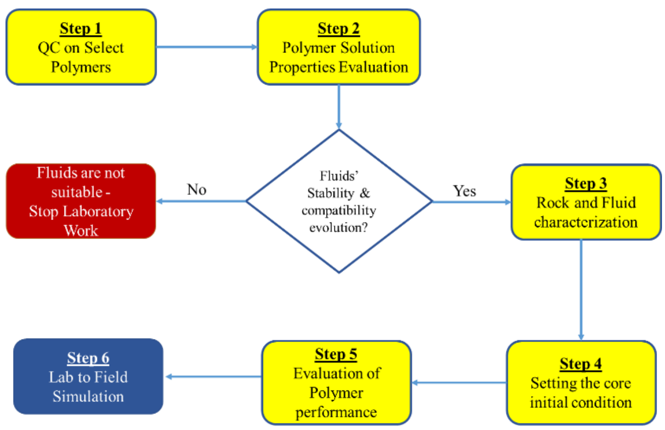

Figure 5. Laboratory workflow for screening polymers, details of each step can be found in Itriago and Fresky, 2019. Redrawn From Itriago and Fresky, 2019.

Further details regarding manufacturing quality assurance and control methodology of surfactants are available in Barens et al. 2018. Armacanqui et al. 2017 proposed an integrated workflow for EOR project management applications. Table 2 is redrawn from the proposed workflow of Armacanqui et al. 2017 Furthermore, five challenges which can cause delay in project execution were discussed as 1) interactions of several disciplines and sub-processes, such as chemical selection, field facilities, up-scaling, HSE, and well integrity, 2) access to reliable EOR screening tool, 3) limited availability of reservoir core samples, 4) limited synthetic/outcrop cores to emulate the adsorption behavior of chemicals, 5) unexpected results and uncertainty of laboratory tests, core flood history match simulation, and SWCTT.

Rommerskirchen et al. 2019 also reported seven steps for the lifecycle of CEOR implementations: 1) EOR screening, 2) laboratory analysis, 3) update analysis (information such as chemical injections, concentrations and volumes), 4) operational plans, 5) facilities design, 6) project implementation, and 7) project monitoring. Moreover, (Zhang 2014) summarized earlier studies on the design and optimization of SP and ASP flooding. The report consisted of design parameters such as objective function, the scale of the study (laboratory, pilot, or field), formulation design, simulation, sensitivity study, and optimization. Also, the author presented the steps for design and optimization. Figure 6 shows three common scales of the lab, pilot, and commercial scales.

Yzenga et al.2019 also reported the process of design with five steps; reservoir selection, feasibility study, design of chemical mixture at the lab scale, field pilot, and field development. In parallel, field simulation and surveillance have to be carried on. An example of milestones and activities, such as reviewing existing infrastructure, training, and technology transfer is available in Tiwary et al. 2018.

Babadagli 2017 offered additional information about planning, design, and optimization. For example, for various recovery strategies such as surfactant, polymer, ASP, micellar-polymer, and alkaline-polymer flooding, the average incremental tertiary recovery of more than 20% was reported. More technical material was also provided by the author for the EOR project's implementation. There are four major phases of EOR technology development: idea, research, technology, and commercialization. The full commercialization of an EOR project may take 3–10 years after completing the laboratory experiments, simulations, one-spot pilot, and inter-well pilots. For chemical flooding, although the laboratory oil recovery results are remarkable, field-scale results in most cases are not very promising due to incomplete sweep efficiency, chemical degradation and retention, and harsh conditions high salinity/high temperature, low permeability, extreme heterogeneity, and long residence time of injected chemicals. Eleven factors give more chance of success: 1) field size, 2) size and type of company (IOC or NOC), 3) low-cost chemicals, 4) high oil price, 5) low CAPEX/ OPEX, 6) technical suitability of technology, 7) a good understanding of reservoir geology and complexity, 8) proper technical design and implementation, 9) successful pilot, 10) expertise and the human factor, and 11) combination of the above. The ongoing large scale CEOR project is the Daqing oil field in Chin.

Furthermore, Al-Murayri et al. 2018b provided additional information on injection fluid compositions, such as volume, chemical composition, injection rate, and injection pressure for 5 different steps, including pre-flush, ASP, caustic-polymer, polymer in seawater with co-solvent, and polymer in seawater. Also, additional chemical composition and formulation design for ASP flooding can be found in Al-Murayri et al. 2017b.

The report of Lopez et al. 2020 discussed ideal formulation and characteristics for ASP design, including ultra-low IFT values, low shear microemulsion viscosity, surfactant mass, surfactant retention per germ of the rock, solubilization ratio, blends of synergistic surfactants, the performance (in terms of residual oil saturation), and optimum salinity. The effect of co-solvent to reduce microemulsion viscosity, improve equilibrium time, and increase IFT was discussed. This information enables suppliers and operators to have ideas about the chemicals, concentrations, and volumes required etc. in the screening and ranking EOR methods before embarking on lengthy and costly laboratory evaluations.

Apart from typical laboratory setups, such as coreflood, spontaneous imbibition Amott cells, phase behavior tests, or micromodel studies, macro reservoir models can be considered as new tools to assess CEOR operations. To the best of our knowledge, Hamza et al. 2018 were the first that used the macro model for their CEOR investigation. Moreover, the authors introduced a new concept to evaluate the performance in macro models as the amount of oil recovered (AOR) due to chemical slug as:

$$AOR = \frac{\textit{Volume of Oil Produced by Chemical Flooding}}{\textit{Original Oil in Place} - \textit{Volume of Oil Produced by Water Flooding}} * 100 \quad (2)$$

Compared to current methods, this approach can provide more realistic conditions for operators. Also, the flooding patterns such as five or seven spots and well spacing can be investigated by this approach. This technique can also provide more information regarding the adsorption of chemical agents or the behavior of fronts during flooding. Here we suggest introducing macro model studies in the last step of screening before pilot or full-field executions.

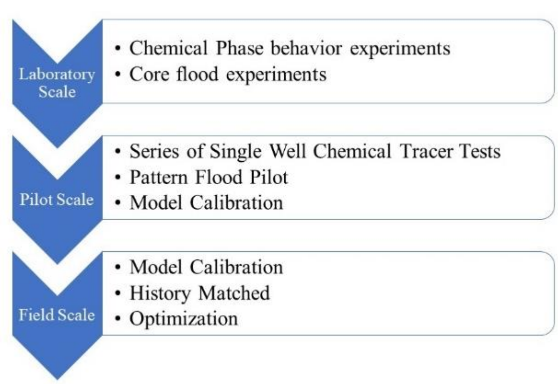

Figure 6. The proposed design for three scales of lab, pilot, and commercial field project. Redrawn from Zhang 2014.

5. Challenges and Economic Issues

Generally, due to the high-cost chemicals, these techniques are not suitable when the price of crude oil is less than $40/bbl. For instance, Pope reported the surfactant cost has decreased by a factor of 5 (from $18.21 to $3.64 per barrel of oil) between 1993 - 2015 (University of Texas at Austin's Webinar, 2015). In this regard, the cost of chemicals has decreased due to the technology enhancements and an increase in the popularity of using these materials (i.e., the economy of scale). Despite the cost efficiency of surfactants, surfactant-based technologies are not used as widely as water flooding or polymer flooding. There are only limited numbers of reports regarding the price and economics of surfactant flooding operations. The next section discusses some challenges that may impact the process efficiency.

5.2. Cost of CEOR Operations

5.2.1 Economic Reports

The economic analysis of CEOR operations is not well-discussed in the literature. Hence, in this section, we look into published data for the cost of CEOR implementation. (Henthorne et al. 2014) emphasized that water quality has a great influence on project economics. In their studies, they mentioned seven water variables that impact injectivity and project performance: salinity, hardness, oxidizing agents, reducing agents, microbial agents, free radicals, and total suspended solids. Also, they provided a table that mentioned the cost of different CEOR agents and associated materials such as HPAM, high-temperature polymer, co-solvent, soda ash, seawater softening, produced water softening, alkali-co-solvent-polymer, and alkali-surfactant-polymer. Two important pieces of information that can be used for the initial economic evaluation, the amortization rate of CAPEX and the amortization period are also available in that report.

The second report about the cost of CEOR operations based on numerical simulations is presented by Al-Murayri et al. 2018c. They reported three CEOR methods which comprise the surfactant, SP, ASP, and equally discussed several production scenarios. Water and polymer injection at different volumes were investigated and the total cost of each scenario was reported. The oil cut for three different pilot sizes was reported (2.2, 3.6 and 5.4 MMbbls). Incremental chemical flood costs varied from $18/bbls to $44/bbls depending on the size of the project. The more technical aspect of economically feasible studies can be found in Al-Murayri et al. 2018c, 2019c, 2020a.

Table 2
Redrawn the proposed workflow of Armacanqui et al. From Armacanqui et al. 2017.

Phase	Stage	Data mining	Laboratory Workflow	Simulation	Field Test	Field Application	Accuracy of Economics
Start	Pre-Screening	EOR Screening Tables					(+/-)100%
		EOR Screening Software					(+/-)80%
		Run Simulation					(+/-)75%
Phase I	Stage I	Input Data SCAL/Fluids/PVT EOR Screening	SCAL of Well in Area of Interests, EOR SCAL, Wettability	Calculation and Pre-simulation Runs			(+/-)80%
	Stage II		Chemical Compatibility Core Flood Experiments	Core Flood Simulation			(+/-)50-70%
	Stage III			Simulation of Pilot Simulation of Sector			(+/-)40-50%
Phase II	Stage I Stage II			Refine Test Simulation	Pilot Test SWCTT Pilot Test Injection-Production		(+/-)20-30%
Phase III	Stage I			Refine Sector Modelling	Multi-well Test		(+/-)10-20%
Implementations						Multi-wells	(+/-)5%

The next report belongs to Dean et al. 2018 who provided the cost of both gas and chemical injection. The cost of SP and three ASP formulations using different alkali agents (NaOH, Na2CO3, NaBO2) was reported. Also, since the report provided details of gas injection, readers can bring gas and CEOR technologies into comparison.

Additional information about improving CEOR economics by optimizing water quality and composition can be found in Henthrone et al.2011's report. The economics of different chemicals were compared through water optimization by sulfate removal, water softening (reduce divalent cations), and lowering salinity. This report provides the economics of hybrid EOR methods such as low salinity surfactant or low salinity polymer flooding. Al-Ghnemi et al. 2018 reported relevant information to de-risk CEOR processes. They presented default value, lower limit, and upper limit of various economic and technical parameters which can affect the risk of CEOR projects. Table 3 summarizes the information from the report.

According to their CEOR risk analysis, "loss of production due to aquifer intrusion" and "oil price crash" were reported to be the highest potential risks. Another concern associated with CEOR is produced by fluid separation (Kaiser et. al.2015). Compared to gas-injection or thermal methods, CEOR operations require additional steps for separating water, produced oil, and emulsions. This step can increase the total OPEX.

5.2.2. Enhanced Oil Production Per Chemical (EOPPC)

Another useful tool for the economic evaluation of CEOR operation is the Enhanced Oil Production Per Chemical (EOPPC). Zhou et al. 2017 proposed an approach to consider both technical and economic aspects of CEOR operations. In their formulation, SP flooding was considered; however, the concept of EOPPC can be extended to other chemical agents like alkali or gel. EOPPC is defined as SP flooding as:

$$EOPPC = \frac{\Delta Q_o}{V_\varphi D_p C_p + V_\varphi D_s C_s \frac{r_s}{r_p}} \tag{3}$$

where ΔQ_o, V_φ, D_p, C_p, D_s, C_s, r_s, and r_p are incremental oil production by SP flooding, pore-volume, polymer slug size, polymer concentration, surfactant slug size, surfactant concentration, price of surfactant, and price of polymer, respectively. EOPPC can be reported as a function of liquid flow rate (before, during, and after chemical flooding), chemical concentration (polymer or surfactant), well pattern, and well spacing. The EOPPC unit is defined as a cubic meter per ton. Figure 7 gives an example of EOPPC vs. polymer concentration for different oil viscosities.

Table 3
Example of economics parameters for CEOR projects. Redraw from Al-Ghnemi et al.2018

Expenses due to	Parameter	Default Value (USD)	Lower Limit (USD)	Upper Limit (USD)
	Oil Price, $/bbl	50	30	100
Process	Lifting cost, $/bbl	0.85	0.50	1.20
	Water handling, $/bbl	0.05	0.02	0.08
	Water injection, $/bbl	0.10	0.05	0.15
	Water softening, $/bbl	0.50	0.30	0.70
Materials	Alkali, $/lb	0.15	0.05	0.30
	Surfactant, $/lb	1.18	0.6	1.80
	Polymer, $/lb	1.23	0.8	2.00
Equipment	Injector, $/well	3,000,000	2,000,000	4,000,000
	Producers, $/well	4,000,000	3,000,000	5,500,500
	Chemical Facilities, $	40,000,000	30,000,000	50,000,000

5.2.3. Equivalent Utility Factor (EqUF)

(Schumi et al. 2020) showed Equivalent Utility Factor (EqUF) as another economic parameter to evaluate and compare the cost of CEOR formulations. Equation 8 shows the mathematical description of the EqUF:

$$EqUF=\frac{\left(\frac{m_P\times C_p+m_{CS}\times C_{CS}+m_A\times C_A+.....}{C_p}\right)}{(N_{Pinc})} \quad (4)$$

where m is the injected mass in kg of the individual components, C is the cost of a component in USD/kg, and NPinc is the incremental oil recovery in bbl. Subscripts are P for polymer, CS for cosolvent, and A for alkaline. If more chemical components are used—e.g., a surfactant—the equation should be extended to n components. Also, the unit of the EqUF is kilogram per barrel and can be calculated from laboratory core floods. Figure 8 shows an example of EqUF for different chemical formations.

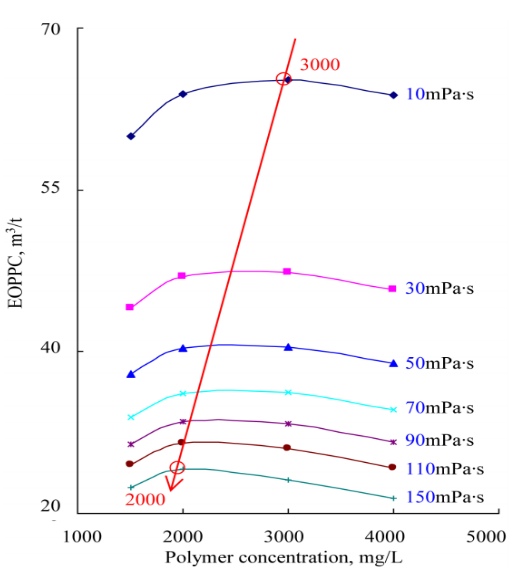

Figure 7. Example of EOPPC for economic and technical evaluations of CEOR processes. The optimum chemical concentration (or highest EOPPC) varies with reservoir properties. The red arrow shows 3000 and 2000 mg/L of a polymer as the optimum concentrations for crude oils with 150 and 10 mPa.s viscosities, respectively. From Zhou et al. 2017.

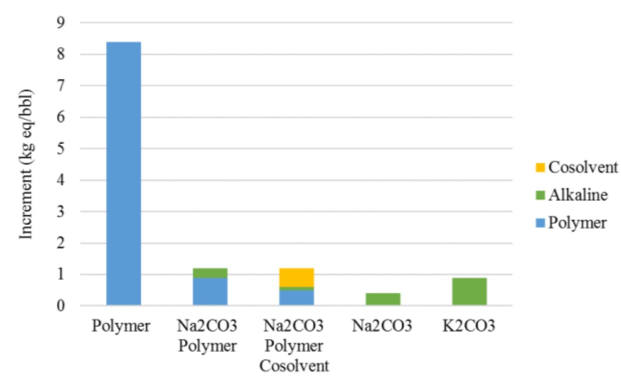

Figure 8. Determined EqUF for different chemical formulations. From Schumi et al. 2020.

5.3. Simulation and Modelling Challenges

5.3.1 Modelling tools

Numerical simulation and studies are essential parts of CEOR projects due to the higher cost of CEOR operations compared to water flooding. It is, therefore, important to have models to more accurately predict the performance. However, due to complexity and associated uncertainties, modelling CEOR floods has unique challenges. It was noted by Najafabadi and Chawathe 2016 that from an economic point of view, CEOR operations are performed on the reservoirs that have a successful water flooding history. The authors mentioned the following challenges for modelling CEOR projects namely: choice of the appropriate sector size, boundary conditions (fluxes and pressures), injectivity (especially for polymer flooding), data integration, slug design, and optimization. This information should be reported and updated for small-scale pilots. Graham and Frigo 2019 discussed other challenges related to the operations, such as corrosion, souring, emulsion, scaling, injectivity decline, and induced-fracture extension that all need to be modelled.

Goudarzi et al. 2016 performed a benchmark study of available reservoir simulators for CEOR and compared different processes for UTCHEM, CMG, and Eclipse-E100 (based on versions available in 2016). Table 4 gives a summary of the comparative study.

Table 4
A summary of the benchmark study of different reservoir simulators. From Goudarzi et al. (2016).

Surfactant Module	UTCHEM	GMS-STARS	ECLIPSE
ME Viscosity	√	Not Included	Not Included
Interfacial Tension	√	Included (Tabulr Format)	Included (Tabular Format)
Phase Behavior	√	Not Included	Not Included
Surfactant Adsorption	√	√	√
Ion Exchange Effect	√	√	√
Effective Salinity Window	√	Not Included	Not Included

Lashgari et al. (2019) presented recent improved models for UTCHEM, such as relative permeability, capillary pressure, the effect of pH on surfactant adsorption, etc. More recently, Fernandes et al. (2019) demonstrated four case studies of polymer and surfactant flooding for large field-scale projects considering adaptive implicit framework for UTCHEMRS simulator.

Furthermore, in order to obtain the optimum design of CEOR operations, we refer to the report by Delshad et al. 2015. In that study, the authors used numerical reservoir simulator, economic model (cash flow analysis), experimental design, response surface methodology, and Monte Carlo algorithm.

More applications of polymer flooding, surfactant flooding, and ASP flooding with CMG simulators are reported in (Pandy et. al.2008, Dukeran et al, 2016, Ghedan et. al.2016, Aslam et al, 2017, Wang et. al.2017, Izadi et. al.2018).

5.3.2 Application of Artificial Intelligence for CEOR operation

Artificial intelligence (AI) and machine learning is becoming one of the most powerful tools for solving the real-world problems and detecting patterns in global scale. Reported by (Alem et al. 2021), AI can be classified into 7 techniques as decision tree, support vector machine, self-organizing map, Artificial neural network, particle swarm optimization, random forest, genetic Algorithm, K- Nearest neighbor.

Among these techniques, an artificial neural network (ANN) is a powerful tool for recognizing the most reliable pattern between input and output without the need for an implicit programming (Abdullah et. al. 2019). This technique enables researchers to solve nonlinear problems faster and is very efficient for computational investigation of compositional models required for simulation of CEOR processes. However, the available CEOR data for data-driven modelling are limited (Cheraghi et al. 2021). Results of our survey show examples of ANN in CEOR in (Al-Dousari and Garrouch 2013, Alghazal 2015, Ahmadi 2015, Abdullah et. al. 2019).

More recently Idogun et al. 2021 reported a comparative analysis of data-driven on Recovery Factor (RF) for Surfactant-Polymer flooding. Seven input variables, such as Kv/Kh ratio, polymer concentration in polymer drive, surfactant slug size, surfactant concentration in surfactant slug, polymer concentration in surfactant slug, polymer drive size and salinity of polymer drive were considered. Eleven Machine learning models were applied on a data set (202 datapoints) and the results revealed that Support Vector Regression, ANN, and Classification and Regression Tree based ensemble techniques had the high R2 values and lowest Mean Squared Error values for the training and test dataset. Also, surfactant concentration and slug size were the most influential parameters.

Furthermore, predicting the physicochemical crude oil properties such as the equivalent alkane carbon number (EACN) by machine learning can be found in Creton et al. 2019. This information indicates that the development of new tools, such as machine learning, artificial intelligence, and the artificial neural network will reduce the uncertainty associated with CEOR operation and forecasts. Meanwhile, these tools are also increasing the computational complexity of CEOR models and are viewed as new R&D topics for academic and research institutes.

The flow and transport of injected chemicals in porous media, rate of injection and production, adsorption, and stability of chemicals at reservoir conditions should be carefully monitored during the entire field execution. Design and examination of CEOR surveillance program include three elements which are: monitoring techniques, measuring points, and frequency of data acquisition (Yznaga et al. 2019). In general, there are two surveillance approaches: deliverability control and quality control. During the first approach, the surveillance program is designed to ensure that chemical fluids are delivered into injection wells properly. The main objective is to confirm that the desired chemical formulation is delivered at the injection point (well) as it was designed in the laboratory-scale studies. The equipment/facilities which should be monitored are chemical storage, chemical dissolution units, mixing locations, pumping location, water supply units, and transportation units including pipelines and tubing that can handle the chemical composition of injection fluids. Meanwhile, for quality control surveillance, it is necessary to consider the following items: operational conditions of production and injection wells (such as temperature, rates, pressure, precipitations, etc.), saturation profiles, sweep efficiency profile including mobility control and sequences of injected fluids, the efficiency of observation and sampling wells, produced fluids quality and efficiency of chemical fluids. The reliability of data acquisition is crucial for CEOR operations.

Moreover, there are five classes of data gathering tools; downhole gauge data, surface gauge data, well-test data, allocated volumes, and laboratory tests. Accuracy, reliability, validation, and reconciliation of data should be discussed in CEOR plans. Furthermore, the cost of installation, maintenance, and repair of surveillance equipment should be considered in the overall project economics. For more details, please refer to Yznaga et al. 2019 and Saputelli et al. 2010.

Volokitin et al. 2017 discussed the pilot surveillance program including estimation of chemical efficiency, evaluation of residual oil saturation (before and after the chemical injection), chemical retention, and dynamic reservoir model calibration. Wellhead fluid sampling seems to be the best surveillance method that can accomplish all of the aforementioned tasks. Various surveillance methods are discussed in Volokitin et al.'s report.

Jain et al. 2020 reported the pilot design of ASP flooding for an onshore field in India. Their report includes chemical formulation development, pilot area selection, well and pattern type, slug size and sequence, slug viscosity, etc. They provided a twelve-step guideline for reservoir management and surveillance plan which can be used as a template for other field operations.

Although various research studies give an overview of CEOR operations, the majority failed to discuss facility requirements. Broadly, researchers focused on chemical formulations and blending chemical agents to design the most effective injection fluids. However, to scale up from laboratory to field operations, it is necessary to have sufficient information about the additional facilities. In this regard, an example is a paper written by (Chang et al. 2013).

The important information is in four flow diagrams illustrated for; surfactant, polymer, ASP, and soda ash units. The flow diagrams can help with the design and installation of facilities. It was noted that Canada, Oman, India, and China are the leading countries for the full-field implementation of polymer flooding. The importance of HSE issues and standards are also discussed. (Du et al. 2011) presented full-field development facilities for offshore St. Joseph's ASP project in Malaysia. Additional information which includes the cost of facilities, CAPEX, OPEX, and economic parameters was investigated by Al-Murayri et al. 2019d.

6. Standardization of Performance Metrics

Another barrier to proper deployment of CEOR operations is the type of data collection/output. We reported the following templates for reporting the results.

61. Dimensionless Plots

The dimensionless curve is a standard output for CEOR operations. A summary of optimized scenarios has been reported by (Qiang et al. 2013) for polymer, SP, and ASP technologies. This plot is a schematic of dimensionless curves with recovery factors of different EOR methods normalized based on water flooding and the normalized recovery factor as a function of hydrocarbon pore volumes injected. The recovery factor as a function of the hydrocarbon pore volume is the most common information for EOR projects whereas total pore volume injected is most customary for CEOR projects.

6.2 Surfactant Formulation Sensitivity Graphs

In the previous section, we discussed the importance of the Winsor sensitivity graph for the evaluation of the surfactant formulation. We suggest an extended version of the Winsor graph reported by Al-Murayri et al. 2018a where aqueous solubility map and static adsorption can be reported.

6.3 Alkali-based Graphs

The third standard output is the alkali-based graphs used by Ibrahim et al. 2006 These graphs can provide phase-type, IFT, aqueous phase coloration, Winsor Type III region as a function of alkali concentration. This plot gives the IFT change as a function of alkali concentration for different chemical solutions and phase-type. They can be put together to form a comparative visualization tool for comparing different chemical formulations.

6.4. IOR-EOR Potential Plot

Noted by Du et al.2011, IOR-EOR potential curves are used to evaluate the ultimate recovery of different EOR methods. They can also be used for comparative research; however, these curves do not provide any information regarding the chemical properties of the formulations being employed.

6.5. Time-dependent Recovery Factor Plot

Time-dependent recovery factor (RF) curves are used for the standardization of CEOR operations. As it was demonstrated by Sandoval et al.2010, time-dependent RF curves are the most beneficial output for comparing different CEOR floods. The advantage is the inclusion of project time to help with project economics.

6.6. Displacement Efficiency Plot

As explained by (Al-Murayri et al.2018b), the overall displacement efficiency of chemicals, such as ASP is plotted as a function of the amount of surfactant. This is the sixth output data to provide insights into the performance of different CEOR operations. The benefit of this sort of report is that the overall displacement efficiencies for both well and core scale may be presented.

6.7 Activity Map

Fortenberry et al. 2015 reported the results of various EOR technologies and used the UTCHEM chemical flooding reservoir simulator to evaluate mobility control in chemical flooding of heavy oils. They used the activity map based on salinity scans of surfactant mixtures at different water-oil ratios (WOR). The activity maps provide critical information for the ASP flooding of active oil where the phase behavior is a function of the amount of oil or *in-situ* soap generated. The optimum formulation attempts a balance between synthetic hydrophilic surfactant(s) and hydrophobic natural soap to make the activity map relatively flat as a function of WOR.

7. Scale-Up of Large Field Projects

(Barnes et. al.2018b) explained chemical solution techniques for lowering the viscosity of high active matter surfactant concentrations. They explained three methodologies for improving the delivery and handling of chemicals during field developments: engineering, blending, and chemical solutions. In the first approach shear rate and temperature are increased, in the second, a series of surfactant chemicals are blended, and the ultimate methodology uses a chemical additive to reduce the viscosity of the final blend. Another challenge discussed by Barnes et al. is the cost of delivery of different chemical products from several manufacturing plants to the field sites. Based on the size of the project, choosing an effective transport option and the activity of chemicals may have a significant impact on the overall project economics. Table 5 highlights the recommendations by Barnes et al.

Table 5
Chemical delivery options based on Barnes et al. From Barnes et. al.2018b.

Scope of The Projects	Recommendation
Small Field Projects	Ship less concentrated products
<30% of Active Matter	55-gallon drums or 275 gallons of intermediate bulk containers
Intermediate to Large volume Projects	Manufactured produced can be shipped
30%<Active Matter<65%	to the field through road, Rail or Ship.
	20-ton ISO-Tanks
Large Projects	Manufactured products should be in the country, region, and near the field
>65% Active Matter	

It is worth mentioning that Internal Olefin Sulfonates and branched Alcohol Alkoxy Sulfates were mentioned as the available surfactants at the commercial scale. For further details, we refer the readers to (Barnes et. al.2015, 2016, 2018, 2018b). However, there have been changes in Shell Chemicals' strategy where they discontinued the production of some of the IOS surfactants and only provide the feedstock for a limited time.

Barnes et al. 2016 also presented information critical for large-scale deployment where 100 to 10,000 tons of surfactant requires rigorous QA/QC procedures. They presented six steps of QA/QC methods including hydrophobic production, pre-large-scale production of surfactant, large-scale production of surfactant, subsurface performance check, QA/QC surfactant concentration at injection facilities, QA/QC of SP/ASP blend at injection facilities. The laboratory tests for surfactant composition, subsurface performance, handling at the facilities, and reliability of data and specifications were key elements for quality control in upscaling the CEOR projects. Quality surveillance is crucial for the successful implementation of CEOR operations. We refer to a seven-stage quality control process proposed by Barnes et al.2016b. The proposed protocol enables operators to check both individuals and blend of chemical components.

As stated by Shaharudin et al. (2013), four questions should be answered in any full-field CEOR implementation and execution namely, (1) the residual oil saturation to chemical flood, (2) level of IFT reduction, (3) amount of chemicals adsorbed/retained, and (4) the trapping number and oil mobilization. Chemical retention is explained by three mechanisms of precipitation, adsorption on reservoir rock minerals, and phase trapping in surfactant flooding. The activation of these mechanisms can determine the amount of remaining oil saturation after the chemical flood . Moreover, residual oil saturation due to water or chemical flood can be investigated by four methods; linear coreflood, radial coreflood, single-well chemical tracer test, and numerical simulation. Other questions raised for full-field implementation based on (Sabzabdi et al. 2014) are: What is the size of injection slug and the optimum time to start the chemical injection? The answer to each of these questions will clarify the scope of the projects. To answer the above questions, we refer to the correlation matrix proposed by Sieberer et al. 2018. The matrix is used to determine the effects of various parameters on the NPV as the objective function. The correlation matrix also shows correlation coefficients between sets of variables with the greatest influence. Chemical concentrations, injection rate, injection duration, well distance, cumulative oil, and cost of operation are parameters that can be used in the correlation matrix.

8. The onset of CEOR Projects

The timing of project start-up is another major challenge due to the complex phase behavior of surfactant formulations and chemical supplies. Different reports address the timing for EOR operations (Jerauld 2000, Sayavedra et. al.2013, Gao et al, 2014, Aitkulov and Mohany 2016). Here we use the 5-year EOR cycle of Gheniem et al. 2017. In their paper, a 5-year cyclic road map was suggested by considering the conceptual design, pilot design, well campaign, facility installation, surveillance and monitoring, pilot expansion, full-field development plan, and reserves and final investment decision. It is important to consider the following aspects, optimized chemical formulation, location of the injector(s), and crude oil price.Thus, the economics of the project depends on the timing of the operation. For example, Li et al. 2019 presented the timing of different injection scenarios. Figure 9 shows the timing of ASP injection and the oil price forecast of different designs.

This information indicates that there is a meaningful relation between timing, economics, simulation, and chemical formulation optimization. Jabbar et al. 2017 provided practical information such as parametric studies, pilot proposal, shareholder endorsement, the potential of SWTTs and pilots' implementation. Figure 10 shows the evaluation process reported by Jabbar et al. 2017.

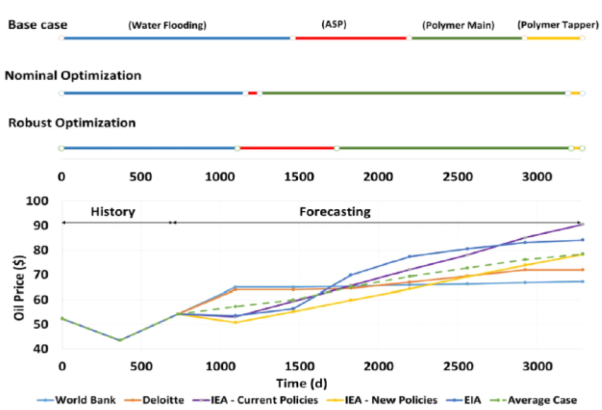

Figure 9. Three different scenarios as a function of time and oil price reported by Li et al. From Li et al. 2019.

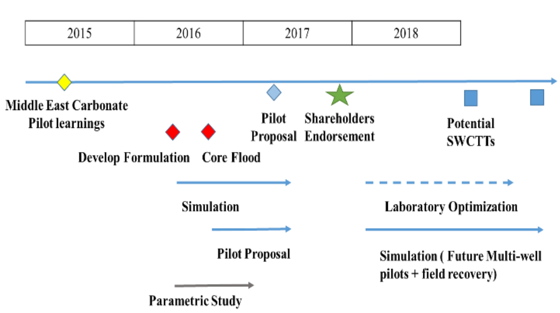

Figure 10. CEOR evaluation chart time reported by Jabbar et al. Redraw from Jabbar et al. 2017.

9. CEOR Environmental Impacts

The scope of CEOR operations is vast. Hence, there is a potential to combine them with other EOR methods such as thermal and gas methods for a wider range of reservoir and oil properties. However, compared to the other EOR methods, CEOR operations are more sensitive to reservoir conditions such as salinity, temperature, and mineralogy. The final challenge of using a chemical is the environmental impacts discussed in the following section.

Although CEOR technologies have their remarkable benefits, they also have the potential to cause formation damage due to fluid-fluid incompatibility, rock-fluid interactions, mechanical, thermal, and biological damages (Yuan and Wood 2018). Chemical flooding such as SP and ASP can result in inorganic and organic depositions, foam/emulsion generation, hydrates, clay swelling, wettability alteration, and ionic molecular adsorption.

Furthermore, Sheng 2016 has reviewed the damages caused by CEOR methods. In that context, formation damage refers to any process that reduces the flow capacity at the reservoir scale. The following can cause damages that have been noted in Sheng's review; clay release and fines migration, polymer particles/liquids, plugging, adsorption, produced water, gelant (gelling agent) placement, surfactant or alkali injection, emulsions, and a combination of these. However, what is important for academia and R&D organizations is before any field implementation they have to include a formation damage evaluation in the field development plans.

10. The Proposed workflow

The most difficult task and contradicting step is when to start the CEOR operation, planning, design, and optimization. An example of appropriate CEOR planning is given by Wong et al. (2016). They considered three phases for CEOR in Powder River Basin Field, Wyoming. These phases are applicable to any CEOR operations. The three phases consisted of 32 tasks, where the details of tasks include, the workflow, team members, and the duration and predecessors of each task were reported. Additional details such as field history and project economics were discussed.

There is one additional reference that can be used as a planning framework presented by Delshad et al. 2015. They performed sensitivity simulations to determine physical parameters and optimization of surfactant slug size and concentrations for two oil reservoirs. They introduced four tasks as the development of uncertainty modules and experimental design models, reservoir simulation, and response surface model, economic analysis, and field-scale studies. Other useful information included the composition of surfactant slug, polymer drive, brine compositions, chemical price, capital, and operating costs, taxation rates and net present values. Also, we recommend readers to pay attention to the important sensitivity variables highlighted in this work. Due to high cost, complex phase behavior, sensitive chemical agents, and the large degree of uncertainties, the results of field pilot tests are determining factors to proceed to commercial-scale execution. As noted earlier, CEOR processes are applicable to both secondary and tertiary stages. Hence, waterflood results and operations can be used to aid in a better design of CEOR operations. Hence, we introduce nine steps to design a full-field implementation in Fig. 11.

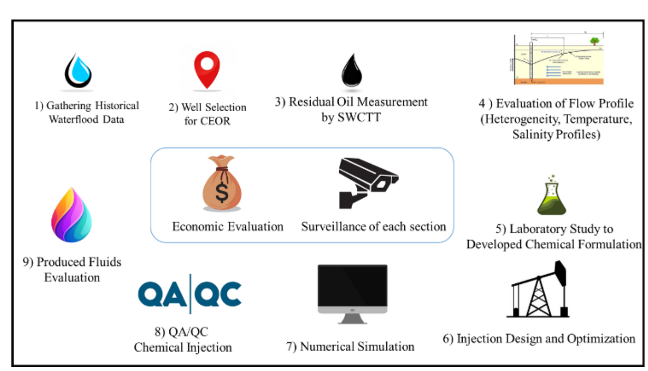

Figure 11. Nine-steps of CEOR pilot design.

It is critical to have access to historical water flood results to select the candidate wells; readers can refer to screening criteria of well selection of Seccombe et al. 2008 (steps 1 and 2 in Fig 12). Several chemical tracer tests must be conducted to evaluate flow patterns, well-well connectivity, sweep efficiency, residual saturations, wettability in the candidate area (i.e., single well, interwell conservative, and interwell partitioning tracer tests). Temperature and salinity profiles should be described precisely due to the sensitivity of the chemical agents (steps 3 and 4). Next, a series of laboratory tests are conducted to develop and finalize the best chemical formulation for the given reservoir. Phase behavior, IFT, contact angle, and dynamic core floods and micromodel flooding are the most common lab tests (step 5). Once the best chemical formulation is obtained, the sequence of injection fluids should be designed based on the reservoir permeability and heterogeneity (step 6). An example of the proposed injection sequence is in (Al-Murayri et al. 2018d)'s reports with three possible scenarios; very optimistic, optimistic, pessimistic scenarios.

The obtained scenarios will be further studied using reservoir simulators with a series of sensitivity analyses (step 7). Once the optimized scenario is selected, it should be considered for the field implemented. AI and machine learning techniques can reduce the computational cost of this step. Here we are assuming that injection and monitoring facilities are already available for the pilot locations. After the pilot execution, produced fluids should be analyzed and use the results to update all of the aforementioned steps especially numerical models, including economic evaluation, and surveillance operations (steps 8 and 9). Also, the sequence, data, and information of the single-well chemical tracer test (SWCTT) of (Al-Murayri et al. 2017c, 2018d, 2018f)'s reports can be used as a template.

11. Conclusions and Recommendations

We presented a comprehensive review of practical considerations such as several screening tools for ranking and selection of CEOR projects and their challenges to scale up from laboratory to pilot to full-field implementations.

This paper aims in decision making to achieve the optimum design, implementation, and evaluation at both laboratory- and field-scale by providing references.

The following recommendations and conclusions are provided based on this review study:

• Optimum formulation and the corresponding salinity based on pipette tests is the keystone of the surfactant based EOR methods. Water composition is critical for assessing the profitability of CEOR methods. Monovalent ions, divalent ions, ion exchange, reaction kinetics, neutrality, and total dissolved solids of injection water, produced water, and formation water is required for each project.

• There is a substantial financial risk, challenges, and uncertainties with the operation of these projects and chemical manufacturing. In general, operators face more risks than chemical suppliers.

• We have reviewed different CEOR technologies and their screening criteria with a structured approach to address practical considerations for field implementation. Foams, emulsions, low tension gas, and nanoparticles are some relatively new materials that need additional pilot studies.

• Screening guidelines need to be up to date and include recent field studies and new hybrid methods. Screening tables need to provide the source of information i.e., lab tests, numerical simulations, analogs, expert opinion, etc.

• Reservoir ranking and recognizing, gauging, and managing uncertainties/risks associated with the subsurface is critical for field development plans. Figure 3 is a good example of field deployment risk and uncertainty analysis.

• It is customary to conduct comprehensive laboratory tests in the feasibility stage consisted of four steps: 1) rock sample and fluid characterization, 2) chemical selection and design, 3) process evaluation and design and 4) optimization and robustness. Significance of capillary desaturation, injection parameters, and chemical formulations can be evaluated by dynamic core floods and novel macro models.

• Access to reliable historical field data and industrial experiences is the key barrier to the deployment of CEOR operations. R&D companies must provide a data bank for their project. Data gathering, data mining, and big data investigations should be integrated into commercial-scale field development plans for major oil and service companies such as Shell, BP, Chevron, Schlumberger, etc. In addition to technical results, we provided information on project economics that can be used as a template. There are additional costs for produced fluid separation and treatment.

• The concepts of EOPPC and EqUF are useful tool for a comparative study of various chemical formulations and obtains the optimum formations with their costs. A combination of Macro models, EOPPC, and EqUF evaluations gives more insights to managers regarding pilot test performance.

• Numerical simulation studies are essential for project design, optimization, and forecast. Additional tools like artificial neural networks (ANN) and machine learning can improve the resolution.

• Surveillance programs and facility monitoring are essential. The degree of complexity of the reservoir, the location of facility installation, type and volume of the chemicals among others greatly will impact the performance.

• Project scale-up, scope, and the onset of CEOR injection are activities that rely on the experience of managers and operators. The managers can use the nine-step flow chart that we introduced here. Facility flow diagrams, hybrid materials, and standardization of performance metrics can be obtained from previous experiences. Design, operation, and surveillance intensively depend on CEOR experiences of asset managers, engineers, and field operators.

• The environmental impact has to be addressed due to the policy of the country where the fields and operators are located.

List of Abbreviation

ACP Alkali, Co-solvent, Polymer
ANN Artificial neural network
AOR Amount of oil recovered
ASP Alkaline surfactant polymer
CAPEX Capital expenditure
CDG Colloidal dispersion gels
CEOR Chemical Enhanced oil Recovery
DME Dimethyl Ether
EACN Equivalent alkane carbon number
EOPPC Enhanced Oil Production Per Chemical
EOR Enhanced oil recovery
EqUF Equivalent Utility Factor
GOR Gas-Oil Ratio
HPAM Hydrolyzed Polyacrylamide
HSE Health, Safety and Environment
HTHS High-temperature high-salinity
IFT Interfacial Tension
IOC International Oil Company
IOR Improved oil recovery
LSWF Low Salinity water Flooding
LTG Low Tension Gas
NOC National Oil Company
NP Nano Particle
NPV Net Present Value
OPEX Operational expenditure
PPG Performed Particle Gel
QA/QC Quality Assurance, Quality Control
R&D Research and Development
RF Recovery Factor
SWCTT Single Well Chemical Tracer Test
UTCHEM University of Texas Chemical Flooding Simulator
WOR Water-Oil Ratio

Authorship contribution statement

Alireza Bigdeli: Drafting the manuscript and designed the figures - Data collection and information - Performing the analysis and developing the theoretical framework; **Mojdeh Delshad**: Supervision of the work - Reviewing the manuscript preparation, Reviewing, and modifying the developed theoretical framework.

Both authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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