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Research paper

Multi-criteria decision making approaches to select appropriate enhanced oil recovery techniques in petroleum industries

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ABSTRACT

To select the optimum methods, such criteria like reservoir heterogeneity, reservoir pressure, reservoir temperature, crude oil type API (American Petroleum Institute), and brine salinity. EOR methods contained water flooding, chemical flooding, nanofluids injection, CO_2 (carbon dioxide) injection, SAGD/WAG (Surfactant assisted gas drainage/water alternative gas injection), and hybrid injection. Multi-criteria decision-making methods of FTOPSIS (a fuzzy technique for order preference by similarity to ideal solution) and FAHP (fuzzy analytic hierarchy process) were used to select the optimum in the EOR method. The hybrid injection is considered the preferable oil recovery enhancement method in both FTOPSIS and FAHP methods. It has a normalized weight of 74% and 23% for FTOPSIS and FAHP, respectively. In the FTOPSIS method, SAGD/WAG and CO_2 methods are the second and third preferred enhanced oil recovery methods with the normalized weight of 65% and 56%, respectively. In the FAHP method, CO2 and SAGD/WAG methods are the second and third preferred enhanced oil recovery methods with the normalized weight of 19% and 14%.

1. Introduction

To overcome the enormous demands of various industries to crude oil supplements and their products, petroleum industries have developed and proposed novel techniques to increase the oil production rate (Zoback, 2007; Adham et al., 2018; Davarpanah et al., 2018; Yang et al., 2021; Bai et al., 2021; Jiang et al., 2018; Liu et al., 2020; Yang and Sowmya, 2015; Zhang et al., 2019a,b; Awan et al., 2020; Bafkar, 2020). Enhanced oil recovery methods consisted of primary, secondary, and tertiary techniques, depending on reservoir heterogeneity and characteristics (Salehi et al., 2008; Pande and Orr, 1994; Sun et al., 2013; Hu et al., 2020a; Chen et al., 2021; Zuo et al., 2015, 2017; Abedini and Zhang, 2020; Zhang et al., 2020a; Huang et al., 2020a). Primary enhanced oil recovery methods are considered conventional oil recovery methods requiring no special requirement and additional facilities to produce oil (Menad et al., 2019; Shokry and Tawfik, 2010; Khanamiri et al., 2015; Zhang et al., 2020b; Alam et al., 2021; Kazemi and Yang, 2021, 2019; Zheng et al., 2021a,b; Huang et al., 2020b). In these methods, oil has been produced by natural mechanism drives and has been lasted until the wellhead pressure cannot provide sufficient energy to mobilize the oil from wellbores (Zhu et al., 2020a; Mao et al., 2019; Lin et al., 2020; Korolev et al., 2020; Davarpanah and Mirshekari, 2019d; Rabbani et al., 2018; Davarpanah, 2019). In this stage, it is recommended to implement secondary and tertiary EOR methods to improve oil production (Yang et al., 2015; Ma et al., 2021; Sabukevich et al., 2020; Palyanitsina and Sukhikh, 2020; Sun et al., 2020; Zhu et al., 2020b). These methods included chemical, thermal, and hybrid application of EOR methods (Zhang et al., 2021; Xue et al., 2020). Chemical flooding has contained foam, polymer, surfactant, alkaline, and nanoparticle flooding to improve oil recovery (Davarpanah, 2018; Davarpanah and Mirshekari, 2020; Davarpanah et al., 2019b). Foams can be applied in the flooding system to block the gas pathways, which helped increase the oil mobilization through porous media (Hu et al., 2020c; Lotfollahi et al., 2015; Sie and Nguyen, 2020; Rogachev et al., 2019; Galkin and Koltyrin, 2021). Surfactants are other helpful chemical agents to change the reservoir rocks' wettability that can be used as the preferable methods to enhance oil recovery (Nesic et al., 2020; Hu et al., 2020b; Valizadeh et al., 2019; Sepahvand et al., 2021; Jalali Sarvestani and Charehjou, 2021). It was experimentally investigated by different surfactant types to distinguish the

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Table 1
Definitions of criteria and functions.

Criteria	Functions
Reservoir heterogeneity (C_1)	Water flooding
Reservoir pressure (C_2)	Chemical flooding
Reservoir temperature (C_3)	Nanofluids injection
Crude oil type (API) (C_4)	CO_2 injection
Brine salinity (C_5)	SAGD/WAG
	Hybrid injection

efficiency of each surfactant on the wettability alteration (Esfandyari et al., 2020c,a; Pan et al., 2020; Esfandyari et al., 2020b; Jia et al., 2021; Maina et al., 2020; Nnaemeka, 2020; Nwankwo et al., 2020). Polymers are other types of chemical agents used in heavy oil reservoirs to improve oil mobilization through porous media (Davarpanah and Mirshekari, 2019a, 2018b; Ebadi et al., 2020; A. et al., 2020; Qayyum et al., 2020). It can be done by increasing the water viscosity, and therefore, oil can be mobilized more efficiently (Mandal, 2015; Brown et al., 1996; Maghzi et al., 2013; Ali et al., 2020; Davarpanah, 2020). As foams, polymers, and surfactants can be used in different EOR techniques simultaneously, they can be used as hybrid techniques in some particular circumstances. Thermal EOR methods are considered effective techniques, especially in tight and low permeable reservoirs with low oil production due to the low permeability of the porous media (Lu and Davarpanah, 2020). Therefore, thermal injection such as CO_2 injection would be crucial to reduce the oil viscosity (Davarpanah and Mirshekari, 2019b; Mazarei et al., 2019; Davarpanah and Mirshekari, 2019c; Davarpanah et al., 2019a; Daryayehsalameh et al., 2021). It can help the crude oil be more mobilized through porous media and improve the oil production rate (Alvarado and Manrique, 2010; Hu et al., 2020d; Amann-Hildenbr et al., 2012; Huang and Ge, 2020; Davarpanah and Mirshekari, 2018a). Surfactant-assisted gas drainage (SAGD) and water alternating gas injection (WAG) are two applicable EOR techniques as they can provide two tasks in particular circumstances (Ebadati et al., 2019). SAG can be sued as a wettability alteration and reduce the oil viscosity used as a hybrid method. Thereby, it can provide better results than implementing special techniques (Ampomah et al., 2016; Wang et al., 2020; Ranaee et al., 2019; Ren et al., 2019). Chamoli (2015) proposed a fuzzy model by FTOPSIS and FAHP to predict the performance of roughened V channel. He considered friction factor ratio, Nusselt number, and thermohydraulic parameters as performance defining attributes (Chamoli, 2015). Davarpanah et al. (2019) developed a fuzzy model to investigate the crucial factors on the hydraulic fracturing techniques and which parameter has been more effective in hydraulic fracturing performances (Davarpanah et al., 2019c).

Due to the importance of multi-criteria decision-making methods in solving complex issues and complex issues, these techniques would be preferable in selecting optimum EOR techniques. This method is based on the specialist decision and their experiences due to the crucial criteria that impact the oil recovery factor. FTOPSIS and FAHP were used in this study to select the optimum EOR method that can be applied in field applications.

2. Methods

The process of multi-criteria decision-making is schematically depicted in Fig. 1. The criteria and functions are depicted in Table 1.

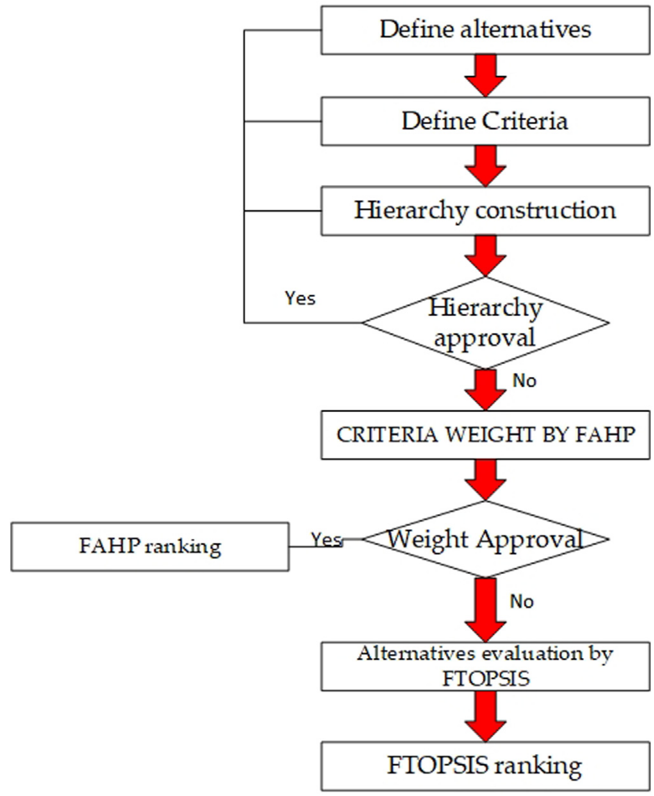

Fig. 1. Schematic of multi-criteria decision making.

Table 2
The procedure of FTOPSIS method.

Step	Description
1	The alternatives and criteria were defined firstly to create the decision matrix. Criteria and alternatives are defined as i and j, respectively. It is calculated via Eq. (1).
2	Ideal (F^+) and non-ideal (F^-) parameters were defined to solve the issues. It is calculated via Eqs. (2) and (3).
3	Ideal (S^+) and non-ideal (S^-) solutions were defined to solve the issues. It is calculated via Eqs. (4) and (5).
4	Relative closeness (C^+) is calculated via equation six, and then the enhanced oil recovery methods were prioritized.

2.1. (FTOPSIS) fuzzy technique for order preference by similarity to the ideal solution method

FTOPSIS is one of the applicable methods that can be a decisive attribute factor to solve multi-decision-making issues provided and improved by Hwang and Yoon. They improved this method to implement as the substitution for the ELECTRE (ELimination Et Choix Traduisant la REalité) method (Davarpanah et al., 2019c; Abasi et al., 2015, 2020). Regarding the complexity and dependency of reservoir characteristics in enhanced oil recovery techniques and determine the efficient method before any field application, FTOPSIS is one of the applicable techniques instead of numerical and analytical models. The process of this method is sequentially explained in Table 2 (Heravi et al., 2017; Khojastehmehr et al., 2019).

The decision matrix is created via Eq. (1).

$$r_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X_{ij}^2}} \quad (1)$$

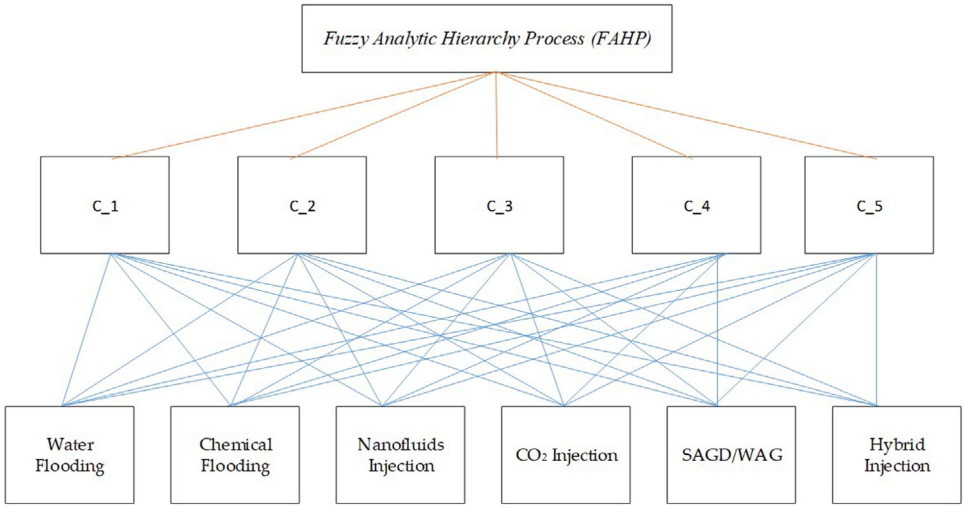

Fig. 2. Schematic hierarchy structure.

Table 3
The procedure of FAHP method.

Step	Description
1	The structure of the hierarchy procedure should be designed to identify the criteria and functions and how they are related together. Functions and criteria are explicitly defined in Table 1. The hierarchy structure is schematically depicted in Fig. 2.
2	Fuzzy pairing matrixes were defined as Eq. (7).
3	The solutions parameter is calculated as Eq. (8).
4	Criteria weights are calculated from Eq. (9).
5	Triangular fuzzy numbers were defined and categorized.

Table 4
Triangular fuzzy numbers Linguistic terms to compare attributes.

Triangular fuzzy numbers	Definition
(1,1,1)	Just equal
(1/2,1,3/2)	Equally important
(1,3/2,2)	Weakly important
(3/2,2,5/2)	Moderately important
(2,5/2,3)	Strongly important
(5/2,3,7/2)	Important

The ideal and non-ideal parameters were calculated accordingly as following equations.

$$F^- = \left\{ (\min_i v_{ij} | j \in J), \left(\max_i v_{ij} | j \in \acute{J} \right) | i = 1, 2, \ldots m \right\} = \left\{ v_1^-, v_2^-, \ldots, v_j^-, \ldots v_n^- \right\} \quad (2)$$

$$F^+ = \left\{ (\max_i v_{ij} | j \in J), \left(\min_i v_{ij} | j \in \acute{J} \right) | i = 1, 2, \ldots m \right\}$$

Table 6
Fuzzy technique for order preference by the similarity of ideal solution parameters in FTOPSIS method.

i	S_i^*	S_i^-	C_i^*
1	0.0768	0.2016	0.7241
2	0.1247	0.09361	0.4288
3	0.1153	0.09417	0.4496
4	0.1026	0.1834	0.6413
5	0.1174	0.1762	0.6001
6	0.2389	0.1084	0.3121

$$= \left\{ v_1^*, v_2^*, \ldots, v_j^*, \ldots v_n^* \right\} \quad (3)$$

The ideal and non-ideal solutions were calculated accordingly as following equations.

$$S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2} \quad i = from\ 1\ to\ m \quad (4)$$

$$S_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^*)^2} \quad i = from\ 1\ to\ m \quad (5)$$

$$C_i^+ = \frac{S_i^-}{S_i^- + S_i^+} \quad 0 < C_i^+ < 1 \quad (6)$$

2.2. FAHP (Fuzzy analytic hierarchy process)

This method is one of the appropriate and useful decision-making criteria methods, which firstly defined by Sun (2010) and Rostamzadeh et al. (2011) to identify the multi-criteria decision-making issues by providing appropriate prioritization for the problem solutions (Rostamzadeh and Sofian, 2011; Sun, 2010).

Table 5
Fuzzy comparison matrixes for influential criteria in FTOPSIS method.

Criteria	Reservoir heterogeneity	Reservoir pressure	Reservoir temperature	Crude oil API	Brine salinity
Reservoir heterogeneity	(1, 1, 1)	(3, 5, 7)	$(\frac{1}{9}, \frac{1}{7}, \frac{1}{5})$	$(\frac{1}{7}, \frac{1}{5}, \frac{1}{3})$	$(\mathbf{\frac{1}{5}}, \mathbf{\frac{1}{3}}, \mathbf{1})$
Reservoir pressure	$(\frac{1}{7}, \frac{1}{5}, \frac{1}{3})$	(1, 1, 1)	$(\frac{1}{5}, \frac{1}{3}, 1)$	(1, 1, 1)	(**1**, **3**, **5**)
Reservoir temperature	(5, 7, 9)	(1, 3, 5)	(1, 1, 1)	(1, 3, 5)	(**3**, **5**, **7**)
Crude oil type (API)	(3, 5, 7)	(1, 1, 1)	$(\frac{1}{5}, \frac{1}{3}, 1)$	(1, 1, 1)	(**1**, **3**, **5**)
Brine salinity	(1, 3, 5)	$(\frac{1}{5}, \frac{1}{3}, 1)$	$(\frac{1}{7}, \frac{1}{5}, \frac{1}{3})$	$(\frac{1}{5}, \frac{1}{3}, 1)$	(**1**, **1**, **1**)

Table 7
The efficiency of the FTOPSIS technique to evaluate the enhanced oil recovery methods.

Rank	EOR schemes	Normalized weight (%)
6	Water flooding	19
5	Chemical flooding	38
4	Nanofluids injection	45
3	CO_2 injection	56
2	SAGD/WAG	65
1	Hybrid injection	74

Decision-makers can use it to finalize the incomplete issues. The procedure of FAHP is explained in Table 3 in more detail.

The hierarchy structure is schematically depicted in Fig. 2. Fuzzy pairing matrix is defined via Eq. (7) by the consideration of a fuzzy number of

$$\tilde{a}_{ij} = \begin{cases} 1 & i = j \\ \tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9} \text{ or } \tilde{1}^{-1}, \tilde{3}^{-1}, \tilde{5}^{-1}, \tilde{7}^{-1}, \tilde{9}^{-1} & i \neq j \end{cases}$$

$$\tilde{A} = \begin{bmatrix} 1 & \cdots & \tilde{a}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \cdots & 1 \end{bmatrix} \tag{7}$$

Then, the solutions parameter is calculated from the following equation;

$$S_i = \sum_{j=1}^{m} M_{gi}^{j} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right]^{-1} \tag{8}$$

Finally, fuzzy triangular numbers were defined and categorized.

$$\acute{w} = (d(A_1), d(A_2), \ldots, d(A_n))^T \tag{9}$$

It is statistically depicted in Table 4.

3. Results

3.1. Fuzzy technique for order preference by the similarity of an ideal solution (FTOPSIS)

To be more precise about the applicability of enhanced oil recovery techniques, the following criteria should be done appropriately before selecting the best method. First, the decision matrix should be normalized and weighted to determine the idealization of the solutions. In the next step, the ideal decision matrix has been chosen to order the enhanced method preferences. Finally, the most and the least applicable enhanced oil recovery methods have been prioritized to evaluate the efficiency of fuzzy technique for order preference by the similarity of an ideal solution. Fuzzy pairing matrixes for influential criteria are statistically depicted in Table 5.

Ideal (S_i^+) and non-ideal (S_i^-) solutions and its mixture (C_i^+) is statistically depicted in Table 6.

In this stage, the efficiency of the FTOPSIS technique is evaluated by ranking the enhanced oil recovery methods regarding the normalized weight for each method. It is statistically depicted in Table 7.

According to the results of the FTOPSIS method (Table 7), hybrid injection is considered the preferable method for oil recovery enhancement. Hybrid injectivity scenarios contained the simultaneous or sequential injection of thermal and chemical enhanced oil recovery methods. It has a normalized weight of 74%. In the following steps, SAGD/WAG and CO_2 methods are the second and third preferred enhanced oil recovery methods with the normalized weight of 65% and 56%, respectively. Water flooding is considered the least efficient technique that cannot be preferred for secondary and tertiary enhanced oil recovery methods. Its normalized weight is about 19%. Chemically enhanced oil recovery techniques are ranked in the middle of the decision criteria making in FTOPSIS methods related to the reservoir heterogeneity or high costs of these techniques, which cannot be profitable for petroleum industries.

3.2. Fuzzy analytical hierarchy process

To be more accurate about the applicability of enhanced oil recovery techniques, the following criteria should be done appropriately before selecting the best method. First, the decision matrix should be normalized and weighted to determine the idealization of the solutions. In the next step, the ideal decision matrix has been chosen to order the enhanced method preferences for each criterion separately to distinguish each criterion's influential viability. Finally, the most and the least applicable enhanced oil recovery methods have been prioritized to evaluate the efficiency of fuzzy technique for order preference by the

Table 8
Fuzzy comparison matrixes for reservoir heterogeneity criteria in FAHP method.

EOR schemes	Water flooding	Chemical flooding	Nanofluids injection	CO_2 injection	SAGD/WAG	Hybrid injection
Water flooding	(1, 1, 1)	(3, 5, 7)	(1, 3, 5)	(1, 3, 5)	$(\frac{1}{5}, \frac{1}{3}, 1)$	$(\mathbf{\frac{1}{5}}, \mathbf{\frac{1}{3}}, \mathbf{1})$
Chemical flooding	$(\frac{1}{7}, \frac{1}{5}, \frac{1}{3})$	(1, 1, 1)	$(\frac{1}{5}, \frac{1}{3}, 1)$	$(\frac{1}{5}, \frac{1}{3}, 1)$	$(\frac{1}{9}, \frac{1}{7}, \frac{1}{5})$	**(5, 7, 9)**
Nanofluids injection	$(\frac{1}{5}, \frac{1}{3}, 1)$	(1, 3, 5)	(1, 1, 1)	$(\frac{1}{5}, \frac{1}{3}, 1)$	$(\frac{1}{9}, \frac{1}{7}, \frac{1}{5})$	$(\mathbf{\frac{1}{7}}, \mathbf{\frac{1}{5}}, \mathbf{\frac{1}{3}})$
CO_2 injection	$(\frac{1}{5}, \frac{1}{3}, 1)$	(1, 3, 5)	(1, 3, 5)	(1, 1, 1)	$(\frac{1}{7}, \frac{1}{5}, \frac{1}{3})$	$(\mathbf{\frac{1}{7}}, \mathbf{\frac{1}{5}}, \mathbf{\frac{1}{3}})$
SAGD/WAG	(1, 3, 5)	(5, 7, 9)	(5, 7, 9)	(3, 5, 7)	(1, 1, 1)	**(1, 3, 5)**
Hybrid injection	(1, 3, 5)	$(\frac{1}{9}, \frac{1}{7}, \frac{1}{5})$	(3, 5, 7)	(3, 5, 7)	$(\frac{1}{5}, \frac{1}{3}, 1)$	**(1, 1, 1)**

Table 9
Fuzzy comparison matrixes for reservoir pressure criteria in FAHP method.

EOR schemes	Water flooding	Chemical flooding	Nanofluids injection	CO_2 injection	SAGD/WAG	Hybrid injection
Water flooding	(1, 1, 1)	$(\frac{1}{7}, \frac{1}{5}, \frac{1}{3})$	$(\frac{1}{9}, \frac{1}{7}, \frac{1}{5})$	$(\frac{1}{7}, \frac{1}{5}, \frac{1}{3})$	$(\frac{1}{7}, \frac{1}{5}, \frac{1}{3})$	**(1, 3, 5)**
Chemical flooding	(3, 5, 7)	(1, 1, 1)	$(\frac{1}{5}, \frac{1}{3}, 1)$	(1, 1, 1)	(1, 3, 5)	$(\mathbf{\frac{1}{5}}, \mathbf{\frac{1}{3}}, \mathbf{1})$
Nanofluids injection	(5, 7, 9)	(1, 3, 5)	(1, 1, 1)	(1, 3, 5)	(3, 5, 7)	**(3, 5, 7)**
CO_2 injection	(3, 5, 7)	(1, 1, 1)	$(\frac{1}{5}, \frac{1}{3}, 1)$	(1, 1, 1)	(1, 3, 5)	**(1, 3, 5)**
SAGD/WAG	(3, 5, 7)	$(\frac{1}{5}, \frac{1}{3}, 1)$	$(\frac{1}{7}, \frac{1}{5}, \frac{1}{3})$	$(\frac{1}{5}, \frac{1}{3}, 1)$	(1, 1, 1)	**(3, 5, 7)**
Hybrid injection	$(\frac{1}{5}, \frac{1}{3}, 1)$	(1, 3, 5)	$(\frac{1}{7}, \frac{1}{5}, \frac{1}{3})$	$(\frac{1}{5}, \frac{1}{3}, 1)$	$(\frac{1}{7}, \frac{1}{5}, \frac{1}{3})$	**(1, 1, 1)**

Table 10
Fuzzy comparison matrixes for reservoir temperature criteria in the FAHP method.

EOR schemes	Water flooding	Chemical flooding	Nanofluids injection	CO_2 injection	SAGD/WAG	Hybrid injection
Water flooding	(1, 1, 1)	$(\frac{1}{9}, \frac{1}{7}, \frac{1}{5})$	$(\frac{1}{11}, \frac{1}{9}, \frac{1}{7})$	$(\frac{1}{7}, \frac{1}{5}, \frac{1}{3})$	(3, 5, 7)	$(\mathbf{\frac{1}{7}}, \mathbf{\frac{1}{5}}, \mathbf{\frac{1}{3}})$
Chemical flooding	(5, 7, 9)	(1, 1, 1)	$(\frac{1}{5}, \frac{1}{3}, 1)$	(1, 1, 1)	(1, 3, 5)	**(1, 3, 5)**
Nanofluids injection	(7, 9, 11)	(1, 3, 5)	(1, 1, 1)	(1, 3, 5)	(3, 5, 7)	**(1, 3, 5)**
CO_2 injection	(3, 5, 7)	$(\frac{1}{5}, \frac{1}{3}, 1)$	$(\frac{1}{5}, \frac{1}{3}, 1)$	(1, 1, 1)	(1, 3, 5)	**(1, 3, 5)**
SAGD/WAG	$(\frac{1}{7}, \frac{1}{5}, \frac{1}{3})$	$(\frac{1}{5}, \frac{1}{3}, 1)$	$(\frac{1}{7}, \frac{1}{5}, \frac{1}{3})$	$(\frac{1}{5}, \frac{1}{3}, 1)$	(1, 1, 1)	**(3, 5, 7)**
Hybrid injection	(3, 5, 7)	$(\frac{1}{5}, \frac{1}{3}, 1)$	$(\frac{1}{7}, \frac{1}{5}, \frac{1}{3})$	$(\frac{1}{5}, \frac{1}{3}, 1)$	$(\frac{1}{5}, \frac{1}{3}, 1)$	**(1, 1, 1)**

Table 11
Fuzzy comparison matrixes for crude oil type (API) criteria in the FAHP method.

EOR schemes	Water flooding	Chemical flooding	Nanofluids injection	CO_2 injection	SAGD/WAG	Hybrid injection
Water flooding	(1, 1, 1)	(3, 5, 7)	(5, 7, 9)	(1, 3, 5)	(1, 3, 5)	**(1, 3, 5)**
Chemical flooding	$(\frac{1}{7}, \frac{1}{5}, \frac{1}{3})$	(1, 1, 1)	(1, 3, 5)	$(\frac{1}{5}, \frac{1}{3}, 1)$	$(\frac{1}{5}, \frac{1}{3}, 1)$	$(\mathbf{\frac{1}{5}}, \mathbf{\frac{1}{3}}, \mathbf{1})$
Nanofluids injection	$(\frac{1}{9}, \frac{1}{7}, \frac{1}{5})$	$(\frac{1}{5}, \frac{1}{3}, 1)$	(1, 1, 1)	$(\frac{1}{5}, \frac{1}{3}, 1)$	$(\frac{1}{7}, \frac{1}{5}, \frac{1}{3})$	$(\mathbf{\frac{1}{5}}, \mathbf{\frac{1}{3}}, \mathbf{1})$
CO_2 injection	$(\frac{1}{5}, \frac{1}{3}, 1)$	(1, 3, 5)	(1, 3, 5)	(1, 1, 1)	$(\frac{1}{5}, \frac{1}{3}, 1)$	$(\mathbf{\frac{1}{5}}, \mathbf{\frac{1}{3}}, \mathbf{1})$
SAGD/WAG	$(\frac{1}{5}, \frac{1}{3}, 1)$	(1, 3, 5)	(3, 5, 7)	(1, 3, 5)	(1, 1, 1)	**(1, 3, 5)**
Hybrid injection	$(\frac{1}{5}, \frac{1}{3}, 1)$	(1, 3, 5)	(1, 3, 5)	(1, 3, 5)	$(\frac{1}{5}, \frac{1}{3}, 1)$	**(1, 1, 1)**

Table 12
Fuzzy comparison matrixes for brine salinity criteria in FAHP method.

EOR schemes	Water flooding	Chemical flooding	Nanofluids injection	CO_2 injection	SAGD/WAG	Hybrid injection
Water flooding	(1, 1, 1)	$(\frac{1}{7}, \frac{1}{5}, \frac{1}{3})$	(5, 7, 9)	(1, 3, 5)	(1, 3, 5)	**(1, 3, 5)**
Chemical flooding	(3, 5, 7)	(1, 1, 1)	(1, 3, 5)	$(\frac{1}{5}, \frac{1}{3}, 1)$	$(\frac{1}{5}, \frac{1}{3}, 1)$	$(\mathbf{\frac{1}{5}}, \mathbf{\frac{1}{3}}, \mathbf{1})$
Nanofluids injection	$(\frac{1}{9}, \frac{1}{7}, \frac{1}{5})$	$(\frac{1}{5}, \frac{1}{3}, 1)$	(1, 1, 1)	$(\frac{1}{5}, \frac{1}{3}, 1)$	$(\frac{1}{7}, \frac{1}{5}, \frac{1}{3})$	$(\mathbf{\frac{1}{5}}, \mathbf{\frac{1}{3}}, \mathbf{1})$
CO_2 injection	$(\frac{1}{5}, \frac{1}{3}, 1)$	(1, 3, 5)	(1, 3, 5)	(1, 1, 1)	$(\frac{1}{5}, \frac{1}{3}, 1)$	$(\mathbf{\frac{1}{5}}, \mathbf{\frac{1}{3}}, \mathbf{1})$
SAGD/WAG	$(\frac{1}{5}, \frac{1}{3}, 1)$	(1, 3, 5)	(3, 5, 7)	(1, 3, 5)	(1, 1, 1)	**(1, 3, 5)**
Hybrid injection	$(\frac{1}{5}, \frac{1}{3}, 1)$	(1, 3, 5)	(1, 3, 5)	(1, 3, 5)	$(\frac{1}{5}, \frac{1}{3}, 1)$	**(1, 1, 1)**

similarity of an ideal solution. Fuzzy comparison matrixes for influential criteria are statistically depicted in Tables 8–12.

According to the results of the FAHP method (Table 13), hybrid injection is considered the preferable method for oil recovery enhancement. Hybrid injectivity scenarios contained the simultaneous or sequential injection of thermal and chemical enhanced oil recovery methods. It has a normalized weight of 23%. In the following steps, CO_2 and SAGD/WAG methods are the second and third preferred enhanced oil recovery methods with the normalized weight of 19% and 14%, respectively. Water flooding is considered the least efficient technique that cannot be preferred for secondary and tertiary enhanced oil recovery methods. Its normalized weight is about 5%. Chemically enhanced oil recovery techniques are ranked in the middle of the decision criteria making in FAHP methods related to the reservoir heterogeneity or high costs of these techniques, which cannot be profitable for petroleum industries.

Table 13
The efficiency of the FAHP technique to evaluate the enhanced oil recovery methods.

Rank	EOR schemes	Normalized weight (%)
6	Water flooding	5
5	Nanofluids injection	9
4	Chemical flooding	10
3	SAGD/WAG	14
2	CO_2 injection	19
1	Hybrid injection	23

4. Conclusion

Due to the applicability and feasibility of enhanced oil recovery methods in petroleum industries, analytical prediction of optimum methods has always been a significant issue that should be taken into consideration. Among a wide range of enhanced oil recovery (EOR) methods, the common and most applicable methods were chosen to select the optimum EOR method. The hybrid injection is considered the preferable method for oil recovery enhancement in both FTOPSIS and FAHP methods. It has a normalized weight of 74% and 23% for FTOPSIS and FAHP, respectively. In the FTOPSIS method, SAGD/WAG and CO_2 methods are the second and third preferred enhanced oil recovery methods with the normalized weight of 65% and 56%, respectively.

Moreover, In the FAHP method, CO_2 and SAGD/WAG methods are the second and third preferred enhanced oil recovery methods with the normalized weight of 19% and 14%, respectively. Water flooding is considered as the least efficient for both methods that cannot be preferred for secondary and tertiary enhanced oil recovery methods. Its normalized weight is about 19% and 5% for FTOPIS and FAHP, respectively. Consequently, chemically enhanced oil recovery techniques are ranked in the middle of the decision criteria making in FTOPSIS methods related to the reservoir heterogeneity or high costs of these techniques, which cannot be profitable for petroleum industries.

Nomenclature

API	American petroleum institute
EOR	Enhanced oil recovery
FTOPSIS	Fuzzy technique for order preference by similarity to an ideal solution
FAHP	Fuzzy analytic hierarchy process
SAGD	Surfactant assisted gas drainage
WAG	Water alternative gas injection
CO_2	Carbon dioxide
ELECTRE	ELimination Et Choix Traduisant la REalité

CRediT authorship contribution statement

Zhenzhen Wei: Methodology, Writing - original draft. **Shanyu Zhu:** Conceptualization. **Xiaodong Dai:** Investigation, Software. **Xuewu Wang:** Writing - original draft. **Lis M. Yapanto:** Conceptualization, Software. **Inzir Ramilevich Raupov:** Writing - review & editing.

Declaration of competing interest

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

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