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## Article

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Energy Reports

## Provided in Cooperation with:

Elsevier

*Suggested Citation:* Khojastehmehr, Mohsen; Madani, Mohammad; Daryasafar, Amin (2019) : Screening of enhanced oil recovery techniques for Iranian oil reservoirs using TOPSIS algorithm, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 5, pp. 529-544, <https://doi.org/10.1016/j.egy.2019.04.011>

This Version is available at:

<https://hdl.handle.net/10419/243608>

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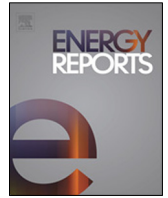
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## Research paper

# Screening of enhanced oil recovery techniques for Iranian oil reservoirs using TOPSIS algorithm



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## HIGHLIGHTS

- The TOPSIS technique from Multi Criteria Decision Making was implemented to screen EOR methods for Iranian oil reservoirs.
- Relative importance of reservoir parameters was determined based on Analytic Hierarchy Process(AHP) in 9 importance levels.
- The findings showed that reservoir lithology is the most influencing parameter in selection of the best EOR method.
- Almost 74% of the considered oil reservoirs were eligible for CO<sub>2</sub> injection, either miscible or immiscible.

## ARTICLE INFO

### Article history:

Received 14 November 2018

Received in revised form 23 March 2019

Accepted 22 April 2019

Available online xxxx

### Keywords:

Enhanced oil recovery

EOR screening criteria

Iranian oil reservoirs

Multi criteria decision making

TOPSIS method

## ABSTRACT

In recent decades, parallel to amazing advances in the development of data mining methods, screening, as the first step of any enhanced oil recovery (EOR) project, has become an interesting subject of data mining methods. Screening of EOR methods is a multi-criteria decision making process, and the Multi-Criteria Decision Making (MCDM) method as a systematic statistical method, can be applied in this regard. In this paper, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) as one of the methods under the MCDM category was used to screen 65 Iranian oil reservoirs. The screening method was employed for 10 different EOR techniques using a wide range of properties and conditions. The analysis used a database including more than 800 successful EOR projects across the world and for 9 ideal reservoir parameter values. The relative importance of the reservoir parameters was determined based on the Analytic Hierarchy Process (AHP) at nine importance levels. The findings showed that among the considered screening parameters, to determine the best EOR technique, lithology of the reservoir is the most influencing parameter. Additionally, almost 74% of the oil reservoirs under study, as a first priority, were eligible for CO<sub>2</sub> injection, either miscible or immiscible. Thermal methods were in the second stage of ranking. The first and second candidate choice for onshore oil reservoirs was immiscible CO<sub>2</sub> and hydrocarbon gas injection, respectively. For offshore reservoirs, CO<sub>2</sub> injection and steam flooding were the best choices. Also, miscible N<sub>2</sub> injection was the least important technique, due to the huge difference of considered reservoir pressure with minimum miscibility pressure (MMP) of N<sub>2</sub> injection. The proposed technique is computationally fast and less expensive than field simulation studies for ranking EOR projects for any oil reservoir in the world.

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## 1. Introduction

Today, a large portion of oil produced in the world comes from matured oil fields that are in the second-half of their life cycles. Meanwhile, due to the costly and time-consuming exploration operation, replacing these hydrocarbon resources with new explorations is difficult. On the other hand, global demand for oil is increasing and it is expected that oil will be the dominating energy resource within the next two decades. With the

increasing conventional oil production rate, recoverable reserves will be decreased and primary and secondary recovery methods like waterflooding cannot produce more than 10%–40% of the initial oil in place. This can result in a large portion of remaining recoverable oil (Dickson et al., 2010; Hashemi-Kiasari et al., 2014; Kang et al., 2014; Takassi et al., 2017).

Dominant oil production from matured oil fields has forced oil companies to consider increasing the recovery factor. In this situation, technologies regarding enhanced oil recovery (EOR) have emerged and proven their capacity to establish a balance between supply and demand in the worldwide energy market (Zendehboudi et al., 2009, 2011; Roustaei, 2014; Madani et al.,

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## Nomenclature

$A^-$	Negative ideal solution
$A^+$	Positive ideal solution
$A_1, A_2, \dots, A_n$	Alternatives
AHP	Analytic Hierarchy Process
$C_1, C_2, \dots, C_n$	Criteria
Capex	Investment Cost \$
CI	Consistency ideal
$CI_i^*$	Relative closeness to ideal solution
COMPO	Composition, fraction
CR	Consistency ratio
$d_i^-$	Distance (Euclidean) of each alternative from negative ideal solution
$d_i^+$	Distance (Euclidean) of each alternative from positive ideal solution
DM	Decision Maker
EOR	Enhanced oil recovery
HC-miscible	Hydro Carbon Miscible
$I$	1, ..., m
IFT	Interfacial Tension, $N/M$
IOR	Improved Oil Recovery
$J$	1, ..., n
$K_n$	Permeability, milli-darcy (md)
Linmap	Linear-Programming for multidimensional analysis of Performance
MCDM	Multi-criteria decision making
$N$	Non-dimensionalized decision matrix
$N_2$	miscible Nitrogen Miscible
NIS	Negative Ideal Solution
Oil sat	Oil saturation, fraction
Perm	Permeability, md
PIS	Positive Ideal Solution
RI	Random index
SAW	Simple Additive Weighting
$S_o$	Oil saturation, fraction
Temp	Temperature, °F
Thick	Thickness, ft
TOPSIS	Technique for order of Preference by Similarity to Ideal
$V$	Non-dimensionalized weighted matrix
$V_{ij}$	$n_{ij}w_{ij}$
Visco	Viscosity, cp
WAG	Water Alternating Gas
$W_{ij}$	Diagonal matrix
$W_j$	Weight of $C_j$
$X_{ij}$	The ratio of $A_i$ to $C_j$
$Y$	Average value of the elements
$\mu$	Dynamic viscosity, cp

and low prices, full investigation, study and screening should be carried out before any decision making process (Kamari and Mohammadi, 2014). Implementation of any EOR project is highly dependent on reservoir rock and fluid properties and it is not feasible to apply one particular method for all of the reservoirs. Full field scale evaluation of an EOR project is a very costly and time-consuming task and evaluation of multi EOR methods for a particular reservoir is usually a hectic job. In fact, the main aim behind the screening and obtaining the best EOR technique for the reservoirs for which no EOR method has been applied on, is to reduce the costs, and time for simulation approaches, and more importantly, to reduce the time of history-matching which is inherently time-consuming. To put it another way, the importance of screening methods is obtaining the best EOR technique without requiring reservoir simulation and history matching tools. Thus, evaluation of an EOR project via primary screening seems to be a very effective method (Bang, 2013).

Screening of EOR methods which aims at finding the best EOR scenario has been carried out before and some results have been published in the literature (Zerfat et al., 2011). There are several research works in the literature that provide clear procedures/strategies for screening criteria, dimensional analysis, and statistical approaches while studying various petroleum production and EOR operations (Al-Bahar et al., 2004; Dickson et al., 2010; Hashemi-Kiasari et al., 2014; Kang et al., 2014; Zendeheboudi et al., 2009, 2011; Taber et al., 1997; Mashayekhizadeh et al., 2014; Gharbi, 2005; Adasani and Bai, 2011; Kamari and Mohammadi, 2014; Bang, 2013; Zerfat et al., 2011).

One of the steps in any EOR process is to study similar projects which have been undertaken successfully in the past (Gharbi and Garrouch, 2001; Moreno et al., 2014). Any screening process usually consists of three main parts; technical and economic aspects, and project location. Technical screening is accomplished through comparing parameters of the desired reservoir with any reservoir that has undergone a successful EOR process. These reservoir parameters might be rock and fluid properties or petrophysical properties. These parameters should be set enough weight on the EOR process.

The second step after technical screening is to evaluate the EOR method from an economical point of view, meaning that much of the recovery factor will be increased after execution of a desired EOR process and whether incremental production from EOR compensates the operational cost or not.

The fact that most EOR projects are costly and time-consuming and have high risk and technical complexity, exposes these projects to failure risk (Mashayekhizadeh et al., 2014; Gharbi, 2005; Bourdarot and Ghedan, 2011). To manage an EOR project and reduce the risk of failure, it is necessary to take the following steps:

- Screening
- Technical evaluation
- Economical evaluation
- Location optimization
- Recovery factor estimation using empirical correlation and the simplified model
- Simulation of the EOR process using a simple 1-D model
- Laboratory tests
- Full field simulation
- Full field economical evaluation
- Pilot testing
- Full field project implementation

Despite the execution of more than 1000 successful EOR projects since 1959, the deployment of these techniques is still limited around the world (Gharbi, 2005; Adasani and Bai, 2011; Kamari and Mohammadi, 2014; Rbeawi, 2013; Alemi et al., 2010).

2019). During the past few years, around 3% of the world oil production has come from EOR operations and this share seems to be increasing every year (Taber et al., 1997; Mashayekhizadeh et al., 2014). EOR methods have drawn much attention to increase the life span of the mature oil fields (Gharbi, 2005; Adasani and Bai, 2011; Kamari and Mohammadi, 2014). Due to the high investment cost (CAPEX), technical complexity and uncertainty in EOR operations and on the other hand, unstable oil market

In the past few decades, screening of EOR techniques has been done at different levels and complexities using different methods. These methods include statistical methods, machine learning, artificial intelligence, simulation, clustering and other composite methods (Dickson et al., 2010; Kang et al., 2014; Taber et al., 1997; Adasani and Bai, 2011; Kamari and Mohammadi, 2014; Bourdarot and Ghedan, 2011; Rbeawi, 2013; Alemi et al., 2010; Clancy et al., 1985; Goodlett et al., 1986; Gharbi, 2000; Jensen et al., 2000; Alvarado et al., 2002; Teletzke et al., 2005; Alkafeef and Zaid, 2007; Frank et al., 2009; Surguchev et al., 2011; Warrlich et al., 2012; Samad et al., 2013; Hama, 2014; Nnang-Avomo et al., 2014; Saleh et al., 2014; Teigland and Kleppe, 2006). In this paper, the main objective is to use TOPSIS technique from the MCDM approach to screen EOR methods for 65 Iranian oil reservoirs. The screening method was employed for 10 different EOR techniques, namely N<sub>2</sub> miscible injection, hydrocarbon gases miscible injection, CO<sub>2</sub> miscible injection, N<sub>2</sub> immiscible injection, hydrocarbon gases immiscible injection, CO<sub>2</sub> immiscible injection, micellar injection, polymer injection, in-situ combustion and steam injection. In this regard, the most updated and effective screening criteria, and real rock and fluid data from 65 Iranian oil reservoirs (both onshore and offshore) were utilized to achieve this goal. For the sake of simplicity, the procedure for screening the aforementioned EOR methods for one of the reservoirs under study (R<sub>59</sub>) is described in detail.

## 2. Methodology

### 2.1. EOR methods

Up to now, different EOR methods have been used across the world including gas injection (either miscible or immiscible), thermal, chemical and microbial methods. The goal of these methods is to improve the reservoir fluid flow through the reservoir rock by increasing temperature and reducing viscosity, reducing the interfacial tension (IFT) between injected fluid and reservoir fluid and eventually reducing capillary pressure, mass transfer or changing the reservoir oil properties (Sheng, 2013; Fathinasab et al., 2015).

Gas injection into reservoir can be performed as either miscible or immiscible including N<sub>2</sub>, CO<sub>2</sub> and hydrocarbon gases or also WAG injection. A number of effective mechanisms facilitating the oil displacement are viscosity and IFT reduction, oil swelling, and escalating the injectivity index (Orr et al., 1982; Jarrell et al., 2002). In addition, injection and production rates, oil–gas density difference, viscosity ratios, oil–gas relative permeabilities, and wetting properties of reservoir rock can influence displacement performance due to gas flooding (Rojas et al., 1991). CO<sub>2</sub> injection, as a secondary and tertiary recovery method, has shown high displacement efficiency and relatively low operation cost and has attracted significant attention in the oil industry. Pure CO<sub>2</sub> can be appropriately mixed with oil within the reservoir which in turn can lead to crude oil viscosity reduction, oil swelling, and therefore prospective oil mobilization (Van Gool and Currie, 2008). Apart from these mechanisms, the formation of carbonic acid and its reaction with reservoir rock can affect the oil production by CO<sub>2</sub> injection method (Bennion and Thomas, 1993). Gas injection methods may be either of two types, miscible and immiscible, to increase the oil sweep efficiency depending on minimum miscibility pressure (MMP). When injection pressure is below MMP, the process is identified as immiscible. However, a collective number of conditions including reservoir temperature and pressure, oil chemical composition, and injected gas composition determine the gas injection process to be of type miscible. It should be pointed out that light-to-medium and heavy crude oil are the best candidate for miscible, and immiscible processes, respectively (Kumar and Mandal, 2017a).

Thermal methods cause viscosity to reduce due to an increase in temperature (Zendehboudi et al., 2014). Heat transfer to the reservoir can be achieved via three ways; steam flooding (Shafiei et al., 2013), hot water injection and in-situ combustion (Kamari et al., 2015). After gas injection, thermal methods include 41% of the total EOR projects in the world. From the production rate point of view, thermal methods produce around two-thirds of the daily oil production by EOR methods and the rest of the methods produce one-third.

In chemical methods, certain chemicals, including polymer flooding (Bai et al., 2008; Guo et al., 2012), micellar flooding (Srivastava et al., 1994), surfactant, alkaline/caustic or gel are injected into the reservoir through the aqueous phase (Dickson et al., 2010; Yellig and Metcalfe, 1980; Carcoana, 1982; Wehunt et al., 2003; Bai et al., 2007; Vahidi and Zargar, 2007; Azamifard et al., 2017). Chemical injection can be used for heavy oil recovery (compared to gas injection) and for ultra-light oil recovery (compared to thermal methods) (Dickson et al., 2010). Chemical injection methods have occupied the third place in terms of usage and include around 8% of the daily oil production in the world from EOR.

In the microbial method, certain micro-organisms are used to recover oil from the reservoir. These micro-organisms produce surfactants inside the reservoir and cause IFT reduction and wettability changes, which can be favorable for oil recovery (Yellig and Metcalfe, 1980).

### 2.2. The technique for order of preference by similarity to ideal solution (TOPSIS)

Today, decision-making and evaluation of existing options and criteria is one of the basic challenges in technical problem solving. To tackle these problems, Multi-Criteria Decision Making (MCDM) is one of the best solutions to rank the available options in a logical and acceptable way.

In recent decades, powerful computing and processing tools are available and thus, we are able to effectively choose the best solution and investigate the interaction between different options.

In MCDM process, the best solutions are obtained among available options. In this method which is a well-organized branch in research, mathematical design is used as a computational tool, aiming to tackle complex problems and rank the available option to support the decision making process (Behzadian et al., 2012; Khamsehchi et al., 2013). MCDM methodologies are implemented in different areas like mathematics, economics, information technology, software engineering, information systems, transportation design, management, and energy management.

In MCDM, a number of options have to be evaluated and compared using multiple criteria. The purpose of MCDM is to help the decision maker in the process of choosing between options. In this way, practical problems are often characterized by a number of conflicting criteria, and there may not be any solutions that are consistent with all the criteria. Therefore, the solution will be based on the decision maker's performance. TOPSIS is based on the notion that the selected alternative should have the shortest distance from the positive ideal solution (PIS) and be farther away from the negative ideal solution (NIS). The final ranking is obtained by the proximity index.

The main steps in MCDM are:

- (1) Establishing system assessment criteria that connects system capabilities to goals
- (2) Development of alternative systems for achievement of goals (creation of options)
- (3) Evaluation of options in terms of criteria
- (4) Use of normative multivariate analysis method



	C <sub>1</sub>	C <sub>2</sub>	...	C <sub>n</sub>
A <sub>1</sub>	X <sub>11</sub>	X <sub>12</sub>	...	X <sub>1n</sub>
A <sub>2</sub>	X <sub>21</sub>	X <sub>22</sub>	...	X <sub>2n</sub>
⋮	⋮	⋮	⋮	⋮
A <sub>m</sub>	X <sub>m1</sub>	X <sub>m2</sub>	...	X <sub>mn</sub>
W	W <sub>1</sub>	W <sub>2</sub>	...	W <sub>n</sub>

Fig. 1. Structure of a decision matrix in MCDM using TOPSIS.

(5) Accepting an alternative as “desirable”

(6) If the final solution is not accepted, collect new information and go to the next multiplication optimization variable.

Steps (1) and (5) are performed at the highest level, while decision makers have a central role, and the other steps are mainly engineering tasks. For step (4), the decision maker should state preferences in relation to the relative importance of the criteria and a method for introducing benchmark criteria.

From thirty years ago, much effort has been made to develop new techniques for MCDM such as AHP, Electere, SAW and TOPSIS (Nureize and Watada, 2010). TOPSIS is one of the most applicable techniques of MCDM to solve real problems, which are very popular among researchers. For the first time, Hwang and Yoon used the TOPSIS method in 1986. In this method, the number of  $n$  options is evaluated using  $n$  number of criteria. This technique is based on the fact that selected options should have the least difference with positive ideal ( $A^+$ ) and the most difference with negative ideal ( $A^-$ ). In general, TOPSIS is a technique to evaluate efficiency of the options and ranking and determining their priority at such a rate that the selected option would be the most similar to the positive ideal (Alemi et al., 2010; Behzadian et al., 2012; Khamehchi et al., 2013; Nureize and Watada, 2010; Wang and Elhag, 2006; Yang and Hung, 2007; Ertugrul and Karakaşoğlu, 2009; Awasthi et al., 2011; Lotfi et al., 2011; Fatahi et al., 2012; Hwang and Masud, 2012; Rostampour, 2012; Vimal et al., 2012; Sadi-Nezhad and Shahnazari-Shahrezaei, 2013; Chen et al., 2014; Esfandiari and Rizvandi, 2014; Kia et al., 2014; Destiny Ugo, 2015).

The overall structure of a MCDM using the TOPSIS technique is the following decision matrix including options and criteria in Fig. 1.

The terms utilized in the decision matrix are briefly explained as follows:

$A_1, A_2, \dots, A_n$ : Possible alternatives (options or candidates) which are selected by decision makers. Alternatives must be mutually different from each other. In this study, they are EOR methods.

$C_1, C_2, \dots, C_n$ : Criteria for which alternatives are selected. A number of criteria can characterize each alternative. In this study, the criteria includes gravity, viscosity, fluid composition, oil saturation, formation lithology, thickness, permeability, depth, and temperature.

$X_{ij}$ : A positive value (up to 9) showing the performance rating of each alternative with respect to each criterion.

$W_j$ : weight of  $C_j$ , which indicates the relative importance of each criterion to the others. The importance of the weights can be

obtained either via a direct way or from the paired comparison. If the weights are obtained from a paired comparison, different methods like AHP and LINMAP can be used. In this study, the weights are obtained from the paired comparison using the AHP method (Saaty, 1990).

Problem solving using the TOPSIS technique includes 6 steps (Nureize and Watada, 2010; Yoon and Hwang, 1995):

**1st step:** quantifying and creating the non-dimensionalized form of the decision matrix ( $N$ ). In this study, the NORM method was used for nondimensionalizing as follows:

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}}, \quad i = 1, \dots, m, \quad j = 1, \dots, n \quad (1)$$

**2nd step:** obtaining non-dimensionalized weighted matrix ( $V$ ): Nondimensionalized matrix ( $N$ ) is multiplied to diagonal matrix ( $W_{ij}$ ) as follows:

$$v_{ij} = n_{ij}w_{ij}, \quad i = 1, \dots, m, \quad j = 1, \dots, n \quad (2)$$

**3rd step:** determination of positive and negative ideal solutions: positive ideal solution ( $A^+$ ) and negative ideal solution ( $A^-$ ) are defined as follows:

$$A^+ = \{v_1^+, \dots, v_n^+\} = \left\{ \left( \max_i v_{ij}, j \in J \right), \left( \min_i v_{ij}, j \in I \right) \right\} \quad (3)$$

$$A^- = \{v_1^-, \dots, v_n^-\} = \left\{ \left( \min_i v_{ij}, j \in J \right), \left( \max_i v_{ij}, j \in I \right) \right\} \quad (4)$$

The best value for positive and negative indexes is the highest and lowest values, respectively. Moreover, the worst value for positive and negative indexes is the lowest and highest values, respectively.

**4th step:** obtaining the distance (Euclidean) of each alternative from positive ( $d_i^+$ ) and negative ( $d_i^-$ ) ideal solutions:

$$d_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2}, \quad i = 1, \dots, m \quad (5)$$

$$d_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2}, \quad i = 1, \dots, m \quad (6)$$

**5th step:** Calculating relative closeness ( $CL^*$ ) to the ideal solution:

$$CL_i^* = \frac{d_i^-}{d_i^- + d_i^+} \quad (7)$$

**6th step:** ranking the alternatives; the alternative that has the biggest  $CL^*$  (closer to unity) has the highest priority.

### 2.3. TOPSIS for EOR method selection

In this study, 65 Iranian hydrocarbon reservoirs (offshore and onshore) were subject to the screening process and for each reservoir, 10 EOR methods were examined. The proposed TOPSIS methodology was able to recommend the most efficient EOR method for each reservoir and also rank the EOR methods. For this purpose, 9 reservoir parameters along with their pertaining rock and fluid data were gathered. The schematic of the proposed workflow is illustrated in Fig. 2.

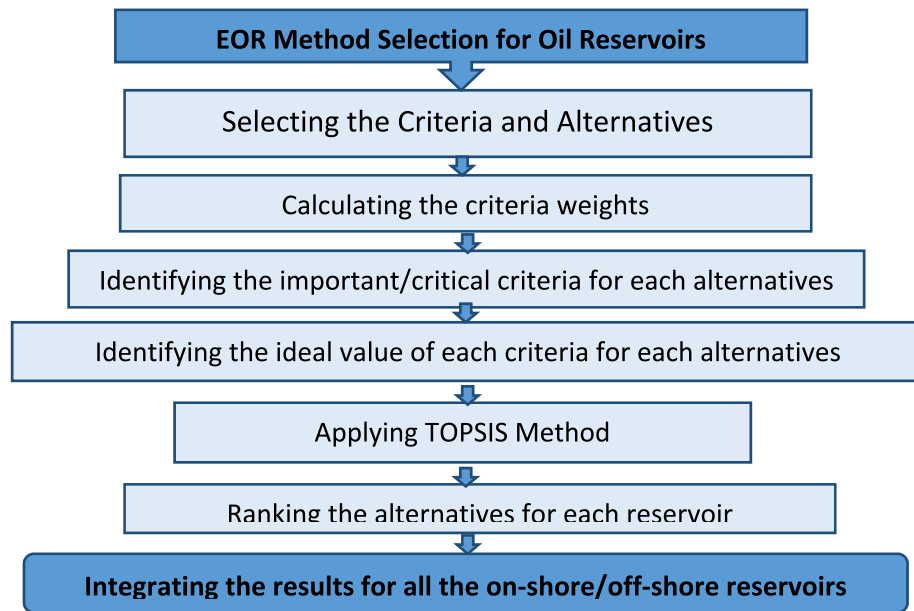


Fig. 2. TOPSIS method for the EOR selection problem.

**Table 1**  
Saaty rating scale.

Intensity of importance	Definition
1	Equal importance
3	Moderate importance of one over another
5	Essential or strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values between the two adjacent judgments

### 2.3.1. Selecting the criteria and alternatives

Screening criteria is usually the first tool for a reservoir engineer in selecting a proper EOR method. Screening criteria for EOR is accomplished by collecting data from successful project and analyzing them to find out important and effective parameters. These criteria determine the application and interval of the selected parameters for an EOR process (Saleh et al., 2014). The criteria and EOR methods used in this work are shown in Fig. 3. 9 reservoir parameters including gravity, viscosity, fluid composition, oil saturation, formation lithology, thickness, permeability, depth and temperature and also 10 EOR methods including N<sub>2</sub> miscible injection, hydrocarbon gases miscible injection, CO<sub>2</sub> miscible injection, N<sub>2</sub> immiscible injection, hydrocarbon gases immiscible injection, CO<sub>2</sub> immiscible injection, micellar injection, polymer injection, in-situ combustion and steam injection were considered for developing the proposed method. Note that the micellar injection is the representative of all micellar, ASP (alkaline–surfactant–polymer), and alkaline injection methods as one unique EOR method throughout this study, the same as what is reported in Taber et al. (1997).

### 2.3.2. Calculating the criteria weights

Initially, each criterion should be assigned a weight. For this purpose, we used the pair wise comparison method, which was used by Saaty et al. in 1990 (Saaty, 1990). In this method, for comparing the importance of different criteria, Saaty proposed the following rating scale (Table 1).

For example, imagine that the decision maker considers the superiority of composition over gravity near equal or intermediate. The value of this judgment will be 2. Also, if permeability

is a little more important than oil saturation, the value of this judgment will be 3. One should note that in a pair wise comparison, the self-priority of each element is equal to 1. Hence, all the elements lying on the diagonal are equal to 1. In Saaty's methodology, if the superiority of element A is equal to 2 over element B, the superiority of element B over element A will be 1/2. According to the data and experts' opinion, the pair wise comparison matrix and the weight of each criterion was determined. Table 2 shows these parameters.

Following the construction of the pair wise matrix, the weight of each criterion should be calculated using the arithmetic averaging method. To calculate the weight of each criterion, we sum up the values of each column, by which each element in the pair wise matrix is divided. This is to normalize the matrix. Then, we calculate the average value of every element in the row of the normalized matrix. These average values are an estimate of the considered weights.

As seen in Fig. 4, the highest and lowest weights are for lithology (0.244) and oil saturation (0.047), respectively.

When using pair-wise comparison between several criteria to determine their relative importance against each other, decision-makers might not make perfect judgments. Therefore, pair wise matrix (Table 2) should be checked to see whether it is accepted or rejected. This process can be carried out by determining the degree of inconsistency of the pair-wise matrix. Generally, the degree of consistency of a matrix or system depends on the decision maker, but Saaty considered 0.1 as an acceptable limit and believed that if the degree of inconsistency exceeds 0.1, it is better to rethink the judgments. In order to calculate the degree of consistency of a matrix, followed by formation of pairwise matrix, first the consistency vector is formed as follows:

1. The elements of each column are divided by the corresponding criterion weight. This leads to a new matrix.
2. All the elements of each row in the new matrix are summed. This yields a column weighted vector characterized by one column and n row.
3. Each element in the weighted vector is then divided by the equivalent criterion weight. The resulting vector is called the consistency vector. Note that average value of the elements in this vector is shown using  $\lambda$ .

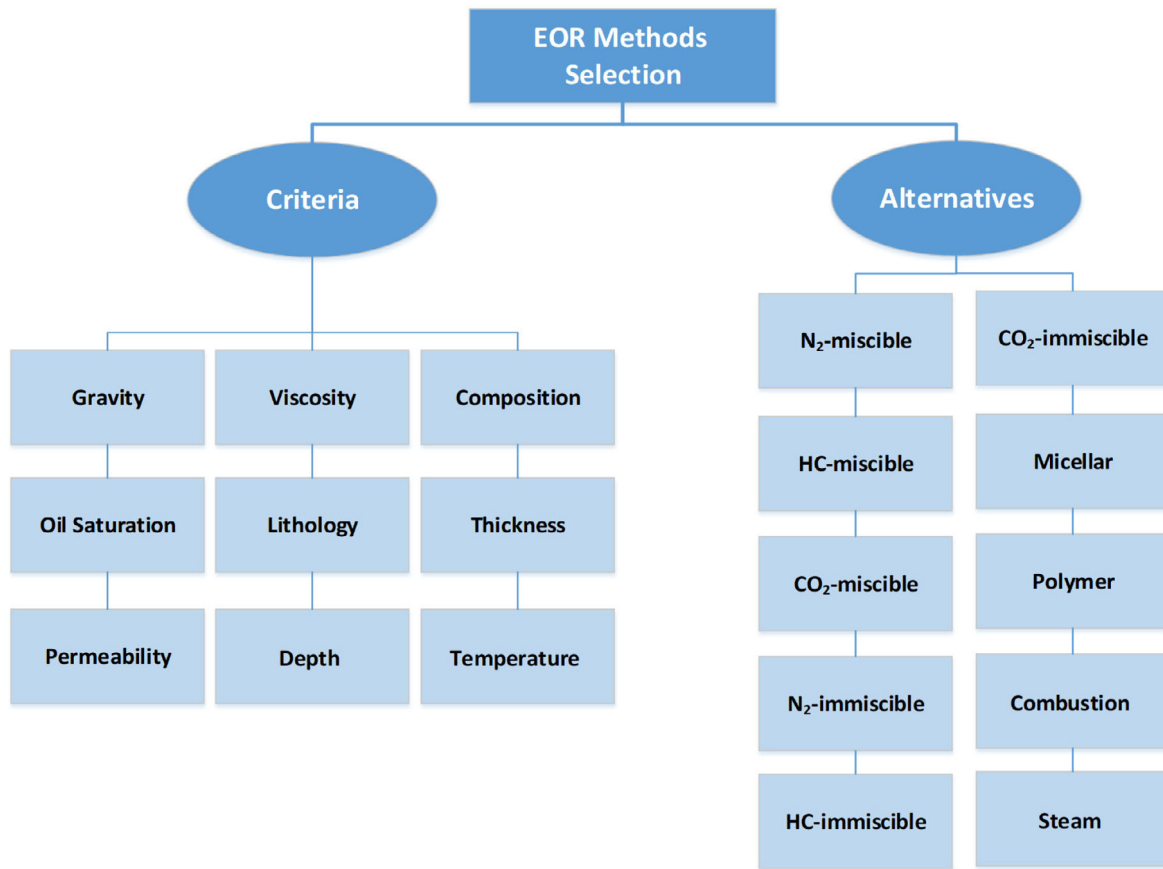


Fig. 3. Criteria and alternatives of the EOR selection problem.

Table 2

The pairwise comparison matrix for criteria.

	Composition	Permeability	Depth	Gravity	Viscosity	Temperature	Oil saturation	Thickness	Lithology
Composition	1	1	1	2	1	1	2	1	1/3
Permeability		1	2	1	1	2	3	2	1/2
Depth			1	1/2	1/2	1	1	1	1/3
Gravity				1	1	2	2	1	1/3
Viscosity					1	2	3	2	1/2
Temperature						1	2	1	1/3
Oil saturation							1	1/2	1/6
Thickness								1	1/3
Lithology									1

Table 3

Important and show-stopper criteria for EOR methods (Dickson et al., 2010).

Important reservoir properties (X denotes show-stopper criteria; ↑ denotes increased weighting)

EOR process	$k_n$	$s_o$	$\mu$	Depth	Pressure	Thick.	Salinity	Temp
Gas injection (miscible/immiscible)	↑	-	↑	-	↑/x	-	-	-
Chemical	↑	-	-	-	-	-	↑	↑/x
Thermal (steam-related)	-	↑	x	↑/x	x	↑	-	-
Hot water	-	↑	x	↑/x	-	↑	-	↑/x

Table 4

Number of applicable EOR methods for all reservoirs.

	N <sub>2</sub> -miscible	HC-miscible	CO <sub>2</sub> -miscible	N <sub>2</sub> -immiscible	HC-immiscible	CO <sub>2</sub> -immiscible	Micellar	Polymer	Combustion	Steam
Number of reservoirs	9	10	54	56	55	12	35	35	35	17

In the next step, the consistency index (CI) is calculated as follows (Alonso and Lamata, 2006):

$$CI = (\lambda - n)/(n - 1) \tag{8}$$

$$CI = (9.23 - 9)/(9 - 1) = 0.03 \tag{9}$$

In which n is the matrix dimension and is equal to 9.

The consistency ratio is calculated using Eq. (10). In this equation, RI is the random index. RI has been calculated for different

**Table 5**

The ideal solution content related to EOR methods.

EOR methods	Gravity (API)	Viscosity (cp)	Composition	Oil saturation (%)	Formation	Permeability (md)	Depth (ft)	Temperature (°F)
N2-imm injection	54	0.07	NC	98.5	NC	2 800	18 500	NC
N2-misc injection	54	0.07	97.56% (C <sub>1</sub> –C <sub>7</sub> )	80	Sandstone or carbonate	2 800	18 500	NC
CO <sub>2</sub> -imm injection	35	0.6	NC	86	NC	1 000	8 500	NC
CO <sub>2</sub> -misc injection	45	0.3	56.4% (C <sub>5</sub> –C <sub>12</sub> )	89	Sandstone or carbonate	4 500	13 365	NC
HC-imm injection	48	0.25	NC	83	NC	1 000	7 000	NC
HC-misc injection	57	0.04	40.21% (C <sub>2</sub> –C <sub>7</sub> )	98	Sandstone or carbonate	5 000	15 900	NC
Combustion injection	38	0.5	Some asphaltic components	94	High porosity sand/sandstone	15 000	400	230
Steam injection	33	3	NC	90	High porosity sand/sandstone	15 001	200	NC
Polymer flooding	42.5	0.4	NC	82	Sandstone preferred	5 500	700	74
Micellar flooding	39	0.4	Light-intermediate	74.5	Sandstone preferred	1 520	2 723	80

Imm = immiscible, Misc = miscible, HC = hydrocarbon, NC = No Comment.

**Table 6**

Technical specifications for reservoir R<sub>59</sub>.

Reservoir	Formation	Depth (ft)	Thick. (ft)	Perm. (md)	Temp. (F)	Oil saturation (%)	Visco. (cp)	Gravity (API)	Composition (C <sub>5</sub> –C <sub>12</sub> , percent)
R <sub>59</sub>	Carbonate	5927	2608	1.13	174	78	4	30	28.11

**Table 7**

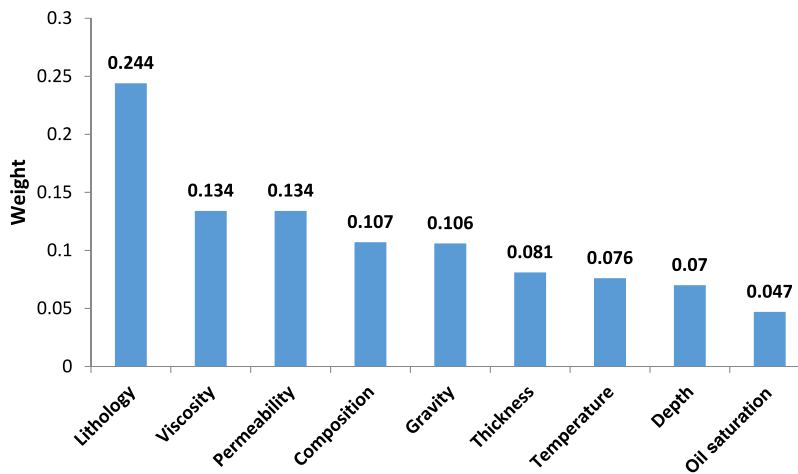
Decision matrix for reservoir R<sub>59</sub>.

	Gravity	Vis.	Compo.	Oil Sat.	Formation	Thick	Perm.	Depth	Temp.
CO <sub>2</sub> -miscible	6.0000	0.6750	4.4856	7.8876	9.0000	5.0000	0.0023	3.9912	5.0000
N <sub>2</sub> -immiscible	5.0000	0.1575	5.0000	7.1269	1.0000	5.0000	0.0036	2.8834	5.0000
HC-immiscible	5.6250	0.5625	5.0000	8.4578	1.0000	5.0000	0.0102	7.6204	5.0000
Micellar	6.9231	0.9000	5.0000	9.0000	3.0000	5.0000	0.0067	9.0000	4.1379
Polymer	6.3529	0.9000	5.0000	8.5610	3.0000	5.0000	0.0018	1.0629	3.8276
Combustion	7.1053	1.1250	5.0000	7.4681	9.0000	5.0000	0.0007	0.6074	9.0000
Steam	8.1818	6.7500	5.0000	7.8000	1.0000	5.0000	0.0007	0.3037	5.0000

**Table 8**

Weighted normalized decision matrix for reservoir R<sub>59</sub>.

	Gravity	Vis.	Compo.	Oil Sat.	Formation	Thick	Perm.	Depth	Temp.
CO <sub>2</sub> -miscible	0.0368	0.0129	0.0368	0.0174	0.1623	0.0306	0.0232	0.0218	0.0261
N <sub>2</sub> -immiscible	0.0307	0.0030	0.0410	0.0157	0.0180	0.0306	0.0372	0.0157	0.0261
HC-immiscible	0.0345	0.0107	0.0410	0.0186	0.0180	0.0306	0.1043	0.0415	0.0261
Micellar	0.0425	0.0172	0.0410	0.0198	0.0541	0.0306	0.0686	0.0491	0.0216
Polymer	0.0390	0.0172	0.0410	0.0189	0.0541	0.0306	0.0190	0.0058	0.0199
Combustion	0.0436	0.0215	0.0410	0.0164	0.1623	0.0306	0.0070	0.0033	0.0469
Steam	0.0502	0.1289	0.0410	0.0172	0.0180	0.0306	0.0070	0.0017	0.0261



**Fig. 4.** Weights of criteria under study.



matrix sizes and for a random matrix ( $9 \times 9$ ) is equal to 1.45 (Alonso and Lamata, 2006).

$$CR = CI/RI \quad (10)$$

$$CR = 0.03/1.45 = 0.02 \quad (11)$$

The CR parameter shows the degree of randomness of matrix elements. Considering that CR is less than 0.1, the degree of inconsistency in this matrix is acceptable.

### 2.3.3. Identifying the important/critical criteria for each alternative

As it was shown in Fig. 2, after the weights of different criteria of the problem were determined, important/critical criteria for each EOR method should be identified. It is worth mentioning that for some EOR methods, one or some parameters may need to be within a specific range and for a specific reservoir, if the parameter cannot satisfy this range, the method will be automatically rejected. This criterion is called the show-stopper criteria or critical criteria. In some EOR methods, some criteria may be more important than the others. For example, in the steam injection method, “depth” criterion is an important/critical parameter (Dickson et al., 2010; Mashayekhizadeh et al., 2014). So, if any reservoir depth is not within an acceptable range, this method cannot be applied for that particular reservoir. Important and show-stopper criteria for EOR methods are mentioned in Table 3. In this table, elements with  $\uparrow$  symbol are important criteria and elements with  $\times$  symbol are show-stoppers for a particular EOR method (Dickson et al., 2010).

It should be noted that with EOR relating technology development, the show-stopper criteria and their corresponding values might change, and thus in this paper, the utilized show-stopper criteria for each EOR method have been taken into account based on the current EOR relating technologies.

Based on the above criteria table, and the gathered characteristic data from 65 oil reservoirs, the applicable EOR methods, which are investigated for each of the 65 reservoirs, are mentioned in Table 4.

As it is seen in Table 4,  $N_2$  injection (immiscible), hydrocarbon gases injection (immiscible) and  $CO_2$  injection (miscible) are applicable in most of the reservoirs (in 56, 55 and 54 reservoirs, respectively).

### 2.3.4. Identifying the ideal value of each criterion for each alternative in EOR methods

It is imperative to note that in any EOR method, each criterion has an ideal value in which similarity of reservoir parameters to the ideal value of the particular criterion will lead to applicability of the EOR method for the reservoir. In the present work, the key screening criteria reported in Taber et al. (1997) and the updated ones in the literature are used (Adasani and Bai, 2011). In addition, the ideal values of the selected criteria for each EOR method have been obtained through the study of a variety of successful worldwide EOR projects reported in Oil & Gas Journal in 1998 to 2012.

The criteria selected here comprise both qualitative parameters (such as formation lithology), and quantitative parameters (such as gravity, viscosity, etc.). For each qualitative criterion, a value of 9 is assigned when the reservoir parameter fully matches with the ideal characteristics specified in Table 5 for any particular EOR technique. For example, consider the lithology criterion in  $CO_2$ -miscible injection. If the target reservoir consists of purely sandstone or carbonate pay zone, a value of 9 is utilized in the decision matrix, while a value less than 9 is incorporated for the reservoirs in which the lithology is not purely sandstone and carbonate. For the quantitative parameters, a value of 9 is assigned when the reservoir parameter is accurately equal to the ideal value reported in Table 5 for any particular EOR technique.

**Table 9**  
Positive and negative ideal solutions for reservoir  $R_{59}$ .

	Gravity	Vis.	Compo.	Oil Sat.	Formation Thick	Perm.	Depth	Temp.	
$A^+$	0.0502	0.1289	0.0410	0.0198	0.1623	0.0306	0.1043	0.0491	0.0469
$A^-$	0.0307	0.0030	0.0368	0.0157	0.0180	0.0306	0.0070	0.0017	0.0199

In the case of non-equality, however, its value is set to a number less than 9 accordingly. For instance, the ideal value of gravity obtained from successful EOR projects in the steam injection method is 33, and for reservoir number 59 ( $R_{59}$ ), gravity is 30. This value is in proportional corrected (reduced) from 9 to 8.18. Note that NC implies No Comment. Because, no specific ideal value was available in the Taber et al. work, and also we cannot consider a maximum or minimum for their roles an average value (5) is dedicated to those described by NC. For the composition criterion in the micellar flooding, those reservoirs identified with light components (API gravity higher than 30) and intermediate components (API gravity between 25 and 30) are assigned 9 and 4.5, respectively, and for the heavy oil reservoirs (API gravity lower than 25), a value less than 4.5 is considered. For the composition criterion in the combustion injection, a positive value up to 9 is considered based on the asphaltene contents of the target reservoir. Based on the explanations, the decision matrix comprised positive-valued elements up to 9.

### 2.3.5. Applying TOPSIS method

We applied TOPSIS for 65 Iranian oil reservoirs and for instance, to see the application procedure, we will observe how this method was applied for reservoir No. 59 ( $R_{59}$ ). This reservoir can be subject to most of the EOR methods (7 methods). Reservoir No. 59 is a producing carbonate oil reservoir and is located onshore. The reservoir depth is 5927 ft and reservoir temperature is 174 °F. The other reservoir parameters such as rock and fluid properties are mentioned in Table 6. The applicable EOR methods for  $R_{59}$  are  $CO_2$ -miscible,  $N_2$ -immiscible, hydrocarbon gases-immiscible, micellar injection, polymer injection, in-situ combustion and steam injection. In the first step, the decision matrix is constructed based on the data from reservoir  $R_{59}$ . In this matrix, for each EOR method based on reservoir data and a comparison with ideal criteria values (Table 5) and necessary corrections, the criteria score of the particular EOR method according to the proposed method by Saaty (Table 1) was calculated. Table 7 shows the decision matrix for this problem.

In the next step, the decision matrix should be normalized. Table 8 shows the normalized decision matrix.

Based on Table 8, the positive and negative ideal values for reservoir 59 are calculated; these values are shown in Table 9.

In the next step, the distance to positive and negative ideal values was calculated. Figs. 5 and 6 show these values.

### 2.3.6. Ranking the alternatives for each reservoir

After completion of steps 1 through 5, the relative closeness of alternatives to the ideal solution ( $CL_i$ ) is calculated; the higher the value of  $CL_i$ , the more desirable the value. The ranking of solutions according to the  $CL_i$  value is shown in Fig. 7.

As it is shown in Figs. 6 and 7, the best EOR method for Reservoir 59, based on the considered criteria in this problem, is  $CO_2$ -immiscible. In-situ combustion and steam injection are in the next level of applicability. The  $CL_i$  value for  $N_2$ -immiscible is 0.141, which is the least.

The quality of screening results is a function of appropriateness of screening criteria, screening algorithm and the accuracy and representativeness of the reservoir parameters used in the screening study. A screening study can only be evaluated by next

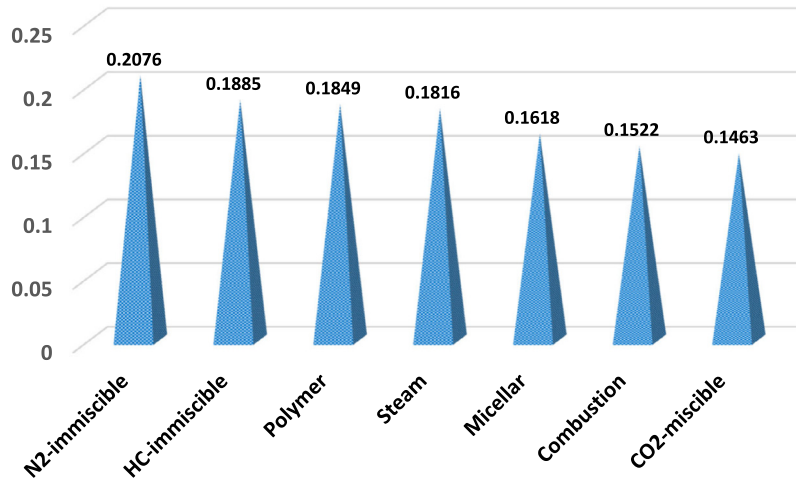


Fig. 5. Separation of alternatives from positive ideal solution for reservoir R<sub>59</sub>.

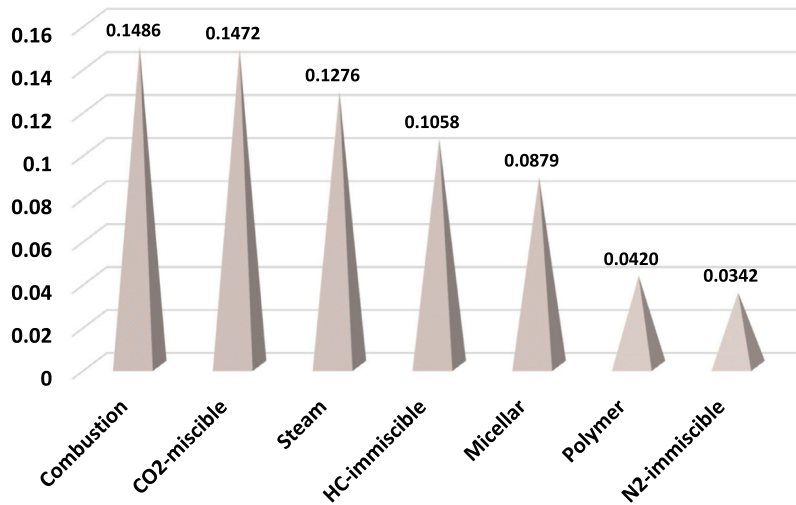


Fig. 6. Separation of alternatives from negative ideal solution for reservoir R<sub>59</sub>.

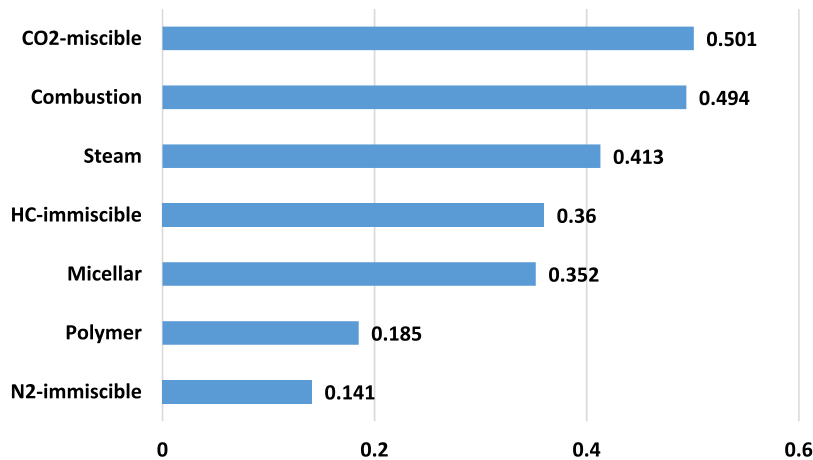


Fig. 7. Ranking the alternatives for reservoir R<sub>59</sub>.

**Table 10**  
Reservoir candidates and their corresponding data adapted from Mashayekhizadeh et al. (2014).

EOR recommended	Reservoir	Porosity (%)	Permeability (md)	Depth (ft)	Gravity (API)	Viscosity (cp)	Temperature (F)	Composition	Oil saturation (%)	Formation	Thickness (ft)	Salinity (ppm)	Pc (psi)	Pi (psi)
Co <sub>2</sub> injection	R2	12.6	0.6	10 656	19.8	2.22	220	Inter-high	72.6	Carbonate	899	–	4145	5678
Co <sub>2</sub> injection	R5	13.7	1.17	10 150	23.7	3.9	225	Inter-high	73	Carbonate	550	200 000	4737	5880
Co <sub>2</sub> injection	R6	9	1.74	10 800	24.8	2.8	235	Inter-high	76	Carbonate	1000	192 000	4658	5775
Co <sub>2</sub> injection	R9	18	3	7 500	32.7	0.57	191	Inter	75.4	Sand and lime	1190	200 000	3747	4437
Co <sub>2</sub> injection	R11	15.4	400	8 885	25.2	0.65	200	Inter-high	73	Carbonate	157	220 000	3800	4639

**Table 11**  
Reservoir candidates and their corresponding data utilized in this study.

EOR recommended	Reservoir	Porosity (%)	Permeability (md)	Depth (ft)	Gravity (API)	Viscosity (cp)	Temperature (F)	Composition	Oil saturation (%)	Formation	Thickness (ft)	Salinity (ppm)	Pc (psi)	Pi (psi)
Co <sub>2</sub> injection	R2	13.8	0.7	10 656	20	2.22	220	High	73	Carbonate	900	–	4145	5680
Co <sub>2</sub> injection	R5	14	1.5	10 500	24	4.1	225	Inter-high	75	Carbonate	600	200 000	4737	5880
Co <sub>2</sub> injection	R6	9	2	10 900	25	2.4	235	Inter-high	78	Carbonate	1000	192 000	4658	5775
Co <sub>2</sub> injection	R9	18	3.2	7 500	33	0.565	191	Inter-high	76	Sand and lime	1190	200 000	3747	4437
Co <sub>2</sub> injection	R11	16	410	8 885	23	0.7	200	Inter	73.3	Carbonate	160	220 000	3800	4640

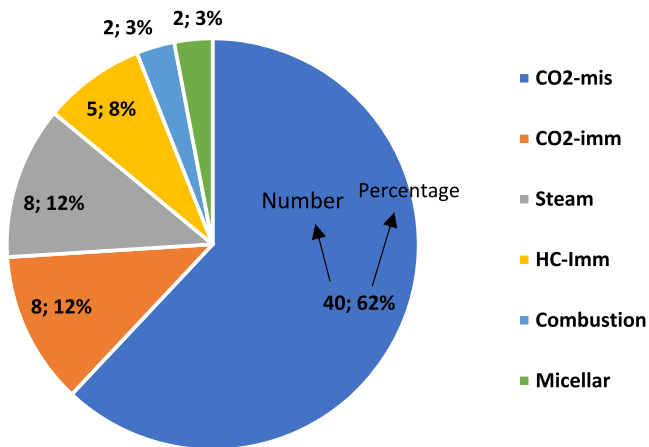


Fig. 8. The percentage of most suitable EOR method for all the reservoirs.

steps of evaluation in the road map of EOR study. For example, a simulation study following EOR screening may or may not confirm the screening results. In this work, no simulation study is performed to check the validity of screening results, because it is hardly possible to simulate 65 different reservoirs for 9 EOR alternatives. Nevertheless, Iranian reservoirs were subject to EOR screening study in a number of publications. For example, Mashayekhizadeh et al. (2014) used the screening algorithm presented by Dickson et al. (2010) to prioritize the EOR methods for 11 Iranian reservoirs, and concluded that CO<sub>2</sub> injection is the best EOR technique for the reservoirs under examination. This is in good agreement with our work where reservoirs with identical data with the ones in the study carried out by Mashayekhizadeh et al. have also ended up with the CO<sub>2</sub> injection as the best EOR technique. Tables 10 and 11 indicate the similar reservoir candidates alongside their corresponding data both in our study and Mashayekhizadeh et al.'s work (2014). Note that in Tables 10 and 11, P<sub>c</sub> and P<sub>i</sub> denote current and initial reservoir pressure, respectively.

After completion of the 6 steps mentioned above and ranking EOR methods for each 65 reservoirs distinctively, eventually, the results are discussed in the next section.

### 3. Results and discussion

According to the screening results, the ranked EOR methods for all the reservoir candidates under study is tabulated in Table 12. The preferred EOR methods for all 65 reservoirs are shown in Table 13. Also, the results of ranked EOR techniques based on reservoir lithology and location are indicated in Tables 14 and 15, respectively.

In this paper, as it is observed in Fig. 8, 74% of the studied Iranian oil reservoirs are privileged to CO<sub>2</sub> injection (62% miscible and 12% immiscible), and in comparison to other EOR methods, they are more frequent. Thus, according to the results of our study, miscible and immiscible CO<sub>2</sub> injections are the most preferred methods for Iranian oil reservoirs (based on the consistency of the reservoir properties with required MMP conditions for these methods). The importance of CO<sub>2</sub>-based EOR methods has been investigated in the literature. For example, Kumar and Mandal (2017a) provided a thorough review study on chemically enhanced water alternating gas/CO<sub>2</sub> injection methods and subsequently their advantage over the conventional EOR methods. Kumar and Mandal (2017b) also investigated the stabilization conditions of CO<sub>2</sub>-foam technique prepared by different types of

ionic and nonionic surfactants alongside different additives such as nanoparticles, polymer, alcohol, etc.

Also, the screening results show that 86% of the studied reservoirs are not good candidates for miscible N<sub>2</sub> because of the inconsistency of the reservoir pressure to required MMP which is necessary for miscibility conditions and only 14% of the reservoirs which are considered as deep and high pressure reservoirs, can be candidate for miscible N<sub>2</sub> injection; however, they are not the first priority compared to other EOR methods. Generally, considering the high pressure required for miscible N<sub>2</sub> injection, most of the reservoirs cannot achieve the required condition for this method (Hemmati-Sarapardeh et al., 2014).

According to the results of our screening, the feasibility of immiscible hydrocarbon gas injection for 55 reservoirs (84.6%) and miscible hydrocarbon gas injection for 10 reservoirs (15.4%) was possible, but in comparison to other EOR methods, none of the reservoirs were privileged as a first method for miscible hydrocarbon gases injection.

Steam injection was not proposed for 48 reservoirs (73.8%) due to the inconsistency of critical parameters like viscosity and reservoir depth. Steam injection was proposed as a first EOR priority in only 8 reservoirs (12.3%).

Also, in-situ combustion was not proposed for 30 reservoirs (46.2%) because of inconsistency of depth and viscosity with required conditions and was proposed only for 2 reservoirs as a first priority EOR method.

In the 30 studied reservoirs (46.2%), polymer flooding was not proposed because of high temperature and polymer degradation risk and for 35 other reservoirs (53.8% including 10 offshore and 25 onshore reservoirs), polymer flooding can be applied but not as a first EOR priority.

Micellar injection was proposed as a first EOR method for only 2 reservoirs (3.1%) and was not approved for 30 reservoirs (46.2%).

Regarding reservoir formation lithology, Table 14 implies that the most first priority EOR method in carbonate, and sandstone reservoirs pertain to CO<sub>2</sub>-miscible injection (38 out of 45 reservoirs, i.e., 84%), and steam injection (6 out of 14, i.e., 43%), respectively. For composite reservoirs, steam and HC-imm injections were the first priority EOR methods (each of which, 2 out of 6 reservoirs, i.e., 33%).

From the reservoir location viewpoint, Table 15 implies that the most first priority EOR method in onshore reservoirs belongs to CO<sub>2</sub>-miscible injection (33 out of 49, i.e., 67%). For offshore reservoirs, steam and CO<sub>2</sub>-miscible injections were the first priority EOR methods (each of which, 7 out of 6 reservoirs, i.e., 44%).

Eventually, according to the results of the screening done in this study, miscible CO<sub>2</sub> injection was the most frequent proposed method (62%). Immiscible CO<sub>2</sub> injection (12%), steam injection (12%), immiscible hydrocarbon gas (HC) injection (8%), in-situ combustion (3%) and micellar injection (3%), respectively, were the next proposed EOR methods for the Iranian oil reservoirs under study. Also, miscible N<sub>2</sub> injection and miscible hydrocarbon gas injection was not proposed as the first desirable EOR method because of the low reservoir pressure. It should be mentioned here that CO<sub>2</sub> injection is proposed not only for enhanced oil recovery, but also for CO<sub>2</sub> sequestration (Gershenson et al., 2015; Ampomah et al., 2017).

The most suitable EOR method is the miscible CO<sub>2</sub> injection (in 40 Reservoirs), then the suitable ones are immiscible CO<sub>2</sub> injection and steam injection (in 8 reservoirs). Other methods including immiscible HC injection, micellar, polymer and immiscible N<sub>2</sub> injection are, respectively, next in ranking.

In addition to selecting the best EOR method for each reservoir, other EOR methods were also ranked, which can be quite

**Table 12**

The ranked EOR methods for all the reservoir candidates under study.

Reservoir candidate	EOR technique									
	N2-misc	HC-misc	CO2-misc	N2-imm	HC-imm	CO2-imm	Micellar	Polymer	Combustion	Steam
R1	Rank Score		1 0.603	4 0.194	3 0.446				2 0.591	
R2	Rank Score			5 0.151	3 0.588	1 0.937	2 0.628	4 0.389		
R3	Rank Score		4 0.37	5 0.235	1 0.769		2 0.716	3 0.412		
R4	Rank Score			6 0.193	3 0.567	1 0.713	2 0.633	5 0.38	4 0.431	
R5	Rank Score		1 0.703	3 0.065	2 0.351					
R6	Rank Score		2 0.594	6 0.146	4 0.397		3 0.47	5 0.308	1 0.595	
R7	Rank Score			5 0.061	4 0.268	1 0.851	2 0.386	3 0.31		
R8	Rank Score		1 0.612	6 0.151	4 0.412		3 0.467	5 0.307	2 0.597	
R9	Rank Score	2 0.298	3 0.286	1 0.719						
R10	Rank Score		1 0.695	5 0.112	3 0.342		2 0.412	4 0.322		
R11	Rank Score		1 0.703	3 0.067	2 0.349					
R12	Rank Score		1 0.689	3 0.117	2 0.363					
R13	Rank Score		1 0.693	3 0.128	2 0.356					
R14	Rank Score		4 0.376	5 0.217	1 0.767		2 0.72	3 0.41		
R15	Rank Score		5 0.3	6 0.23	2 0.673		1 0.681	4 0.35	3 0.401	
R16	Rank Score		1 0.618	6 0.166	4 0.42		3 0.457	5 0.307	2 0.605	
R17	Rank Score		1 0.599	4 0.195	3 0.451				2 0.589	
R18	Rank Score	2 0.298	3 0.286	1 0.719						
R19	Rank Score		3 0.532	1 0.678	4 0.37				2 0.643	
R20	Rank Score		1 0.673	5 0.081	3 0.32		2 0.421	4 0.317		
R21	Rank Score	2 0.297	3 0.286	1 0.719						
R22	Rank Score	2 0.298	3 0.286	1 0.719						
R23	Rank Score	2 0.322	3 0.298	1 0.706						
R24	Rank Score	2 0.298	3 0.286	1 0.719						
R25	Rank Score		1 0.504	5 0.169	4 0.394				2 0.482	3 0.396
R26	Rank Score	2 0.301	3 0.287	1 0.718						
R27	Rank Score		1 0.504	5 0.167	4 0.393				2 0.481	3 0.396
R28	Rank Score		7 0.168	4 0.263	2 0.485		3 0.422	6 0.232	5 0.263	1 0.551
R29	Rank Score		4 0.254	7 0.215	3 0.313		2 0.332	6 0.227	5 0.231	1 0.688
R30	Rank Score			6 0.173	3 0.424	2 0.462	4 0.36	7 0.122	5 0.207	1 0.584

(continued on next page)



Table 12 (continued).

Reservoir candidate	EOR technique									
	N2-misc	HC-misc	CO2-misc	N2-imm	HC-imm	CO <sub>2</sub> -imm	Micellar	Polymer	Combustion	Steam
R31	Rank Score		7 0.175	4 0.253	3 0.361		2 0.445	6 0.178	5 0.186	1 0.585
R32	Rank Score			6 0.164	3 0.418	2 0.454	4 0.374	7 0.123	5 0.203	1 0.576
R33	Rank Score		1 0.67	4 0.275	3 0.408				2 0.64	
R34	Rank Score		1 0.676	3 0.172	2 0.373					
R35	Rank Score			4 0	3 0.3	1 0.981			2 0.658	
R36	Rank Score			6 0.172	3 0.425	2 0.461	4 0.361	7 0.122	5 0.208	1 0.583
R37	Rank Score		1 0.716	4 0.281	3 0.383				2 0.659	
R38	Rank Score		1 0.676	5 0.178	3 0.356		2 0.427	4 0.342		
R39	Rank Score			5 0.17	2 0.595	1 0.863	3 0.581	4 0.37		
R40	Rank Score		1 0.687	3 0.117	2 0.364					
R41	Rank Score		6 0.171	5 0.2	2 0.471		3 0.399	7 0.144	4 0.202	1 0.54
R42	Rank Score		1 0.505	5 0.181	3 0.401				2 0.489	4 0.395
R43	Rank Score		1 0.691	5 0.141	3 0.347		2 0.416	4 0.327		
R44	Rank Score		5 0.353	6 0.278	1 0.703		2 0.651	4 0.355	3 0.421	
R45	Rank Score			6 0.125	4 0.356	1 0.841	3 0.437	5 0.296	2 0.63	
R46	Rank Score	3 0.124	2 0.208			1 0.988				
R47	Rank Score		3 0.366	4 0.278	1 0.699				2 0.435	
R48	Rank Score		4 0.429	6 0.367	2 0.662		1 0.75	5 0.421	3 0.479	
R49	Rank Score		1 0.697	3 0.11	2 0.354					
R50	Rank Score		3 0.395	4 0.262	1 0.673				2 0.428	
R51	Rank Score		1 0.504	5 0.165	3 0.395				2 0.481	4 0.394
R52	Rank Score		1 0.702	5 0.108	3 0.339		2 0.407	4 0.317		
R53	Rank Score		1 0.601	4 0.197	3 0.446				2 0.592	
R54	Rank Score			2 0.553	1 0.774	3 0.253				
R55	Rank Score		1 0.503	7 0.144	4 0.362		5 0.348	6 0.184	2 0.496	3 0.413
R56	Rank Score		1 0.51	7 0.141	4 0.361		5 0.347	6 0.187	2 0.488	3 0.408
R57	Rank Score	2 0.56		1 0.641		3 0.444				
R58	Rank Score		1 0.685	5 0.077	3 0.324		2 0.41	4 0.312		
R59	Rank Score		1 0.501	7 0.141	4 0.36		5 0.352	6 0.185	2 0.494	3 0.413
R60	Rank Score		1 0.505	7 0.163	4 0.365		5 0.349	6 0.197	2 0.498	3 0.414

(continued on next page)

**Table 12** (continued).

Reservoir candidate	EOR technique										
		N <sub>2</sub> -misc	HC-misc	CO <sub>2</sub> -misc	N <sub>2</sub> -imm	HC-imm	CO <sub>2</sub> -imm	Micellar	Polymer	Combustion	Steam
R61	Rank Score			2	7	4		5	6	1	3
				0.496	0.127	0.34		0.333	0.25	0.503	0.414
R62	Rank Score			1	5	3		2	4		
				0.704	0.125	0.337		0.408	0.321		
R63	Rank Score			1	6	5		3	4	2	
				0.779	0.23	0.314		0.445	0.369	0.717	
R64	Rank Score				5	3	1	2	4		
					0.066	0.279	0.841	0.366	0.252		
R65	Rank Score				7	4	2	3	6	5	1
					0.143	0.393	0.427	0.394	0.151	0.173	0.566

**Table 13**

The most suitable EOR method for all the reservoirs.

N <sub>2</sub> -miscible	HC-miscible	CO <sub>2</sub> -miscible	N <sub>2</sub> -immiscible	HC-immiscible	CO <sub>2</sub> -immiscible	Micellar	Polymer	Combustion	Steam
-	-	40	-	5	8	2	-	2	8

**Table 14**

Number of first ranked EOR technique based on reservoir lithology.

Reservoir lithology	The first EOR method priority									
	N <sub>2</sub> -mic	HC-misc	CO <sub>2</sub> -misc	N <sub>2</sub> -imm	HC-imm	CO <sub>2</sub> -imm	Micellar	Polymer	Combustion	Steam
Carbonate			38			5			2	
Sandstone			2		3	2	1			6
Composite					2	1	1			2

**Table 15**

Number of first ranked EOR technique based on reservoir location.

Reservoir location	The first EOR method priority									
	N <sub>2</sub> -mic	HC-misc	CO <sub>2</sub> -misc	N <sub>2</sub> -imm	HC-imm	CO <sub>2</sub> -imm	Micellar	Polymer	Combustion	Steam
Onshore			33		5	6	2		2	1
Offshore			7			2				7

**Table 16**

The first and second priority of EOR methods for all the reservoirs.

	First priority									
	N <sub>2</sub> -Miscible	HC-miscible	CO <sub>2</sub> -miscible	N <sub>2</sub> -immiscible	HC-immiscible	CO <sub>2</sub> -immiscible	Micellar	Polymer	Combustion	Steam
Second priority	N <sub>2</sub> -Miscible		8							
	HC-Miscible		1				1			
	CO <sub>2</sub> -miscible								2	
	N <sub>2</sub> -immiscible									
	HC-immiscible			7			1	2		2
	CO <sub>2</sub> -immiscible									4
	Micellar			7			3	4		2
	Polymer									
	Combustion			17			2	2		
	Steam									

useful for decision makers. In this study, we only considered technical parameters and other influencing factors like economic feasibility and availability of facilities and technologies were not included in our work, which may be considered in future studies.

It is worth mentioning that there is no limitation on the incorporated qualitative and quantitative criteria in the TOPSIS algorithm. In fact, the criteria pertaining to any reservoir around the world including the production mechanisms, geological structures, and fluid/rock parameters can be embedded in the TOPSIS method. Therefore, TOPSIS can be used for any worldwide reservoir for the purpose of screening EOR methods. Also, the proposed technique in this study is much more prompt and less expensive than a full field simulation study or pilot project. Table 16 shows the results of first and second priority of EOR methods for all reservoirs.

Fig. 9 shows the number of EOR methods based on first, second and third priority.

#### 4. Conclusions

In this study, the importance of EOR screening was highlighted prior to any decision making for field application. The ideal values of the desired criteria were selected from several successful EOR projects across the world. Also, a data bank consisting of rock and fluid properties of 65 oil reservoirs (onshore and offshore) were acquired and real reservoir properties were compared with ideal values of desired criteria. The implemented method was TOPSIS, which is one of the MCDM techniques. We considered 10 widely-used EOR methods for our screening. To determine the importance of screening criteria, a pair wise comparison method was used. Lithology was the most important criteria and other important criteria were viscosity, permeability, composition, gravity, thickness, temperature, depth and oil saturation, respectively. The results show that 74% of the studied reservoirs

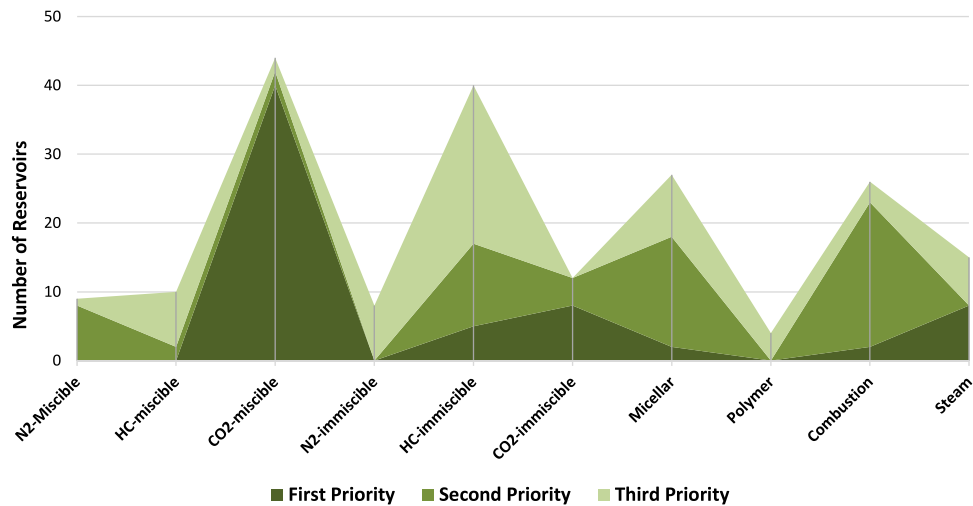


Fig. 9. The three EOR methods with highest priority for all the reservoirs.

were suitable for CO<sub>2</sub> injection (62% as miscible and 12% as immiscible), which is the most suitable EOR method among the others. Thus, CO<sub>2</sub> injection is recommended for the studied reservoirs based on the required Minimum Miscibility Pressure (MMP). Miscible N<sub>2</sub> injection was not recommended because of the highly required reservoir pressure and the most important constraints for implementation of thermal methods for Iranian oil reservoirs are viscosity and reservoir depth. Also, most of the studied reservoirs were not suitable for chemical and polymer flooding due to the high reservoir temperature. At the end, the EOR methods for each reservoir were ranked which can be quite useful for the decision-making process. For 17 reservoirs, in which CO<sub>2</sub>-miscible injection was the first priority, in-situ combustion was the second method and among the 65 considered reservoirs, a majority of them followed this kind of ranking for EOR priority. The proposed technique in this study can be implemented for any worldwide reservoir for the purpose of screening EOR methods.

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