scientific reports

Check for updates

OPEN

Updated screening criteria for enhanced oil recovery methods and their application to the T oilfield in eastern Mongolia

Anuudari Arvis & Baehyun Min✉

Enhanced oil recovery (EOR) plays a vital role in maximizing oil production from depleting reservoirs. As EOR technologies advance, updating screening criteria is essential to evaluate and recommend suitable EOR methods for target reservoirs. This study aims to establish updated screening criteria to identify the most effective EOR methods based on specific reservoir characteristics. A structured selection approach facilitates the evaluation of advanced EOR technologies to ensure the suitability for particular reservoirs while optimizing recovery processes and improving overall efficiency. To demonstrate this approach in practice, we present a case study using field data collected from the T oilfield in Mongolia. The estimated recovery factor based on primary and secondary recovery is in the range of 10% to 17%. Therefore, the field development plan considers the application of EOR to the T oilfield. An integrated methodology that combines EOR screening with score assignment is applied to provide a comprehensive evaluation of potential EOR technologies. The results show that the miscible carbon dioxide (CO_2) injection, miscible hydrocarbon (HC) injection, and immiscible nitrogen (N_2) injection methods have the highest scores without any violation of criteria. This approach ensures a thorough selection process by considering various technical factors relevant to reservoir characteristics and aligning with the study's objective. The case study demonstrates the effectiveness of the proposed screening criteria in real-world scenarios and offers valuable insights for operators selecting EOR methods under similar conditions.

Keywords Enhanced oil recovery (EOR), Screening criteria, Score assignment, T oilfield in mongolia, Reservoir evaluation

Enhanced oil recovery (EOR) includes advanced techniques that were designed to extract additional oil from reservoirs once conventional methods can no longer sustain production[1]. As technologies evolve and sustainability becomes a priority, EOR remains a crucial focus in energy research and application[2]. The advancement of EOR technologies has led to the widespread adoption of screening as a method for identifying and ranking the most suitable EOR techniques based on specific reservoir characteristics[3]. A well-structured screening process enhances the accurate evaluation of EOR potential, increasing reservoir value while reducing development risks[4].

EOR has been widely employed in oilfields with low production rates caused by high water cuts despite significant remaining oil saturation[5]. EOR methods are categorized based on the type of displacing fluids into gas flooding (miscible or immiscible), chemical flooding, thermal flooding, and microbial flooding[1]. Each category includes different techniques that were designed to improve recovery efficiency based on specific reservoir conditions. Gas flooding is further classified into miscible and immiscible methods. Miscible gas flooding injects gas that fully mixes with oil, reducing its viscosity and improving flow[1,6], while immiscible gas flooding uses gases that do not mix with oil but assist in displacement by maintaining pressure or driving oil through gas expansion mechanisms[3,6]. Chemical methods involve injecting surfactants, polymers, or alkaline surfactant polymer (ASP) to modify the properties of oil or reservoir rock, improving oil recovery[2,7]. Thermal methods apply heat to reduce oil viscosity and facilitate extraction, with common techniques including hot water injection, steam injection, and combustion[8]. Lastly, microbial methods use microorganisms or their byproducts to enhance oil recovery through biochemical processes[9–11].

Department of Climate and Energy Systems Engineering, Ewha Womans University, 52, Ewhayeodae-gil, Seodaemun-gu, Seoul 03760, Republic of Korea. ✉email: bhmin01@ewha.ac.kr

The selection of EOR processes depends on specific crude oil properties and reservoir conditions, with the primary goal of maximizing recovery while taking into account both economic and environmental factors. Miscible gas flooding is particularly effective for light crude oil, as it involves injecting gases such as carbon dioxide (CO_2) or hydrocarbon (HC) gases that mix with the oil, thereby reducing viscosity and improving mobility[12]. Chemical processes have also been effective for light crude oil by improving both displacement and sweep efficiency[13]. In contrast, thermal processes are primarily used for heavy crude oil because they significantly reduce viscosity, utilizing mechanisms such as oils, which makes extraction easier[13–15]. Microbial EOR applies fundamental chemical principles, utilizing mechanisms such as interfacial tension (IFT) reduction, emulsification, wettability alteration, mobility ratio enhancement, selective plugging, viscosity reduction, oil swelling, and increased reservoir pressure due to gas formation[14,30]. This comprehensive understanding of EOR techniques underscores the need for tailored approaches that align with the specific reservoir characteristics and crude oil types.

A structured table format for EOR screening is essential for maximizing oil extraction from reservoirs. It enables efficient comparison of multiple reservoir properties against predefined criteria for various EOR methods. This approach allows for the rapid identification of suitable techniques based on factors such as rock properties (e.g., porosity and permeability) and fluid properties (e.g., gravity, viscosity, and saturation). Furthermore, a structured table format facilitates the simultaneous evaluation of multiple reservoirs, which helps oil companies prioritize their EOR efforts across their asset portfolios.

A notable example is the EOR screening criteria table developed by Taber et al. (1997a)[18], which incorporates nine reservoir properties across twelve EOR methods. This tabular format provides a comprehensive framework for evaluating and selecting suitable EOR technologies for a given oilfield. By structuring complex data in a clear and accessible manner, these tables help engineers and geologists make well-informed decisions when assessing EOR implementation for specific reservoirs. Building on this approach, Dickson et al. (2010)[13], Adasani et al. (2011)[5], and Hartono et al. (2017)[16] derived average reservoir properties to enhance the robustness of screening and reservoir evaluation frameworks for EOR methods. The use of average values not only improves the standardization of input data but also simplifies the comparative analysis of different EOR techniques.

Furthermore, these studies introduced the concept of defining lower and upper limits for the reservoirs property relevant to a given EOR method. This systematic approach saves time and minimizes the risk of overlooking viable EOR candidates, which ultimately supports more informed decision-making and better resource allocation in EOR projects.

This study updates EOR screening criteria by integrating insights from multiple researchers over the past four decades[5,13,15–26]. The revision process carefully evaluates rock and fluid properties, which broadens the applicability and effectiveness of EOR methods. The updated criteria enable engineers to assess field feasibility at an early stage, providing improved guidance for subsequent evaluation phases. A case study of the T oilfield in Mongolia is presented to illustrate the practical application of the updated screening criteria. Exploration of the T oilfield began in 1991 and reached the appraisal stage in 2011. According to the Mineral Resources and Petroleum Authority of Mongolia (MRPAM), its proven reserves are approximately 150.13 million barrels or about 21.018 million tons[27]. The case study evaluates various EOR methods, including gas injection, chemical flooding, thermal recovery, and microbial flooding, to identify the most suitable approach for this reservoir. By applying these comprehensive screening criteria and assigning scores to EOR methods, this study aims to establish a more robust framework for selecting effective techniques, ultimately enhancing oil recovery and optimizing resource utilization.

Screening of EOR technologies

The screening of EOR processes is essential for identifying the most effective and economically viable techniques suited to specific reservoir characteristics and project objectives. Various authors and institutions have developed screening guidelines and criteria to support the successful implementation of EOR methods, including those established by respected organizations such as the Society of Petroleum Engineers (SPE)[13,15,16,18,21,24]. In addition to academic research and documented case studies, these resources offer valuable insights and practical examples drawn from real-world EOR projects[1,6,7].

Utilization of these guides and criteria enables operators to make well-informed decisions, thereby optimizing the implementation of EOR strategies while improving project efficiency and profitability. When applying EOR criteria to a specific reservoir, each factor must be individually evaluated to ensure alignment with reservoir conditions and project objectives[13].

Effective application of EOR criteria requires assessing each factor based on its relevance to reservoir and project conditions[4,5]. This assessment should be supported by comprehensive technical analyses to fully understand the implications and expected outcomes of different EOR methods. In addition, identifying any gaps or inconsistencies in the criteria is crucial to selecting a practical and effective EOR approach that maximizes recovery. Carefully evaluating each criterion and addressing potential problems individually leads to more informed decision-making and improves the success of EOR projects. For a more comprehensive understanding of the mechanisms and effectiveness of different EOR methods, refer to the studies by Terry et al. (2003)[1] and Thomas et al. (2007)[14].

Updated screening criteria for EOR methods

This study presents an updated version of the screening criteria for EOR originally established by Taber et al. (1997a)[18], a foundational contribution to petroleum engineering that is widely cited in scholarly literature. Their criteria cover twelve EOR methods evaluated using nine key reservoir properties, with statistical parameters (i.e., lower, upper, and average values) derived from various EOR surveys conducted between 1974 and 1996, including those published in *the Oil and Gas Journal*[5,18], as shown in Table 1. For each EOR method, italic

EOR Method		Oil Properties			Reservoir Characteristics					
		Gravity (°API)	Viscosity (cp.)	Composition	Oil Saturation (% PV)	Formation type	Net Thickness (ft)	Permeability (mD)	Depth (ft)	Temperature (°F)
Gas Injection Methods (Miscible)										
1	Misc–N_2 and flue gas	>35↗ *48*↗	<0.4↘ *0.2*↘	High % of C_1 to C_7	>40↗ *75*↗	Sandstone or carbonate	Thin unless dipping	NC	>6000	NC
2	Misc–HC	>23↗ *41*↗	<3↘ *0.5*↘	High % of C_2 to C_7	>30↗ *80*↗	Sandstone or carbonate	Thin unless dipping	NC	>4000	NC
3	Misc–CO_2	>22↗ *36*↗ [a]	<10↘ *1.5*↘	High % of C_5 to C_{12}	>20↗ *55*↗	Sandstone or carbonate	Wide range	NC	>2500 [a]	NC
1–3	Immiscible gases	>12	<600	NC	>35↗ *70*↗	NC	NC if dipping and/or good vertical permeability	NC	>1800	NC
(Enhanced) Water-flooding										
4	Micellar/ Polymer, ASP, and Alkaline Flooding	>20↗ *35*↗	<35↘ *13*↘	Light, intermediate, and some organic acids for alkaline floods	>35↗ *53*↗	Sandstone preferred	NC	>10↗ *450*↗	<9000↘ *3250*	<200↘ *80*
5	Polymer Flooding	>15	<150, >10	NC	>50↗ *80*↗	Sandstone preferred	NC	>10↗ *800*↗ [b]	<9000	<200↘*140*
Thermal/Mechanical										
6	Combustion	>10↗*16*→?	<5000 ↓ *1200*	Some asphaltic components	>50↗ *72*↗	High-porosity sand/ sandstone	>10	>50[c]	<11,500↘ *3500*	>100↗*135*
7	Steam	>8↗*13.5*→?	<200,000 ↓ *4700*	NC	>40↗ *66*↗	High-porosity sand/ sandstone	>20	>200↗ *2540*↗[d]	<4500↘ *1500*	NC
-	Surface mining	7 to 11	Zero cold flow	NC	>8 wt% sand	Mineable tar sand	>10[e]	NC	>3:1 overburden to sand ratio	NC

Table 1. Summary of the screening criteria for EOR methods developed by Taber et al. (1997a)[18] . Misc = Miscible, HC = hydrocarbon, N_2 = Nitrogen, Alkaline-Surfactant-Polymer = ASP, NC = Not critical. Italic values represent the approximate mean or average for current field projects. [a]See Table 3 (CO_2 flooding) of Ref.[19]. [b]>3 mD from some carbonate reservoirs if the intent is to sweep only the fracture system. [c]Transmissibility >20 mD-ft/cp. [d]Transmissibility >50 mD-ft/cp. [e]See depth.

values indicate the average or mean of a given parameter. For example, in miscible nitrogen floods, an oil gravity notation of "*>35↗48↗*" signifies that this method is suitable for oils with a gravity exceeding 35° API (provided other criteria are met), that higher-gravity oils are preferable (↗) and that the approximate mean or average of existing miscible nitrogen projects is *48*° API (Taber et al., 1997a)[18].

In this study, the updated EOR criteria incorporate comprehensive data from multiple EOR projects conducted between 1997 and 2024. Table 2 presents a summary of these revised screening criteria, including a range of reservoir values derived from field data and established oil displacement mechanisms relevant to each EOR method. Building on the work of Taber et al. (1997a)[18], this study introduces several key enhancements: porosity is now included as an evaluation criterion, four additional EOR methods (miscible WAG, microbial EOR, hot water flooding, and a combined approach of immiscible HC with WAG) have been integrated, and the statistical parameters of the evaluation criteria have been updated. As a result, the comprehensive list of ten reservoir properties is as follows: oil gravity, oil viscosity (μ_o), oil composition, oil saturation (S_o), formation type, net thickness (h), permeability (k), reservoir depth (d), temperature (T), and porosity (ϕ). Furthermore, we categorized the sixteen EOR methods into six groups: miscible gas, immiscible gas, chemical, thermal, mechanical, and microbial methods. More specifically, the miscible gas category includes four methods: CO_2, HC, Water Alternating Gas (WAG), and N_2 injection. The immiscible gas category also consists of four methods: N_2, CO_2, HC, and HC combined with WAG. The chemical category includes three methods: polymer flooding, alkaline/ surfactant/polymer (ASP), and surfactant combined with polymer or alkaline. The thermal category comprises three thermal techniques: combustion, steam injection, and hot water flooding. In addition, one mechanical method (surface mining) and one microbial method are included. Furthermore, this study updated not only the EOR criteria and EOR methods but also expanded statistical parameter ranges of lower and upper limits, as well as average values of criteria based on field data collected from various EOR projects, as summarized in Table 2[1,3,5,6,9,12,13,16–18,21,23,24,26,29]. The updates to reservoir properties and improved methodologies for EOR indicate a considerable advancement in the field. The refinement of reservoir property assessments and advanced EOR methodologies is expected to facilitate a more accurate selection of suitable EOR techniques that are tailored to specific oilfield characteristics. For each EOR method, every reservoir property provides a range of favorable EOR operating conditions, with an average representing the primary weighting value. For example, the criterion for oil gravity (°API) in miscible N_2 floods can be expressed as "Min > 20↗, Avg *48*↗". This notation means that the EOR method is effective for oils with a gravity exceeding 20° API and that higher-gravity oils are preferable

No	EOR Method	Gravity		Viscosity		Composition	Oil saturation		Formation type		Net Thickness	Permeability		Depth		Temperature		Porosity	
		°API		cp.			%		*S	**C	ft.	mD		ft.		°F		%	
		Min	Avg	Max	Avg	-	Min	Avg	-	-	-	Min	Avg	Min	Avg	Min	Avg	Min	Avg
1	Misc-CO_2	> 21↗	*36*↗	< 35↘	*1.65*↘	High % of C_5 to C_{12}	> 15↗	*52.8*↗	1	1	Wide range	NC	NC	> 1500	*6171*	NC	NC	> 2↗	*14.8*↗
2	Misc-HC	> 13↗	*40*↗	< 18,000↘	*134.3*↘	High % of C_2 to C_7	> 30↗	*76.5*↗	1	1	Thin unless dipping	NC	NC	> 1970	*6192*	NC	NC	> 1↗	*14.5*↗
3	Misc-WAG	> 33↗	*35.6*↗	< 0.4↘	*0.175*↘	NC	> 40↗	*75*↗	1	1	NC	> 130↗	*143.3*	> 1312	*9108*	> 194	*229.4*	> 11↗	*18.3*↗
4	Misc-N_2	> 20↗	*48*↗	< 25↘	*0.2*↘	High % of C_1 to C_7	> 40↗	*75.8*↗	1	1	Thin unless dipping	NC	NC	> 3340	*7436*	NC	NC	> 4	*11.2*↗
5	Imm-N_2	> 16	*41*	< 18,000↘	*2256.8*↘	NC	> 35↗	*70.5*↗	1	1	NC if dipping and/ or good vertical permeability	NC	NC	> 1700	*7914*	NC	NC	> 11↗	*19.5*↗
6	Imm-CO_2	> 11	*22.6*	< 660↘	*65.5*↘	NC	> 15↗	*63*↗	1	1		NC	NC	> 1150	*3385*	NC	NC	> 17↗	*26.3*↗
7	Imm-HC	> 22	*38*	< 4↘	*2.1*↘	NC	> 35↗	*74.5*↗	1	1		NC	NC	> 1800	*6500*	NC	NC	> 5↗	*13.5*↗
8	Imm-HC + WAG	> 9.3	*34*	< 16,000↘	*3948.2*↘	NC	> 35↗	*70*↗	1	1		> 100↗	*2392*	> 2650	*7219*	> 131	*198.7*	> 18↗	*25*↗
9	Polymer	> 13	*33*	< 4000↘	*111.6*↘	NC	> 34↗	*72*↗	1	0.5	NC	> 1.8↗	*817.1*↗	> 700	*6611*	> 74	*153.5*	> 10.4↗	*22.5*↗
10	ASP Flood	> 16↗	*33*↗	< 6500↘	*444.4*↘	Light, intermediate, some organic acids for alkaline floods	> 35↗	*63.4*↗	1	0.5	NC	> 10↗	*486.5*↗	> 500	*3117*	> 80	*119.8*	> 4↗	*26.6*↗
11	S + P/A Flood	> 20↗	*33*↗	< 35↘	*11.15*↘		> 43.5↗	*48*↗	1	0.5	NC	> 10↗	*55*↗	> 625	*3096*	> 122	*138.5*	> 11↗	*16.4*↗
12	Combustion	> 10↗	*20*	< 5000↘	*1200*↘	Some asphaltic components	> 50↗	*69.5*↗	1	1	> 10	> 10↗	*1033*	> 400	*5570*	> 60	*155.3*	> 14↗	*23.3*↗
13	Steam	> 8↗	*13.5*	< 5,000,000↘	*18,836*↘	NC	> 32↗	*66*↗	1	0.5	> 10	> 1↗	*2573*↗	> 200	*1572*	> 10	*175*	> 10↗	*32.2*↗
14	Hot Water	> 8↗	*16*	< 200,000↘	*3351*↘	NC	> 15↗	*62.3*↗	1	0.5	> 20	> 200↗	*2943*↗	> 500	*1721*	> 60	*98.5*	> 25↗	*31.2*↗
15	Microbial	> 12↗	*26.6*	< 8900↘	*2977.5*↘	NC	> 25↗	*45*↗	1	0.5	Wide range	> 50↗	*133.75*	> 1572	*5786*	> 86	*150*	> 12↗	*19*↗
16	Surface Mining	7 to 11		Zero cold flow		NC	>8 wt% sand		Mineable tar sand		> 10	NC		> 3:1 overburden-to-sand ratio		NC		NC	

Table 2. Updated EOR screening criteria for EOR methods. Imm = Immiscible; Misc = Miscible; HC = Hydrocarbon; N_2=Nitrogen; Alkaline = A, Surfactant = S, Polymer = P (ASP); NC = Not critical; *S = Sandstone; **C = Carbonate.

(↗). In addition, the approximate average oil gravity for current miscible nitrogen projects is *48°* API, as shown in Table 2.

While Table 2 provides valuable insights, it is important to understand that the parameters are not intended to establish definitive threshold limits but rather to provide indicative guidelines that should be interpreted with nuanced consideration and contextual understanding. Specifically, the proposed limits should be subject to continuous reassessment and refinement through rigorous scientific research. The presented parameters serve primarily as examples and provide an approximate range of EOR criteria that have been associated with successful project outcomes. These guidelines are intended to offer a starting point for reservoir evaluation rather than definitive standards and should be adapted based on project-specific factors and emerging industry insights.

Table 3 provides reference numbers that enable readers to access relevant information, including authors, titles of works, publication years, and other important citations.

Scoring of EOR methods

A scoring mechanism is integrated into the reservoir evaluation and ranking process of EOR methodologies. By using a stairwise scoring system, each of the ten reservoir properties listed in Table 2 is assessed against the established screening criteria of the sixteen recovery methods.

Scores range from 0 to 1 and represent the degree to which a given reservoir property aligns with the EOR criteria. If a property only partially falls within the defined EOR range, a proportional score is assigned based on its level of compliance. In this study, the minimum (X^{min}) and maximum (X^{max}) values serve as threshold limits, while the average value (X^{avg}) acts as the primary weighting factor. In addition, if any criterion receives a score of zero, the corresponding EOR method is excluded from consideration, regardless of its overall score.

The scoring approach using the range between X^{min} and X^{avg} applies to reservoir properties such as oil gravity, oil saturation, permeability, reservoir depth, temperature, and porosity. This method is governed by (Eq. 1) through (Eq. 3):

For the *i*-th screening parameter

$$If\ X_i^{\min} \le X_i \le X_i^{\text{avg}}, \quad then\ S_i = \frac{X_i - X_i^{\min}}{X_i^{\text{avg}} - X_i^{\min}}; \tag{1}$$

$$Else\ if\ X_i > X_i^{\text{avg}}, \quad then\ S_i = 1; \tag{2}$$

$$Else\ if\ X_i < X_i^{\min}, \quad then\ S_i = 0; \tag{3}$$

- where X_i denotes a reservoir property value for the *i*-th screening parameter.
- where $X_i^{\min}$ is a minimum reservoir property value for the *i*-th screening parameter.
- where X_i^{avg} signifies an average reservoir property value for the *i*-th screening parameter.

A score of 1 is assigned when the given property value is equal to or greater than the X^{avg}, as defined in (Eq. 2). Conversely, a score of 0 is assigned when the given property value falls below the X^{min} threshold, as shown in (Eq. 3). Figure 1 outlines the score assignment procedure.

For the composition criterion, a score of 1 is awarded when a property meets the specified conditions outlined in Table 2. Unless it meets these conditions, it receives a score of 0. Specifically, for miscible gases such as CO_2, HC, and N_2, a "high % of carbon components" refers to the predominance of carbon number, specifically defined by its weight%. This definition is presented in the composition criterion of Table 2. For example, in the case of miscible CO_2, it is recommended to use a high percentage of hydrocarbons ranging from C_5 to C_{12}, according to Taber et al. (1997a)[18]. This indicates that the majority ($X_i \ge 50\%$) of the carbon weight should consist of hydrocarbons within the C_5 – C_{12} range, which is considered acceptable and should be assigned a score of 1.

If a property only partially meets the condition, a proportional score is granted based on its level of compliance. For instance, if the inclusion of C_5 – C_{12} hydrocarbons only constitutes 30% (X_i) of the total, while the remaining 70% (X_y) consists of other carbon numbers, (Eq. 4) will be applied to calculate the score accordingly.

$$\text{If } X_i < X_y, \quad \text{then } S_i = \frac{X_i}{X_y}; \tag{4}$$

- where X_i denotes a carbon percentage value for the *i*-th screening parameter.
- where X_y is a remaining carbon percentage value for the *y*-th screening parameter.

As an example, the given data can be calculated as shown below, using (Eq. 4):

$$S_i = \frac{30}{70} = 0.429 \tag{5}$$

In addition, "NA" is utilized to signify "Not Available" in instances where no specific value is provided. It is important to note that any criteria corresponding to "NA" should be excluded from the overall calculation. For further clarification, please refer to Fig. 1 below. Also, it is crucial to clarify that "NC" denotes Not Critical. Given the absence of a specific ideal value in the study by Taber et al. (1997a)[18], so a score of 1 is assigned to those

No	EOR Method	Gravity		Viscosity		Composition	Oil saturation		Formation type		Net Thickness	Permeability		Depth		Temperature		Porosity	
		°API		cp.			%		*S	**C	ft.	mD		ft.		°F		%	
		Min	Avg	Max	Avg	-	Min	Avg	-	-	-	Min	Avg	Min	Avg	Min	Avg	Min	Avg
1	Misc-CO_2	[24]	[16]	[16]	[16]	[12, 17, 18, 21]	[16]	[16]	[16]	[16]	[5, 17, 18, 21]	[17, 18, 21]	[17, 18, 21]	[16]	[16]	[17, 18, 21]	[17, 18, 21]	[26]	[16]
2	Misc-HC						[1, 29]							[24]					
3	Misc-WAG	[29]		[29]		[12]	[29]				[5]	[26]	[16]	[29]		[26]	[16]	[16]	
4	Misc-N_2	[3]		[3]		[12, 17, 18, 21]	[1]				[5, 17, 18, 21]	[17, 18, 21]	[17, 18, 21]	[3]		[17, 18, 21]	[17, 18, 21]		
5	Imm-N_2	[16]		[16]		[17, 18, 21]	[16]				[18]			[16]					
6	Imm-CO_2			[24]															
7	Imm-HC			[16]										[18]					
8	Imm-HC + WAG		[16]		[16]			[16]	[16]			[16]	[16]	[16]	[16]	[16]	[16]		[16]
9	Polymer						[29]				[5, 18, 29]								
10	ASP Flood	[24]					[16]				[5, 17, 18, 21]							[24]	
11	S + P/A Flood	[1, 29]		[1, 29]			[29]				[5, 18, 21]	[26]	[16]	[13, 16]		[26]	[16]	[26]	
12	Combustion	[1]		[16]			[16]			[5, 16]	[1, 5, 17, 18, 21]			[16]		[24]		[24]	
13	Steam	[16]		[16]			[24]			[16]	[1, 5, 17, 18, 21, 23]	[5. 16, 23]		[5, 16, 23]		[5, 16, 23]		[26]	
14	Hot Water						[16]				[13]	[13]		[16]		[16]		[16]	
15	Microbial	[5, 9, 16]		[9, 16]			[9]				[6]	[26]		[6]		[6]		[9, 16]	
16	Surface Mining	[5, 18]																	

Table 3. Reference table listing of the "Updated EOR screening criteria". Imm = Immiscible; Misc = Miscible; HC = Hydrocarbon; N_2=Nitrogen; Alkaline = A, Surfactant = S, Polymer = P (ASP); NC = Not critical; *S = Sandstone; **C = Carbonate.

Reservoir and fluid properties			Formation	Table 2. Updated EOR screening criteria (Misc-CO_2)		
			X_i (reservoir property value)	X_i^{min}	X_i^{avg}	X_i^{max}
1	Gravity	°API	37.4	>21↗	36↗	-
2	Viscosity (μ_o)	cp	3.96	-	1.65↘	<35↘
3	Composition	-	NA	High percent of C_5 to C_{12}		
4	Oil saturation (S_o)	%	54.7	>15↗	52.8↗	-
5	Formation type	*S, **C	*S	*S	*S	*S
6	Net thickness (h)	ft.	54.7	Wide range		
7	Permeability (k)	md	11.8	NC	NC	-
8	Reservoir depth (d)	ft.	3456	>1500↗	6171	-
9	Temperature (T)	°F	130	NC	NC	-
10	Porosity (ϕ)	%	15.4	>3↗	14.8↗	-
Misc = Miscible, NA = Not available, NC = Not critical, *S = Sandstone, **C = Carbonate						

→ Score assignment

Reservoir and fluid properties			Formation
1	Gravity	°API	1
2	Viscosity (μ_o)	cp	0.93
3	Composition	-	NA
4	Oil saturation (S_o)	%	1
5	Formation type	*S, **C	1
6	Net thickness (h)	ft.	1
7	Permeability (k)	md	1
8	Reservoir depth (d)	ft.	0.419
9	Temperature (T)	°F	1
10	Porosity (ϕ)	%	1
Average score (S^{avg}) of Misc-CO_2 method			**0.928**

Score for each property

Final averaged score

Fig. 1. Criteria of the score assignment procedure (favorable case).

categorized as NC. The scoring methodology and its implications have been thoroughly examined in the prior research conducted by Trujillo et al. (2010)[15].

For net thickness, a score of 1 is assigned if the property meets the conditions presented in Table 2, while a score of 0 is given if it does not.

In the context of formation types, EOR techniques are applicable to both sandstone and carbonate reservoirs. However, the methodologies employed and the associated challenges differ significantly due to the inherent characteristics of each formation type.

A scoring system is utilized to evaluate these reservoirs based on their classification: sandstone reservoirs are assigned a score of 1, whereas carbonate reservoirs are assigned a score of 0.5. For instance, the score of 1 depicted in Fig. 1 corresponds to the classification of the reservoir as sandstone, as outlined in Table 2. This

scoring methodology and its implications were comprehensively examined in the research conducted by Hartono et al. (2017)[16].

The scoring method using the range between X^{avg} to X^{max} applies only to oil viscosity, as lower viscosity is generally preferred. This method is governed by (Eq. 6) through (Eq. 8):

For the *i*-th screening parameter:

$$\text{If } X_i^{\text{avg}} \leq X_i \leq X_i^{\text{max}}, \quad \text{then } S_i = \frac{X_i - X_i^{\text{avg}}}{X_i^{\text{max}} - X_i^{\text{avg}}}; \tag{6}$$

$$\text{Else if } X_i < X_i^{\text{avg}}, \quad \text{then } Score = 1; \tag{7}$$

$$\text{Else if } X_i > X_i^{\text{max}}, \quad \text{then } Score = 0; \tag{8}$$

- where X_i denotes a reservoir property value for the *i*-th screening parameter.
- where X_i^{avg} is an average reservoir property value for the *i*-th screening parameter.
- where X_i^{max} signifies a maximum reservoir property value for the *i*-th screening parameter.

For oil viscosity, a score of 1 is assigned if the viscosity value falls below the X^{avg}, as lower viscosity is preferred – see (Eq. 7). If the viscosity exceeds the X^{max} threshold, a score of 0 is given, as outlined in (Eq. 8).

For net thickness, a score of 1 is assigned if it meets the conditions specified in Fig. 1. Similarly, a score of 1 is assigned for the formation type if it is classified as sandstone, as summarized in Table 2.

To assess the average score (S^{avg}) of the formation, the following steps are followed: First, all assigned criteria scores are summed, and the total is divided by the number of evaluated criteria, as described in (Eq. 9):

$$S^{\text{avg}} = \frac{1}{n} \sum {}_{i=1}^{n} S_i; \tag{9}$$

- where S^{avg} denotes the average score.
- where *n* is the number of evaluated criteria.
- where S_i signifies individual scores for the *i*-th assigned criteria.

As an example, the data in Fig. 1 can be calculated as shown below, using (Eq. 9):

$$S^{\text{avg}} = \frac{(1 + 0.93 + 1 + 1 + 1 + 1 + 0.419 + 1 + 1)}{9} = 0.928 \tag{10}$$

To complete the overall performance, we need to use the final average scores to rank the list of EOR methods. After calculating the average score for each candidate, the ranking is determined by ordering the EOR methods in descending order based on their overall average scores.

If Fig. 1 illustrates a favorable scenario for Misc-CO_2, where no criteria were violated. Conversely, Fig. 2 below presents an unfavorable case for "Hot water" injection, which failed to satisfy the 2/10 criterion, as indicated in Fig. 2.

In Fig. 2, illustrating the "Hot Water" injection case, the criteria for permeability and porosity are assessed as "0" and are highlighted in red. The given values (X_i) can be found in Table 5 below. When we compare the given values (X_i) with "Table 2. Updated EOR screening criteria (Hot water)" as shown in Fig. 2, we can observe the following results. The following analysis pertains to the application of "hot water" injection concerning permeability characteristics. The specified permeability ranges are " $X_i^{\min} = > 35 \nearrow \mid X_i^{\text{avg}} = 2943 \nearrow$ ". This implies that this injection method is appropriate for oils with a permeability exceeding 35, if provided other criteria are met. Furthermore, it is suggested that oils with higher gravities are preferable, as denoted by the upward trend (↗). The approximate average permeability for existing hot water projects is 2943. As a result, the permeability values presented in Fig. 2 for hot water are recorded equal to 11.8, which fails to meet the lower limit of the criteria. Consequently, this has been marked as a violation, resulting in a value of "0" which is indicated in red as illustrated in Fig. 2.

In the context of the previously discussed permeability case, the criteria of "hot water" injection concerning porosity characteristics are established within the range of " $X_i^{\min} = > 25 \nearrow \mid X_i^{\text{avg}} = 31.2 \nearrow$ ". The value indicated in Fig. 2 for hot water porosity is "15.4" which does not meet the lower limit of the criterion. Consequently, this value is recorded as "0" and is marked in red, as shown in Fig. 2.

Mongolia's oil industry and the T oilfield

Historical phases of mongolia's oil industry development

The development of Mongolia's oil industry can be divided into two phases. The first phase began in 1931 with the discovery of the Zuunbayan and Tsagaan-els oilfields in Dornogobi province, supported by technical and logistical assistance from the former Soviet Union. This stage established the foundation for subsequent regional exploration and extraction efforts.

The second phase started in 1991 with the enactment of the Mongolian Petroleum Law, which Congress ratified. This legislative milestone led to the establishment of the national petroleum company, Mongol Gazariin Tos, in the same year. Mongol Gazariin Tos partnered with Texas-based joint exploration companies, which enabled extensive hydrocarbon research in Mongolia and facilitated two successful rounds of exploration bidding. Currently, Mongolia's sedimentary oil basins have been delineated into 33 distinct petroleum exploration blocks, with the T oilfield prominently illustrated in Fig. 3[27]. These blocks have been compared to major production

Reservoir and fluid properties			Formation	Table 2. Updated EOR screening criteria (Hot water)		
			X_i (reservoir property value)	X_i^{min}	X_i^{avg}	X_i^{max}
1	Gravity	°API	37.4	>8↗	16↗	-
2	Viscosity (μ_o)	cp	3.96	-	3351↘	<200000↘
3	Composition	-	NA	NC		
4	Oil saturation (S_o)	%	54.7	>15↗	62.3↗	-
5	Formation type	*S, **C	*S	*S	*S	*S
6	Net thickness (h)	ft.	54.7	>20		
7	Permeability (k)	md	11.8	>35↗	2943↗	-
8	Reservoir depth (d)	ft.	3456	>500	1721	-
9	Temperature (T)	°F	130	>60	98.5	-
10	Porosity (ϕ)	%	15.4	>25↗	31.2↗	-
Misc = Miscible, NA = Not available, NC = Not critical, *S = Sandstone, **C = Carbonate						

→ Score assignment

Reservoir and fluid properties			Formation
1	Gravity	°API	1
2	Viscosity (μ_o)	cp	1
3	Composition	-	NA
4	Oil saturation (S_o)	%	0.839
5	Formation type	*S, **C	1
6	Net thickness (h)	ft.	1
7	Permeability (k)	md	0
8	Reservoir depth (d)	ft.	1
9	Temperature (T)	°F	1
10	Porosity (ϕ)	%	0
Average score (S^{avg}) of Hot water method			**0.760**

Score for each property

→ Final averaged score

Fig. 2. Criteria of the score assignment procedure (unfavorable case).

fields in China because the two countries share a border[4]. In addition, the T oilfield is located adjacent to China's Hailar oilfield, with both fields situated within similar Mesozoic and Cenozoic sedimentation layers. The Hailar Basin, located in the northern part of the Inner Mongolia Autonomous Region, has been identified as a significant oil-producing area with the potential for large-scale production.

Since 2010, Mongolia has been recognized as an oil-producing country, with reserves registered in blocks XIX, XXI, and PSC-97 under the Mongolian Minerals Fund[4]. These reserves are estimated to contain approximately 2.45 billion barrels (332.64 million tons) of "proved plus probable" reserves, while 318.6 million barrels (43.258 million tons) are classified as "proved" reserves[27]. The evaluation of these reserves was conducted by Petro China Daqing Tamsag LLC, a subsidiary of the Chinese National Petroleum Corporation (CNPC), the largest integrated petroleum company in China, along with Dongsheng Petroleum (Mongol) LLC, a subsidiary of Sinopec, the country's second-largest petroleum company. Since 1993, these two companies have conducted

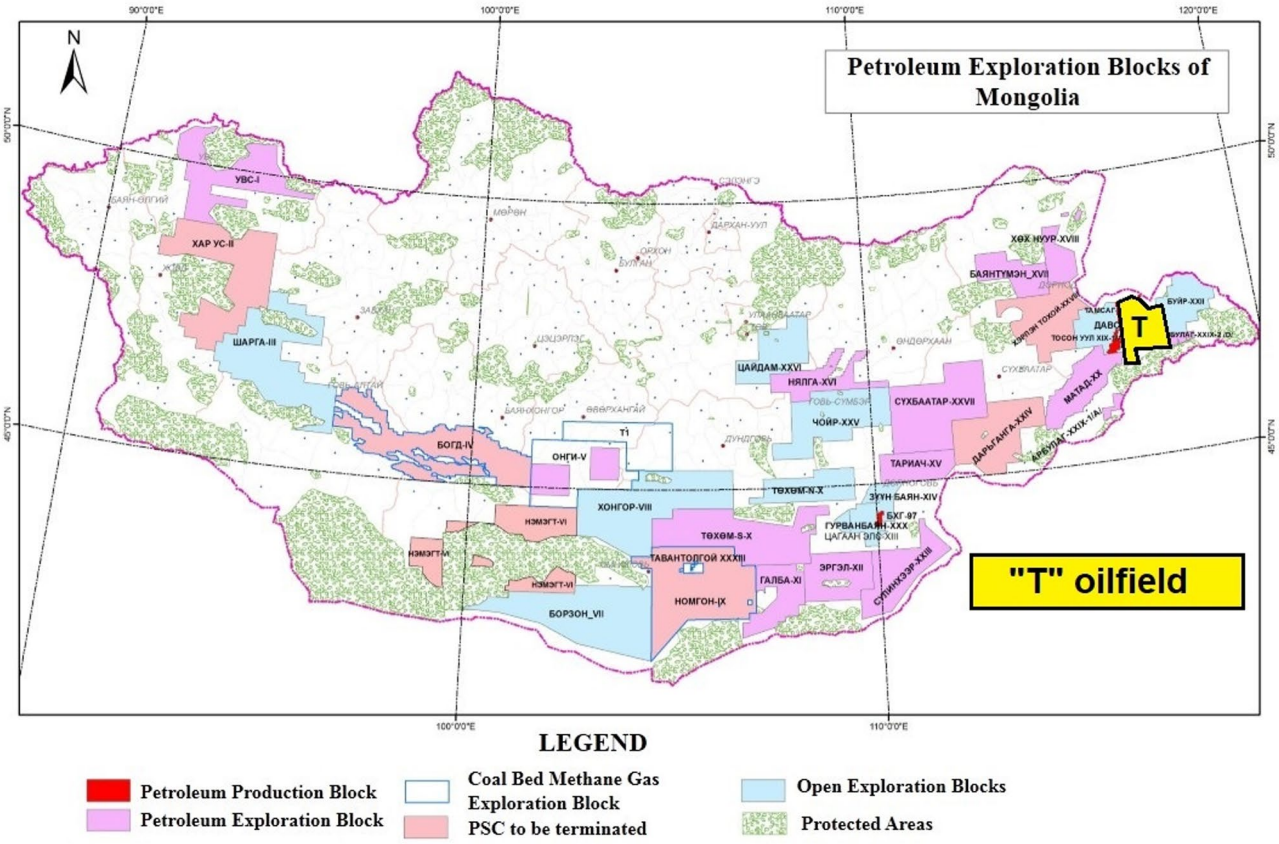


Fig. 3. Map of petroleum blocks in Mongolia. (modified from Reference[27]).

extensive drilling operations, with a total of 1,728 wells dedicated to exploration, appraisal, and development. Specifically, 988 wells were drilled in the XIX block, 609 in the XXI block, and 131 in the PSC-97 blocks[27]. Presently, the government of Mongolia has formalized production-sharing contracts (PSCs) for 28 out of the 33 blocks, collaborating with 31 companies in the sector[27].

Overview of the T oilfield in eastern Mongolia

This study validates the updated EOR screening method by applying it to the T oilfield in eastern Mongolia. This oilfield has an average elevation ranging from 587 m to 702 m. Flat grasslands characterize the region, which falls within the arid climate of the medium extratropical zone and exhibits significant diurnal temperature variations – see Fig. 4. The exploration at this oilfield commenced in 1991. In 2005, Petro China Daqing Tamsag LLC entered a production-sharing contract and advanced to the appraisal stage in 2011. According to MRPAM[27], as of 2011, proved reserves amount to 150.13 million barrels (21.018 million tons). Petro China Daqing Tamsag LLC has evaluated these reserves. Based on exploration and appraisal tests, oil displacement is expected to occur primarily through solution gas and water drive. The estimated recovery factor under primary and secondary recovery schemes ranges from 10 to 17%, which highlights the need for EOR applications in this field.

The T oilfield and Hailar oilfield share similar Mesozoic and Cenozoic environments, with comparable formation, alluviation, and structural characteristics. The stratigraphic sequence of the T oilfield, from bottom to top, consists of the basement (pre-Cretaceous formations with an unclear era division), the Tsagaantsav (TSA) Formation of the Lower Cretaceous system, Lower-Lower Zuunbayan Formation (LLZ), Lower-Upper Zuunbayan Formation (LUZ), Sainshand Formation, the Bayanshiree Formation, and formations from the Tertiary and Quaternary systems.

Notable hiatuses and unconformities exist between various formations, particularly between the basement and the TSA Formation, the TSA and LLZ Formations, and the Sainshand and Bayanshiree Formations. Detailed characteristics of these formations, from the basement to the uppermost layers, are summarized in Table 4. The LUZ, LLZ, and TSA formations serve as the primary oil-bearing layers essential for development and production, which makes them the focus of this study.

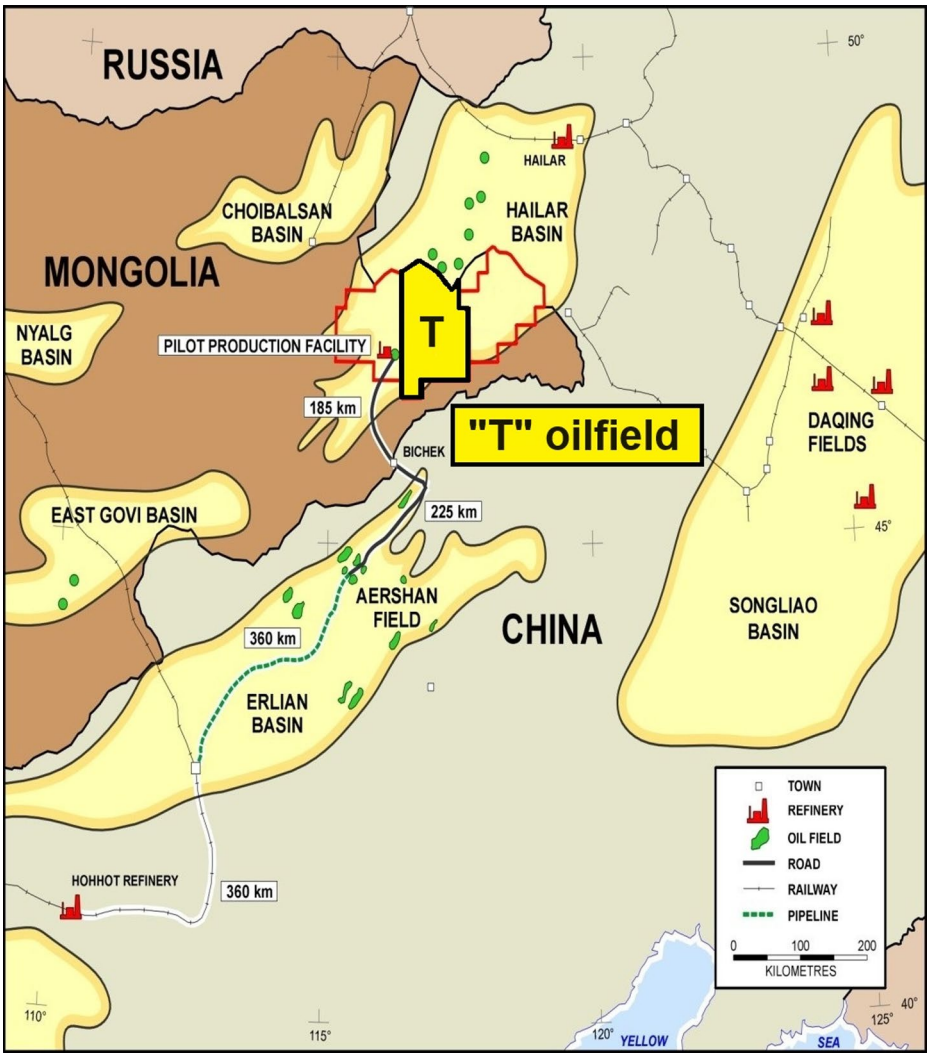


Fig. 4. Geographical Location of the T oilfield. (modified from Reference[28]).

Reservoir characteristics of the T oilfield

Each formation was evaluated and scored individually, accounting for the diverse reservoir properties across different formations[4]. Table 5 presents the average reservoir properties for the LUZ, LLZ, and TSA formations[4,25,27,28]. Given the presence of numerous thin layers within these formations, averaging the reservoir properties has been adopted as a practical approach for screening and evaluating EOR methods. Fluid composition data were unavailable, which necessitated the exclusion of this criterion from the calculation. As shown in Table 6, this absence of data prevents its inclusion in the score assignment process.

Results and discussion

The developed EOR screening method was applied to the LUZ, LLZ, and TSA formations in the T oilfield, with each formation evaluated separately to account for its distinct reservoir properties. Table 6 presents the scores for fifteen EOR recovery methods using a color-coded system for clarity:

· Deep green (0.75 < score for the i-th screening criteria (S_i) ≤ 1): most favorable case, strong applicability.
· Light green (0.5 < S_i ≤ 0.75): favorable case.
· Yellow (0.25 < S_i ≤ 0.5): moderate case.
· Orange (0 < S_i ≤ 0.25): barely applicable case.
· Red (S_i = 0): exclusion due to violation of lower or upper limits.

Note that the red color indicates an exclusion from the criteria. Methods marked red must be removed from the EOR ranking list, even if they have a high overall score. Additionally, a score of zero (also represented in red) signifies a violation of either the lower or upper limits. Hence, any method identified and marked red is automatically excluded from the EOR options.

Furthermore, it is essential to highlight that surface mining method have been excluded from this analysis due to the low viscosity of the oil present in the "T" oilfield. In general, mining is used only when the oil is so

System	Series	Formation	Code of Formation	Thick–ness (ft.)	Description of Lithology and Lithofacies
Quaternary	–	–	Q	100 ~ 200	Loose gravel layer and varicolored sand and mud layer, with quartz and feldspar as the primary components
Tertiary	–	–	R	200 ~ 360	The upper section consists of gray sandstone and varicolored conglomerate; the middle section is red mudstone; the lower section is varicolored sandstone.
Cretaceous	Upper	Bayanshiree	K_2bs	500 ~ 720	Hoary–brown sandstone interbedded varicolored mudstone
	Lower	Sainshand	K_1ss	3940 ~ 5580	Mainly fluvial facies sedimentation: the upper section is gray mudstone interbedded with hoary and gray siltstone and sandstone; the middle section is gray mudstone, hoary and gray siltstone, sandstone and argillaceous conglomerate with irregular interbedding; the lower section is gray siltstone, sandstone, and conglomerate
		Upper Zuunbayan (LUZ)	K_1zb_2	660 ~ 1640	Shallow lake–limnetic facies sedimentation: the middle and lower sections contain thick dark gray mudstone interbedded with thin dark gray argillaceous sandstone and siltstone; the upper section is dark gray mudstone interbedded with hoary and gray siltstone, sandstone, and conglomerate
		Lower Zuunbayan (LLZ)	K_1zb_1	660 ~ 2630	Predominantly fan delta, nearshore underwater fan, far shore underwater fan, deep lake–semi-deep lake facies sedimentation: the bottom section is thick dark gray and gray-black mudstone and oil shale interbedded with calcareous sandstone and siltstone; the middle section is dark gray mudstone interbedded with thin gray siltstone; the upper section comprises light gray siltstone, sandstone and dark gray mudstone with irregular interbedding
		Tsagaantsav (TSA)	K_1cc	980 ~ 3940	The upper section represents shallow lake facies sedimentation, with lithology consisting of hoary and gray bulk glutenite and tuffaceous sandstone and siltstone interbedded with gray and dark gray mudstone and shale. The middle section represents relatively deep lake facies sedimentation, with lithology consisting of brown to dark gray mudstone and shale interbedded with hoary and gray siltstone. The lower section is diluvial (alluvial) and fan delta facies sedimentation, featuring gray tuffaceous sandstone and glutenite, glauconitic tuffaceous conglomeratic mudstone, gray tuffaceous mudstone, varicolored bulk breccia, conglomerate and volcanic rock with irregular interbedding.
–	–	Basement	–	–	Varicolored tuffaceous glutenite, altered volcanic rock, altered and lightly metamorphosed sand and mud rock, and sandy pyroclastic rock, with localized distributions of magmatic and metamorphic rock.

Table 4. Regional formation sequence division table of the T oilfield in Mongolia. (modified from Reference[28]).

Property		Unit	Formation		
			LUZ	LLZ	TSA
1	Gravity	°API	37.4	37.4	37.4
2	Viscosity (μo)	cp.	3.96	5.55	6.4
3	Composition	-	NA	NA	NA
4	Oil saturation (So)	%	54.7	57.4	52.5
5	Formation type	-	*S	*S	*S
6	Net thickness (h)	ft.	54.7	74	37.6
7	Permeability (k)	md	11.8	14.7	6.1
8	Reservoir depth (d)	ft.	3456	4277	4780
9	Temperature (T)	°F	130	162	189.5
10	Porosity (ϕ)	%	15.4	15.6	11.5

Table 5. Average reservoir and fluid properties of the T oilfield. (modified from Reference[25]). NA = Not available, *S = Sandstone.

viscous that it cannot be recovered by any other technique because the mining and upgrading of bitumen are more costly than in-situ recovery methods[18].

The updated final EOR scoring results, presented in Table 7, indicate that miscible CO_2, miscible HC, and immiscible N_2 achieved the highest scores without violating any criteria. Following these methods, miscible N_2 ranked fourth, steam injection ranked fifth, polymer flooding ranked sixth, and miscible WAG ranked seventh. These results suggest that the top three methods have the highest likelihood of success in the T oilfield. Methods highlighted in red should be excluded due to incompatibility with reservoir properties.

Each formation presented a distinct, most compatible EOR methodology. However, considering the cost of EOR, these may not be optimal options. Therefore, an average score for each formation was suggested. Based on the screening results, the three highest-ranked candidates—miscible CO_2, miscible HC, and immiscible N_2—were selected for further evaluation.

A comparative study was also conducted using the criteria (Table 1) established by Taber et al. (1997a)[18]. The results are presented in Table 7. This analysis showed that both miscible CO_2 and immiscible gas methods (CO_2, N_2, and HC) achieved the highest scores without violating any criteria. Notably, the miscible CO_2 process scored highly in both assessments (Table 7) without violating any criteria. It ranked first in this updated

No'	EOR Method	Gravity °API			Viscosity cp			Oil saturation %			Formation type			Thickness ft.			Permeability mD			Depth ft.			Temperature °F			Porosity %		
		LUZ	LLZ	TSA	LUZ	LLZ	TSA	LUZ	LLZ	TSA	LUZ	LLZ	TSA	LUZ	LLZ	TSA	LUZ	LLZ	TSA	LUZ	LLZ	TSA	LUZ	LLZ	TSA	LUZ	LLZ	TSA
1	Misc-CO_2	1	1	1	0.931	0.883	0.858	1	1	0.992	1	1	1	1	1	1	1	1	1	0.419	0.594	0.702	1	1	1	1	1	0.742
2	Misc-HC	0.904	0.904	0.904	1	1	1	0.531	0.589	0.484	1	1	1	1	1	1	1	1	1	0.352	0.546	0.666	1	1	1	1	1	0.778
3	Misc-WAG	0.791	0.791	0.791	0.680	0.545	0.474	0.631	0.680	0.591	1	1	1	1	1	1	0.080	0.100	0.040	0.275	0.380	0.445	0.146	0.421	0.657	0.603	0.630	0.068
4	Misc-N_2	0.621	0.621	0.621	0.901	0.784	0.750	0.540	0.599	0.492	1	1	1	1	1	1	1	1	1	0.013	0.104	0.160	1	1	1	1	1	1
5	Imm-N_2	0.856	0.856	0.856	1	1	1	0.555	0.631	0.493	1	1	1	1	1	1	1	1	1	0.283	0.415	0.496	1	1	1	0.518	0.541	0.059
6	Imm-CO_2	1	1	1	1	1	1	0.827	0.883	0.781	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
7	Imm-HC	0.963	0.963	0.963	1	0	0	0.499	0.567	0.443	1	1	1	1	1	1	1	1	1	0.352	0.527	0.634	1	1	1	1	1	0.7647
8	Imm-HC + WAG	1	1	1	1	1	1	0.563	0.640	0.500	1	1	1	1	1	1	0	0	0	0.176	0.356	0.466	0	0.458	0.864	0	0	0
9	Polymer	1	1	1	1	1	1	0.721	0.765	0.685	1	1	1	1	1	1	0.012	0.016	0.005	0.466	0.605	0.690	0.704	1	1	0.413	0.430	0.091
10	ASP Flood	1	1	1	1	1	1	0.694	0.789	0.616	1	1	1	1	1	1	0.004	0.010	0	1	1	1	1	1	1	0.504	0.513	0.332
11	Surfactant + Polymer/ Alkaline	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.118	0.178	0.002	1	1	1	0.707	1	1	0	0	0
12	Combustion	1	1	1	1	1	1	0.241	0.379	0.128	1	1	1	1	1	1	0.006	0.008	0.001	0.591	0.750	0.847	0.735	1	1	0.151	0.172	0
13	Steam	1	1	1	1	1	1	0.668	0.747	0.603	1	1	1	1	1	1	0.004	0.005	0.002	1	1	1	0.727	0.921	1	0.243	0.252	0.068
14	Hot Water	1	1	1	1	1	1	0.839	0.896	0.793	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	0	0	0
15	Microbial	1	1	1	1	1	1	0.849	0.926	0.786	1	1	1	1	1	1	0.040	0.056	0.010	1	1	1	0.733	1	1	0.486	0.514	0

Table 6. Score-assigning of the "T" oilfield based on reservoir and fluid properties. Imm = Immiscible, Misc = Miscible, HC = Hydrocarbon, N_2 = Nitrogen, Alkaline-Surfactant-Polymer = ASP, NC = Not critical, S* = Sandstone, C** = Carbonate. Color identification: Deeper green = 0.75 < score ≤ 1; Lighter green = 0.5 < score ≤ 0.75; Yellow = 0.25 < score ≤ 0.5; Orange = 0 < score ≤ 0.25; Red = 0.

No`	EOR Method	Overall score calculated using Table 1 (Taber et al., 1997a[18])					Overall score calculated using the proposed method (Table 2)				
		Target formations			Overall score	EOR rank	Target formations			Overall score	EOR rank
		LUZ	LLZ	TSA			LUZ	LLZ	TSA		
1	Misc–CO_2	0.944	0.918	0.9	0.921	2	0.928	0.942	0.922	0.930	1
2	Misc–HC	0.699	0.829	0.821	0.783	NA	0.865	0.893	0.870	0.876	2
3	Misc–WAG	NA	NA	NA	NA	NA	0.578	0.616	0.563	0.586	7
4	Misc–N_2	0.689	0.693	0.685	0.689	NA	0.786	0.790	0.780	0.785	4
5	Imm–N_2	0.973	0.978	0.969	0.973	1	0.801	0.827	0.767	0.798	3
6	Imm–CO_2	0.973	0.978	0.969	0.973	1	0.870	0.876	0.865	0.870	NA
7	Imm–HC	0.973	0.978	0.969	0.973	1	0.868	0.784	0.756	0.803	NA
8	Imm–HC + WAG	NA	NA	NA	NA	NA	0.527	0.606	0.648	0.593	NA
9	Polymer	0.712	0.7	0.674	0.696	NA	0.702	0.757	0.719	0.726	6
10	ASP Flood	0.802	0.754	0.725	0.76	NA	0.800	0.812	0.772	0.795	NA
11	Surfactant + Polymer/ Alkaline	0.802	0.754	0.725	0.76	NA	0.758	0.798	0.778	0.778	NA
12	Combustion	0.845	0.806	0.772	0.808	NA	0.636	0.701	0.664	0.667	NA
13	Steam	0.783	0.778	0.724	0.762	NA	0.738	0.770	0.741	0.750	5
14	Hot Water	NA	NA	NA	NA	NA	0.760	0.766	0.755	0.760	NA
15	Microbial	NA	NA	NA	NA	NA	0.790	0.833	0.755	0.793	NA

Table 7. Comparison of overall scores for the "T" oilfield. Imm = Immiscible, Misc = Miscible, HC = Hydrocarbon, N_2 = Nitrogen, Alkaline–Surfactant–Polymer = ASP, NA = Not available.

study and second in the Taber et al.[18] study (Table 7). However, the results of Taber et al.[18] did not include miscible HC, miscible N_2, and polymer flooding processes due to differences in reservoir value ranges (Table 7). This comparison underscores the importance of continually updating EOR screening criteria as scientific understanding improves.

Conclusions

The proposed EOR screening and scoring methodology is an efficient tool for engineers to assess reservoirs more quickly and streamline the evaluation process, which results in faster decision-making. Additionally, it reduces costs associated with detailed analyses and testing while offering a straightforward and user–friendly approach to EOR method selection. The introduced methodology is applicable to various reservoir types and allows for a more accurate selection of EOR methods, even with limited reservoir data. Each EOR method is scored against the defined criteria, providing a quantitative measure of its suitability. Scores are assigned based on how well each method aligns with the criteria, using the average reservoir property value in the calculations. These averages represent a central tendency that simplifies analysis and aids in making initial assessments.

This study updates the EOR selection criteria originally published by Taber et al. (1997a) and includes a comprehensive comparative analysis, which enhances the understanding of EOR techniques in the context of recent technological advancements and industry practices. By applying the proposed EOR screening methodology, engineers can streamline the EOR selection process, making it more efficient and practical while ensuring that the chosen EOR methods align well with the reservoir conditions.

The T oilfield was introduced as a case study to demonstrate the practical application of the proposed methodology. The results identified miscible CO_2, miscible HC, and immiscible N_2 as the highest-scoring EOR methods, all meeting the screening criteria without violations. While analysis of the three main formations in the T oilfield revealed distinct optimal EOR methods for each, implementing separate methods for each formation may not be economically viable due to cost considerations. To support future investment decisions, the three top-ranked candidates have been selected for further detailed studies, including reservoir simulation. This next phase will provide deeper insights into the feasibility and effectiveness of each method, ensuring a well-informed strategy for optimizing oil recovery in the T oilfield.

Data availability

The field data underpinning this study are held by the Mineral Resources and Petroleum Authority of Mongolia (MRPAM) and are not publicly accessible due to confidentiality agreements. The data may be obtained from the authors upon request and with the explicit permission of MRPAM.

Received: 19 June 2025; Accepted: 23 September 2025
Published online: 06 October 2025

References

1. Terry, R. E. Enhanced oil recovery. *Encyclopedia Phys. Sci. Technol.* **12**, 503–508 (2003).
2. Pothula, G. K., Vij, R. K. & Bera, A. An overview of chemical enhanced oil recovery and its status in India. *Pet. Sci.* **20** (4), 2305–2323 (2023).
3. Hassan, A., Azad, M. S. & Mahmoud, M. An analysis of nitrogen EOR screening criteria parameters based on the up–to–date review. *J. Pet. Sci. Eng.* **220** (A), 111123 (2023).
4. Arvis, A. & Chon, B. H. Analyses of the field development plan and EOR screening based on reservoir properties of the A field in Mongolia. *Int. J. Appl. Eng. Res.* **12** (23), 13696–13710 (2017). https://www.ripublication.com/ijaer17/ijaerv12n23_87.pdf
5. Adasani, A. & Bai, B. Analysis of EOR projects and updated screening criteria. *J. Pet. Sci. Eng.* **79** (1–2), 10–24 (2011).
6. Tham, M. et al. Research needs to maximize economic producibility of the domestic oil resource, K & A Energy Consultants, Inc. (1991). https://api.semanticscholar.org/CorpusID:106812601
7. Jain, S. et al. A systematic review – Chemical EOR using surfactants and polymers. *Proceedings* **62** (13), 7220–7223 (2022).
8. Gomaa, S. & Salem, K. G. El-hoshoudy, A. N. Enhanced heavy and extra heavy oil recovery: current status and new trends. *Petroleum* **10** (3), 399–410 (2023).
9. Wu, B. et al. Research advances of microbial enhanced oil recovery. *Heliyon* **8** (11), e11424 (2022).
10. Purwasena, L. A. et al. Stability test of bio–surfactant produced by Bacillus licheniformis DS1 using experimental design and its application for MEOR. J. Pet. Sci. Eng.183, 106383 (2019).
11. Sen, R. Biotechnology in petroleum recovery – The microbial EOR. *Prog. Energy Combust. Sci.* **34** (6), 714–724 (2008).
12. Khojastehmehr, M., Madani, M. & Daryasafar, A. Screening of enhanced oil recovery techniques for Iranian oil reservoirs using TOPSIS algorithm. *Energy Rep.* **5**, 529–544 (2019).
13. Dickson, J. L., Leahy-Dios, A. & Wylie, P. L. Development of improved hydrocarbon recovery screening methodologies. *Proceedings – SPE Symposium on Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA*. (2010). https://doi.org/10.2118/129768-MS
14. Thomas, S. Enhanced oil recovery – An overview. *Oil Gas Sci. Technol.* **63** (1), 9–19 (2007).
15. Trujillo, M. et al. Selection methodology for screening evaluation of enhanced oil recovery methods. *SPE Latin American and Caribbean Petroleum Engineering Conference Proceedings, Lima, Peru*. (2010). https://doi.org/10.2118/139222-MS
16. Hartono, A. D. et al. Revisiting EOR projects in Indonesia through integrated study, EOR screening, predictive model, and optimization. *SPE/IATMI Asia Pac. Oil Gas Conf. Exhib. Jakarta Indonesia*. https://doi.org/10.2118/186884-MS (2017).
17. Taber, J. J. & Martin, F. D. Technical screening guides for the enhanced recovery of oil. *SPE Annual Technical Conference and Exhibition San Francisco, California*. (1983). https://doi.org/10.2118/12069-MS
18. Taber, J. J., Martin, F. D. & Seright, R. S. EOR screening criteria revisited, part 1: introduction to screening criteria and enhanced recovery field projects. *SPE. Reserv. Eng.* **12** (03), 189–198 (1997a).
19. Taber, J. J., Martin, F. D. & Seright, R. S. EOR screening criteria revisited, part 2: applications and impact of oil prices. *SPE. Reserv. Eng.* **12** (03), 199–206 (1997b).
20. Kamari, A. et al. Efficient screening of enhanced oil recovery methods and predictive economic analysis. *Neural Comput. Applic.* **25**, 815–824 (2014).
21. Bourdarot, G. & Ghedan, S. Modified EOR screening criteria as applied to a group of offshore carbonate oil reservoirs. *SPE Reservoir Characterisation and Simulation Conference and Exhibition, Abu Dhabi, UAE*. (2011). https://doi.org/10.2118/148323-MS

22. Guerillot, D. R. EOR screening with an expert system. *Petroleum Computer Conference, San Jose, California*. (1988). https://doi.org/10.2118/17791-MS
23. Hama, M. Q. et al. Updated screening criteria for steam flooding based on oil field project data. *SPE Heavy Oil Conference–Canada, Calgary, Alberta, Canada*. (2014). https://doi.org/10.2118/170031-MS
24. Armacanqui, T. J. S. et al. Improvements in EOR screening, laboratory flood tests and model description to effectively fast track EOR projects. *Abu Dhabi International Petroleum Exhibition & Conference, Abu Dhabi, UAE*. (2017). https://doi.org/10.2118/188926-MS
25. PetroChina, D. & Tamsag, L. L. C. The Report on the Reserves Change in the Development Area of the Tamsag oilfield, (English version) (2014).
26. Mahdaviara, M., Sharifi, M. & Ahmadi, M. Toward evaluation and screening of the enhanced oil recovery scenarios for low permeability reservoirs using statistical and machine learning techniques. *Fuel* **325**, 124795 (2022).
27. Official website of Mineral Resources and Petroleum Authority of Mongolia (MRPAM). Petroleum exploitation and production. (2025). https://mrpam.gov.mn/page/678 (accessed 10 January 2025).
28. PetroChina, D. & Tamsag, L. L. C. Plan of Development and Operation (PDO) of Toson-Uul oilfield (Translated from Mongolian version) (2012).
29. Zeqiraj, D. Enhanced oil recovery (EOR) project scheduling with multiobjective of maximum net present value and minimum Makesapn. *Results Eng.* **13**, 100339 (2022).
30. Lourdes, R. S. et al. Prospects of microbial enhanced oil recovery: mechanisms and environmental sustainability. *Sustain. Energy Technol. Assess.* **53** (B), 102527 (2022).

Acknowledgements

This work is supported by the National Research Foundation of Korea (NRF) funded by the Ministry of Education (No. 2018R1A6A1A08025520), the Korea Institute of Energy Technology Evaluation and Planning (KETEP) funded by the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20212010200010), and the Korea Agency for Infrastructure Technology Advancement (KAIA) grant funded by the Ministry of Land, Infrastructure and Transport (MOLIT) (No. RS-2022-00143644). We thank to the supports by the specialized university program for confluence analysis of Weather and Climate Data of the Korea Meteorological Institute (KMI) funded by the Korean government (KMA). We are grateful for permission from the Mineral Resources and Petroleum Authority of Mongolia (MRPAM), which provided unpublished data, exhaustive field guidance, and general support.

Author contributions

A.A.: conceptualization, methodology, formal analysis, investigation, resources, writing-original draft. B.M.: investigation, writing—review and editing, supervision, project administration, funding acquisition.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to B.M.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by-nc-nd/4.0/.

© The Author(s) 2025