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Building shared knowledge for EOR technologies: Screening guideline constructions, dashboards, and advanced data analysis

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BUILDING SHARED KNOWLEDGE FOR EOR TECHNOLOGIES: SCREENING GUIDELINE CONSTRUCTIONS, DASHBOARDS, AND ADVANCED DATA ANALYSIS

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ABSTRACT

Successful implementation of enhanced oil recovery (EOR) technology requires comprehensive knowledge and experiences based on existing EOR projects. EOR screening guidelines and EOR reservoir analog are served as such knowledge which are considered as the first step for a reservoir engineer to determine the next step techniques to improve the ultimate oil recovery from their assets. The objective of this research work is to provide better assistance for EOR selection by using fundamental statistics methods and machine learning techniques.

In this dissertation, a total of 977 worldwide EOR projects with the most uniformed, high-quality, and comprehensive information were collected from scattered publications and sources, which lays the foundation for further analysis and reasoning. Conventional screening guidelines for 12 EOR technologies were updated with the augment of critical parameters (e.g. MMP, net thickness) compared with previous studies. Hierarchical clustering and principal component analysis are applied for the construction of advanced EOR screening models. Furthermore, a hybrid EOR screening system was established with the combination of conventional and advanced screening technology. Finally, reservoir analog technology was applied to the steam flooding projects to detect the most similar case to assist the decision-making process with limited data information. The results show wider applicability from conventional guidelines; an advanced EOR selection model with discriminative screening results; a hybrid model which combines the advantages of conventional and advanced screening technologies; and an accurate reservoir analog results for steam flooding projects.

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1. INTRODUCTION

1.1. STATEMENT AND SIGNIFICANCE OF THE PROBLEM

In the global context of growing energy needs and considering the depletion of oil and gas resources, extending the life of hydrocarbon reservoirs and improving oil recovery is a challenge for all petroleum engineers, especially for reservoir engineers. To improve oil recovery, more than 20 enhanced oil recovery (EOR) techniques have been developed over years. Generally, by applying various EOR technologies to different oil fields, an additional up to 60% of crude oil could be produced from the reservoir. Therefore, EOR technologies are vitally important in the oil industry, and these technologies have been used worldwide.

EOR selection is a complex process that involves reservoir characterization, technology feasibility, and commercial evaluations. In the oil industry, the EOR screening process has been considered as the first step for EOR selection. Since the 1970s, a variety of EOR screening methods have been proposed to find the suitable EOR method for a new candidate reservoir, which could be classified as conventional and advanced screening technology. The conventional screening technology is also called the “go/no-go” approach, where look-up tables are provided for screening based on several reservoir and fluid properties. The common problems of the conventional screening technology are that the screening guidelines are lack of updating, missing critical parameters, region-specific guidelines, and more importantly, has no discriminative power if a candidate reservoir is suitable for multiple EOR methods from the conventional screening results. The advanced screening technology is the implementation of various machine learning algorithms, which has the capability to provide a quantitative information to support decision-making in EOR selection for a given reservoir situation. However, the reliability and accuracy of the established models requires a great amount of data to be fed into the model due to the complexity of problems.

Reservoir analog is an advanced data analysis technique that assists the decision-making process for project design (e.g. well design, injection rate, injection pressure, etc.) by finding the most similar cases. Although the idea of the reservoir analog is only based on the computation of distances, the definition of the distances is very complex in different EOR methods, which requires further discussion and evaluation for the analog results. In the literature, there are only limited studies related to reservoir analog and no reservoir analog evaluation method exists.

To improve the decision-making results for conventional/advanced screening technologies and reservoir analog studies, this research will provide a more comprehensive reservoir and fluid characterization for 12 EOR methods (steam flooding, CO_2 miscible flooding, CO_2 immiscible flooding, etc.) by establishing the most up-to-date datasets with the collection of more valuable information. It will contribute to a better knowledge and more applicable guidelines of worldwide EOR projects. Meanwhile, the implementation of machine learning algorithms will bridge the gap between data science and EOR.

1.2. RESEARCH OBJECTIVE

The ultimate objective of this research is to build an adaptive, web-based, shared knowledge and decision-making system that will assist operators in accessing integrated knowledge of EOR technologies and in selecting EOR methods. The specific objectives are to:

1) Understand the mechanisms and reservoir/fluid characteristics of various EOR technologies.
2) Establish and update the conventional screening guidelines for 12 EOR technologies.
3) Implement machine learning algorithms to provide discriminative EOR screening results.
4) Build a hybrid EOR screening scoring system by combining conventional and advanced screening technologies.
5) Design and evaluate reservoir analogy technology for the worldwide steam flooding projects.
6) Provide a comprehensive platform for online data collection/integration, dashboard visualization, and real-time conventional and advanced data analysis.

1.3. RESEARCH SCOPE

This research aims to study the characteristics of reservoir/fluid properties for different EOR technologies to provide the recommendations for EOR selection and to analog to the similar cases. Figure 1.1 presents the workflow of this research. The research methods are proposed as follows: (1) updating conventional EOR screening guidelines based on fundamental statistical methods; (2) constructing advanced screening guidelines by the implementation of hierarchical clustering algorithm and principal component analysis; (3) establishing EOR screening scoring system with the combination of conventional screening guidelines, random forest, and fuzzy logic; (4) designing and evaluating of reservoir analog techniques.

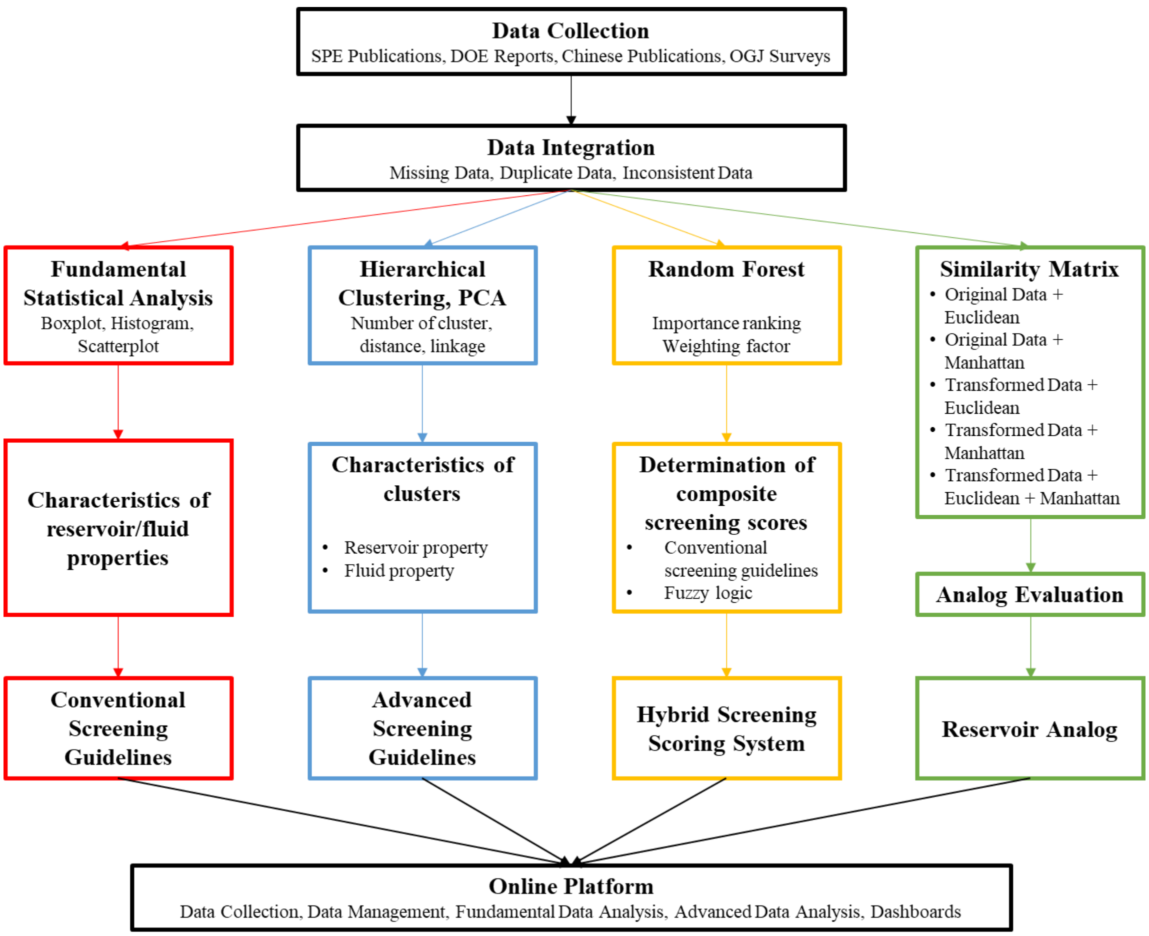

Figure 1.1. Research workflow.

The above study results were presented in two published journals and two completed manuscripts:

1. In the first paper, the conventional screening guidelines for CO_2 miscible flooding projects were updated by collecting information from about 100 publications. Net thickness and minimum miscibility pressure (MMP) were also included in the conventional screening guidelines for the first time in the literature as these parameters are crucial for CO_2 flooding. Duplicate, missing, and inconsistent data problems were detected and resolved to enhance the data quality. Statistical method including boxplots, scatterplots, and histograms were applied to study the applicability of CO_2 miscible flooding technology.
2. In the second paper, a statistical and analytical review was conducted for CO_2 immiscible flooding based on the newly established dataset. At first, statistical methods were applied to study the applicability of CO_2 immiscible flooding by revealing the distributions and ranges of important reservoir and fluid properties. Furthermore, the influences of operation to the productions (CO_2 sources, injection strategy, gas composition, and CO_2 utilization), the performances of fields (CO_2 injection efficiency, incremental oil recovery, and incremental oil production rate per well), and the operational problems were discussed and summarized.
3. In the third paper, a hybrid scoring system was proposed to assist EOR selection by combining the conventional screening technology and the random forest algorithm. At first, twelve EOR conventional screening guidelines were updated and established based on 977 worldwide EOR projects. Then the weighting factors for each EOR method and reservoir/fluid property were determined by the

implementation of random forest and domain knowledge. Finally, the composite score of each EOR method for a candidate reservoir is computed by the fuzzification membership of conventional screening scores and the weighting factors.

4. In the fourth paper, five hidden patterns of steam flooding applications were revealed in the implementation of hierarchical clustering and principal component analysis, and the characteristics of each cluster were studied. Detailed clustering design including the optimal number of clusters, linkages, and distance were discussed to build the best model for steam flooding projects. Meanwhile, reservoir analog technology is also applied to find the most similar case to the candidate case which assists the decision-making for EOR design and EOR performance prediction, especially with the limited reservoir/fluid information.

PAPER

I. IDENTIFICATION OF CO_2 SEQUESTRATION OPPORTUNITIES: CO_2 MISCIBLE FLOODING GUIDELINES

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ABSTRACT

Carbon dioxide (CO_2) flooding has been demonstrated as an economically feasible technique for carbon capture and storage (CCS) via enhanced oil recovery (EOR). In the oil industry, most of the CO_2-EOR projects were implemented in miscible phase (CO_2 miscible flooding), and it has become the most productive EOR method in the United States since 2012. Successful implementation of CO_2 miscible flooding requires comprehensive guidelines about where CO_2 can be applied. With the development of new technology, the suitable conditions for CO_2-EOR have changed. Therefore, updating the guidelines for CO_2-EOR is necessary. In this study, we updated the guidelines for field CO_2 miscible applications in the United States by collecting valuable information from about 100 publications. Significant parameters for CO_2 miscible flooding such as minimum miscibility pressure (MMP) and pay zone net thickness were considered for the first time in comparison with existing research studies. After data processing/cleaning, 207 projects have remained in the dataset. Combination plots were created to explore the ranges, distributions, and cumulative frequencies of each property. Meanwhile, descriptive values were calculated based on statistical methods. The guidelines for CO_2 miscible flooding were presented with important parameters, including porosity, permeability, depth, reservoir temperature, net thickness, oil saturation, oil gravity, oil viscosity, and MMP. The analyzed results show that the reservoir pressure should be greater than 1020 psi to achieve miscibility, and CO_2 miscible flooding project could be successfully applied in a reservoir with an oil gravity greater than 25 °API, oil viscosity less than 4 cp, and a reservoir temperature less than 120 °F.

Key worlds: CO_2 miscible flooding; Screening guidelines; Field applications; Minimum miscibility pressure; Statistical analysis

1. INTRODUCTION

CO_2 sequestration has been proved as an effective method for greenhouse gas emission. Due to the large volume of CO_2 remains in the reservoir, CO_2-EOR has been considered as an option for permanently CO_2 sequestration [1]. In the oil industry, CO_2 miscible flooding is a mature technology in the United States which finds broad applications. With the country-wide development of CO_2 pipelines and the support from government (Department of Energy, tax reduction), the number of CO_2 miscible projects has increased significantly since 1971, and no obvious decrease was observed in the past 40 years based on the fluctuation of oil prices [2], which indicates that CO_2 miscible flooding is economical even at low oil prices.

The main mechanisms of CO_2 miscible flooding are caused by the dissolution of CO_2 into oil, where CO_2 can extract or vaporize hydrocarbons from crude oil. During the injection of CO_2, CO_2 dissolves into the crude oil, leading to oil swelling from 10 to 60 % (of original volume) based on different pressure, temperature, oil composition, and the mole fraction of CO_2 in the oil [3]. At the same time, both oil viscosity and interfacial tension reduce dramatically [4-6], allowing oil to flow easily through the porous medium. Molecular diffusion is also one of the mechanisms for CO_2 miscible flooding where CO_2 diffuses into the matrix and produces oil. However, diffusion is not considered as the main mechanism in high permeable reservoirs because the type of fluid flow is viscous dominated where the viscosity reduction and oil swelling mechanisms are more important. In tight naturally fractured reservoirs, the diffusion mechanism is critical since CO_2 flows slowly and have sufficient time to diffuse into the tight matrix where the gravity forces neglected [7].

Existing field projects have shown that CO_2 miscible flooding could be implemented under different fluid/reservoir conditions, but these projects are only largely successful in the United States. Better understanding of existing CO_2 miscible flooding is an urgent not only to enhance oil recovery, but also to facilitate the utilization of CO_2 in other countries. In literature, many EOR guidelines have been established based on the data availability and the understanding of EOR mechanisms. With more CO_2 projects have been implemented in recent years, it is crucial to update the screening guidelines. Table 1 summarizes existing guidelines for CO_2 miscible flooding that have been published by different investigators. Taber et al. proposed one of the earliest technical criteria for seven main EOR methods based on oil recovery mechanisms [8]. They updated their work in

1997 after more EOR projects were conducted in fields [9, 10]. Gao et al. presented the guidelines based on field experience, but there was no detailed examination included in their results [11]. Mohammed-Singh et al. proposed the criteria for CO_2 huff 'n' puff operations based on the data from Forest Reserve [12], where this guideline could be only used in this field. Al-Adasani and Bai established the most recent comprehensive EOR guidelines based on the *Oil and Gas Journal Biannual EOR Surveys* from 1998 to 2010 [13, 14], which includes the projects from different countries and provides meaningful guidance about where/which EOR technologies could be successfully applied in a new field.

Table 1. Existing guidelines for CO_2 miscible flooding.

Parameters	Taber et al. (1997, [9, 10])	Gao et al. (2010, [11])	Mohammed-Singh et al. (2006, [12])			Aladasani and Bai (2010, [14])
			Light Oils	Medium Oils	Heavy Oils	
Porosity, %		>12	13-32	25-32	12-32	
Permeability, mD	NC	>10	10-3000	150-388	250-350	3-37
Oil Gravity, °API	>22	>27	23-38	17-23	11-14	NC
Viscosity, cp	<10	<10	0.1-8	32-46	415-3000	28-45
Temperature, °F	NC					0-35
Depth, ft	>2500	>2500	1200-12870	3600-4200	1150-4125	82-250
Oil Saturation, % PV	>20					1500-13365
Net Thickness, ft	Wide range		6-60	36-220	200	15-89

The status of EOR screening guidelines is that most of the work was designed for a specific field, which could only be used for one field (limitation of applicability). Also, the worldwide guidelines are lack of the update as collecting and integrating project information is a big challenge. In addition, significant parameters are missing for guidelines. The objective of this paper is to provide the most recent and complete guidelines for CO_2 miscible flooding applications in the United States. To fulfill this goal, a high-quality CO_2 miscible field dataset was established at first. The dataset was collected based on all EOR surveys and with the supplied publications from various sources. Then data processing/cleaning methods were used to solve data quality problems, including inconsistent, noisy, duplicate, and missing data. Boxplots and histograms were combined for visualization to detect the special cases and to find the most applicable reservoir/fluid property ranges. Both graphical and descriptive guidelines are included in this paper.

2. DATA PREPARATION AND DESCRIPTION

A dataset was set up based on the data collected from the Worldwide EOR Surveys reported by the *Oil and Gas Journal* (OGJ) [15-38]. The first EOR survey was published in 1971, and this survey has been a regular biannual OGJ feature for three decades. OGJ EOR surveys provide general information (reservoir properties, fluid properties, locations) of projects that use various EOR technologies, but some important parameters were not included for each EOR method. For CO_2 flooding or gas injection, the minimum miscibility pressure (MMP) and net thickness are also important criteria which should be included in the screening guidelines because the MMP guidelines could provide the condition about when the miscible injection could be achieved, and the net thickness give a range recommendation about when some of the operational problems could be prevented (e.g. early gas breakthrough). Therefore, supplemental sources, including AAPG databases, presentations, reports, and papers are used to assist the updating of dataset [39-80]. Because successful CO_2 miscible flooding projects have only been greatly found in the United States, projects conducted in the United States were analyzed.

The original dataset contained massive duplicate, missing, and inconsistent data due to the long life of CO_2 miscible projects. The blue line in Figure 1 shows the number of CO_2 flooding projects that have been collected for each year. In 1971, only one CO_2 flooding project was recorded in the survey, which was initiated in the Strawn formation in Texas in 1964 [15].

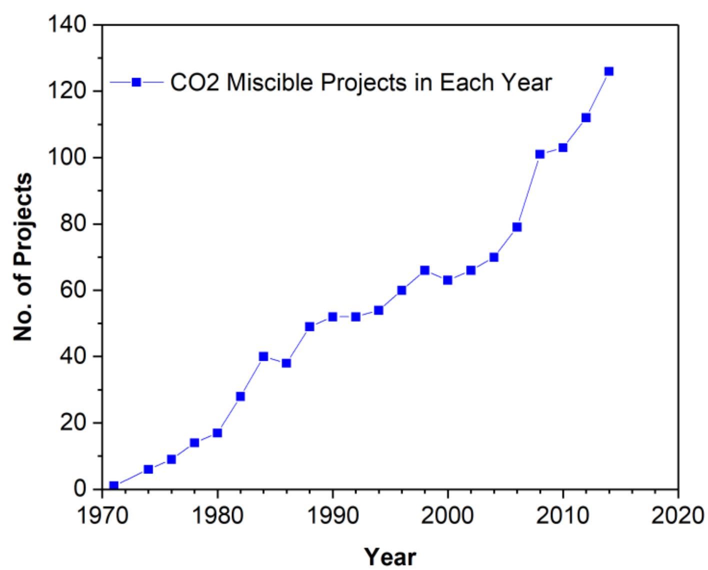

Figure 1. Number of CO_2 flooding projects in the United States in each year. Original Sources: [15-36]; Supplemental Sources: [39-80].

With the construction of CO_2 pipelines from McElmo Dome/Doe Canyon and Bravo Dome to Denver City in Texas, CO_2 projects reached the first burst of growth in the Permian Basin in the early 1980s [81]. After that, more CO_2 pipelines were developed, and more natural CO_2 sources were employed to supply to the oil fields (e.g., Cortez Line, Sheep Mountain Line, etc.), which made the CO_2 projects cheaper and more economical than other EOR methods (around 20 US dollars per barrel) [2]. Along with the support from the Department of Energy (DOE) and the tax act in Texas, the number of CO_2 projects has increased significantly, especially in 2008, and CO_2-EOR has become the most popular EOR method since 2002.

2.1. STATUS OF CO_2-EOR PROJECTS

In the United States, CO_2 flooding is mainly implemented throughout Texas, Louisiana, Mississippi, Wyoming, Oklahoma, Colorado, New Mexico, and Utah. The highlighted areas in the Figure 2 map indicate the current locations and formation types for CO_2 projects. In Montana, Colorado, Louisiana, and Mississippi, CO_2 miscible flooding was only applied in sandstone formations, while in Utah, New Mexico, and Michigan, only carbonate formations were found that conduct CO_2 flooding. Meanwhile, projects in Wyoming, Texas, and Oklahoma implemented CO_2 flooding in both sandstone and carbonate formations. The highest production areas are the Permian Basin, Rangely Field, and Salt Creek Field.

In 2014, twenty four oil companies implemented CO_2 miscible flooding and produced 292735 b/d [36]. Table 2 lists the top five operators and their contributions to the productions, and Figure 3 illustrates the state distributions of CO_2-EOR projects for the top five operators.

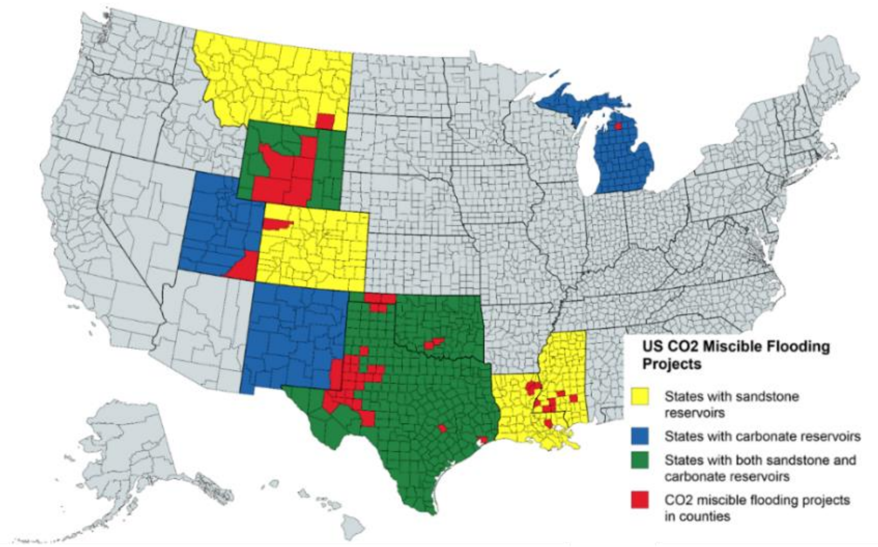

Figure 2. Current CO_2-EOR project state distributions in the United States.

Table 2. Top five CO_2 miscible flooding operators and productions [36].

Operator	No. of Active CO_2-EOR Projects	Total Production, Mb/d	Enhanced Production, Mb/d
Occidental	31	100.0	87.7
Denbury Resources[a]	18	29.0	29.0
Core Energy[b]	9	0.5	0.5
Chaparral Energy[c]	8	5.9	4.3
Chevron	7	23.6	20.2
Other[d]	53	300.0	265.2
Total	126	458.9	407.0

a. Five missing values
b. Three missing values
c. One missing values
d. Two missing values

The bars in blue, red, and yellow represent the percentage of contributions from operators to the total number of projects, total production, and enhanced production, respectively. Currently, Occidental is the biggest company for CO_2 flooding, where 30 out of 31 projects were conducted in Texas and one project was conducted in New Mexico. Among all the projects, most of the CO_2-EOR projects were applied in Texas, Wyoming, and Mississippi.

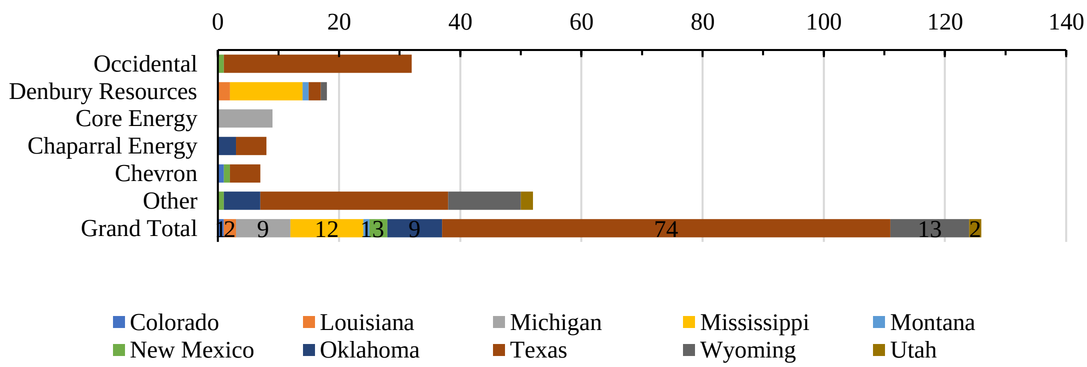

Figure 3. CO_2-EOR state distributions for top five operators.

2.2. DATA PRE-PROCESSING

Before data analysis, data processing or data cleaning is crucial to ensure the high quality of results, as they detect and remove errors and inconsistencies from the dataset [82]. Data quality problems presented in a single EOR survey were mainly caused by spelling errors during data entry, invalid data, or missing information. With the integration of 22 EOR surveys, the need for data processing increases significantly because the combined surveys include severe duplicate data with different representations. To improve the quality of the dataset, consolidation of different data representations and the elimination of duplicate data becomes necessary.

Because the purpose of constructing the criteria is to provide the guidelines for operators to find where CO2 miscible flooding technology could be successfully applied, only successful projects were considered for statistical analysis. Four common data problems and solutions in this dataset are described in the following subsections, including inaccurate (noisy), inconsistent, duplicated, and incomplete or missing data.

2.2.1. Inconsistent Data. Different formats and units were the main causes of the inconsistent data problem, and this problem particularly occurs when combining heterogeneous datasets. In this dataset, porosity and oil saturations were reported as either fractions or percentages. To solve this problem, all porosities and oil saturations were converted and formatted with the representation of percentages. In addition, because of the complications of reservoir conditions, some parameters were provided as a range instead of a specific value. This situation is common for carbonate reservoir permeability. When there are fractures, the permeability of the rock matrix and fractures are significantly different. For the permeability that is provided as a range, an average permeability was calculated for data analysis.

2.2.2. Inaccurate/Noisy Data. The inaccurate data problem consisted of typos and values outside the valid range. Typos are mainly caused by the improper count of “0”. For example, the depth of the Seminole Unit (Texas, San Andres formation) was reported as 53000 ft in the 2012 survey; however, the deepest record for the same pay zone was 5500 ft in the same project, and most of the surveys indicated that the depth of this field/pay zone was 5300 ft. In this case, the depth of this project was manually changed from 53000 ft to 5300 ft. Also, projects with oil saturations equal to 100% were considered as inaccurate data due to the existence of water/gas in the reservoirs. Table 3 presents an example of data corrections based on inconsistent and inaccurate data.

2.2.3. "One Field/Pay-zone, One Project" Policy. After the integration of all EOR surveys, the severe data duplication problem was observed. Many projects were listed several times with the exact same data in different years of surveys. One of the possible reasons for this is that the operators did not update their EOR project information, and the survey editors retained the same information based on the previous survey if they knew the projects were still active [28, 52, 83]. On the other hand, some projects were still considered as duplicates even though not all the information was the same. Since the span of CO_2 miscible flooding projects could be several decades (e.g., SACROC Unit), the same projects were reported in each survey with the change of operators, areas, number of production wells, number of injections, total production, and enhanced production. None of these parameters were used in the establishment of guidelines [14, 84-87]. In contrast, the characteristics of reservoirs and fluids were the common properties that were used to draw the guidelines, and these parameters were merely changed during the production process. To avoid the biased results of data analysis and to provide an accurate criterion for CO_2 miscible flooding, we applied the "one field/pay-zone, one project" policy to clean the dataset, where only one project was kept with the same reservoir and fluid properties. As a result, only 207 projects remained in the dataset.

Table 3. Example of data correction in the dataset.

Field	Correction	Report Year
Grieve	Porosity: 0.2 to 20.4	2014
SACROC Unit	Porosity: 4 to 9	2002 - 2014
Bell Creek	Porosity: 0.23 to 23	2014
Hastings	Porosity: 0.3 to 30	2014
Delhi	Porosity: 0.3 to 30	2014
Seminole Unit	Permeability: 1.3-123 to 62.15	1994-2004, 2008,2010,2014
Seminole Unit	Depth: 53000 to 5300	2012
Hastings	Delete start oil saturation (100)	2014
Oyster Bayou	Delete start oil saturation (100)	2012
S. Gillock	Delete start oil saturation (100)	1976

2.2.4. Incomplete Data and Missing Values. Missing data is a pervasive problem in datasets. Table 4 shows the number and percentages of missing data after removing the duplicate projects. Oil saturations before applying the CO_2 miscible flooding and oil viscosity are the two parameters with the highest number of missing values, which are 21.26% and 14.49%, respectively. All missing values were ignored during the data analysis process.

Table 4. Number and percentage of missing values for each property.

	Properties	No. of missing values	Percentage, %
Reservoir Properties	Porosity, %	1	0.48
	Permeability, mD	7	3.38
	Depth, ft	2	0.97
	Temperature, °F	7	3.38
	Oil Saturation, start, %	44	21.26
Oil Properties	Oil Gravity, °API	2	0.97
	Oil Viscosity, cp	30	14.49

As mentioned before, data from the original EOR surveys were not complete for CO_2 miscible flooding guidelines construction. Important parameters, including MMP and reservoir thickness, were not reported in the surveys. Therefore, we manually collected 33 and 52 entries for MMP and thickness based on the given reservoir information from various publications.

3. DESCRIPTIVE STATISTICAL ANALYSIS METHODOLOGIES

After data processing, the number of CO_2 miscible flooding projects decreased from 1189 to 207. Descriptive statistical analysis methods were used to analyze the suitable ranges for CO_2 miscible flooding. In this study, we propose a new combination plot by integrating boxplot, histogram, and scatterplot together to visualize the data. The purposes of the combination plots are not only to condense the information but also to provide an easy analysis approach for each parameter. Figure 4 illustrates the graphic view of the combination plot.

The boxplots are employed to display the ranges of each parameter and to detect special cases, as shown in Figure 5. Minimum, Q1 (25 percentile), median (50 percentile), Q3 (75 percentile), and maximum observation values are illustrated in the plot, and special cases are detected if the observed parameter is beyond the upper and lower limit. In the histogram, the frequencies (number of projects) were presented on the y-axis based on the ranges of properties shown on the x-axis. Properties with skewed distribution were also presented with local refined information, which helped to show the distributions and to identify the most suitable ranges for each parameter in a more condensed scale. In addition, scatterplots were employed to present the cumulative frequencies of reservoir/fluid properties.

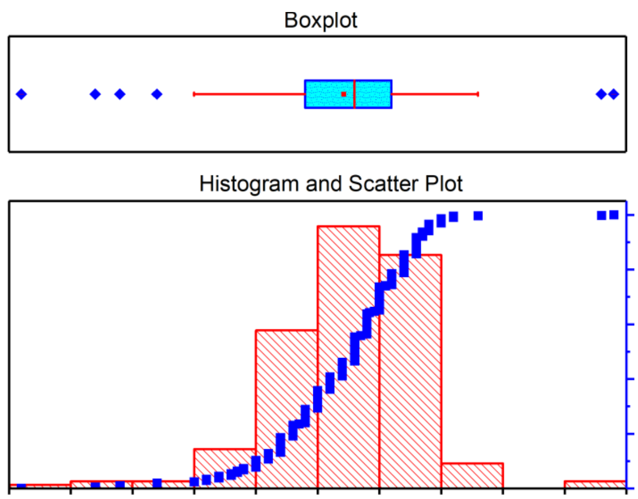

Figure 4. Schematic of combination plot [88].

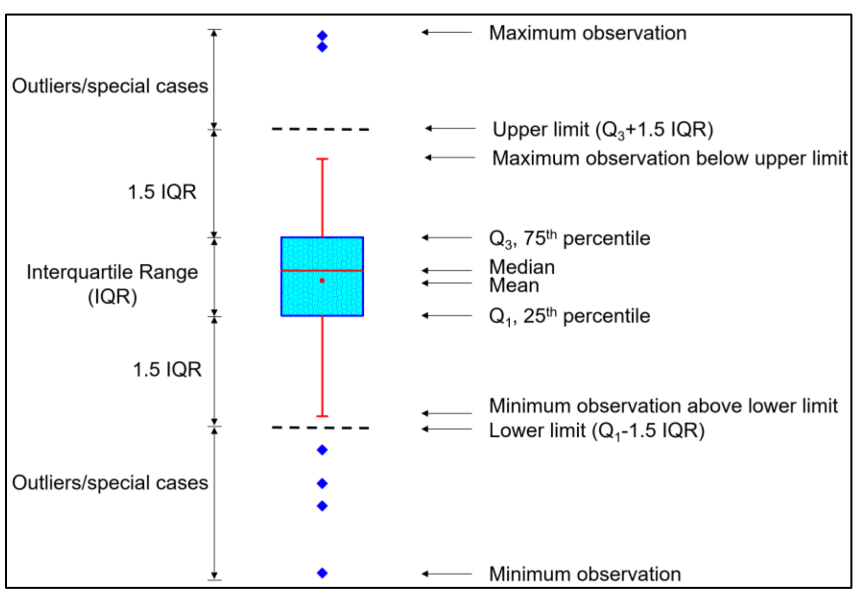

Figure 5. Descriptions of the boxplot.

4. IMPLEMENTATION GUIDELINES

In order to find the conditions for applying CO_2 miscible flooding, graphical and descriptive guidelines were used.

4.1. GRAPHICAL GUIDELINES

The purpose of graphical guidelines is to visualize the CO_2 miscible flooding data to detect the special cases and to present the distributions for reservoir, fluid, and operational properties.

4.1.1. Porosity and Permeability. Figure 6a illustrates that CO_2 miscible flooding could be successfully applied in a porosity range from 3 to 37%, and the peak distribution occurred in the range between 10 and 15%. The cumulative frequency value depicts that more than 90% of projects were implemented with a porosity value less than 30%. Figure 6b presents the combination plot for average reservoir permeability, which ranges from 0.1 to 10000 mD. The huge variance of this property was caused by the existence of fractures. All the high permeabilities were detected as special cases from the boxplot. The red histogram shows the distributions of permeability from 0.1 to 130 mD, which represents about 80% of the projects. Most projects were applied in the range from 0.1 to 10 mD. The smaller histogram detailed the project distributions from 0.1 mD to 10 mD, where the bimodal shape was from 4 to 5 mD and 5 to 6 mD, respectively. The relationship between porosity and permeability is revealed in Figure 7, which shows that these two properties are positively correlated. In addition, state information is also included in Figure 7 with different colors.

4.1.2. Depth and Temperature. Figure 6c represents the unimodal distribution of depth, where the cumulative frequency increases dramatically between 4000 and 6000 ft. About 25% of the project depth was located from 4878 to 5600 ft with the combination analysis of the boxplot and the scatterplot. Reservoir depths greater than 12000 ft were denoted as special cases, which were the Bridger Lake Field (15600 ft) and the Weeks Island Field (14000 ft).

For the guidelines of depth, there was a threshold depth for CO_2 miscibility with reservoir oil. Two widely accepted CO_2 miscible threshold depths are 2500 [11, 89] and 3000 ft [90]. Even though 2500 ft was taken as the threshold depth, the cumulative frequency curve indicates that about 10% of the projects that had CO_2 injected below this depth. From the boxplot in Figure 6c, the depth was as shallow as 1150 ft, which is much shallower than 2500 ft.

Reservoir temperature is an important parameter in a CO_2 flooding operation. CO_2 minimum miscibility pressure is a direct function of temperature and it increases linearly corresponding to temperature [91]. MMP increases as temperature increases. For some high-temperature reservoirs, achieving miscible flooding is impossible because if the MMP is higher than the formation fracture pressure, the injection at MMP will cause the formation to fracture, thus creating CO_2 pathways. Figure 6d indicates that the reservoir temperature ranges from 70 to 260 °F, and the range from 100 to 120 °F has the most records. The maximum temperature was from the Cranfield reservoir in Mississippi, and the temperatures of 11 other projects in the nearby area were above 220 °F. In these cases, CO_2 minimum miscibility pressures were calculated above 3000 psi.

According to an empirical correlation of CO_2 MMP provided by the National Petroleum Council, for reservoir temperatures greater than 120 °F, additional pressure is needed to achieve miscibility. Additional pressure ranges from 200 to 500 psi. Thus, for CO2 miscible flooding, reservoir temperatures less than 120 °F are preferred.

4.1.3. Oil Saturation and Net Thickness. Even though reservoir oil saturation is not the main factor that CO_2 displacement depends on, many researchers still take it into account as a rough guideline for economic concerns. Figure 6e presents a multimodal distribution for oil saturation before the implementation of CO_2 miscible flooding. Most of the frequency values are between 30% PV and 60% PV.

Although reservoir net thickness was not considered as a criterion for CO_2 flooding by previous researchers, it is regarded as a critical parameter for flooding success estimation. Thick net pay is economic and productively beneficial, while thin layers could avoid CO_2 gravity segregation to some extent. According to Song (2014), when the net thickness is less than 98.4 ft, the increase of the net thickness would increase the technical efficiency of WAG flooding [92]. The net thickness summarized from 52 CO_2 miscible flooding projects is shown in Figure 6f.

The skewed distribution was found from the boxplot, histogram, and the scatterplot, where most of the projects were applied with a reservoir thickness less than 100 ft. The thickest reservoir for the implementation of CO_2 miscible flooding was found in the Wolfcamp reservoir, which is an 824 ft pay zone located at the Wellman Field in Texas [79].

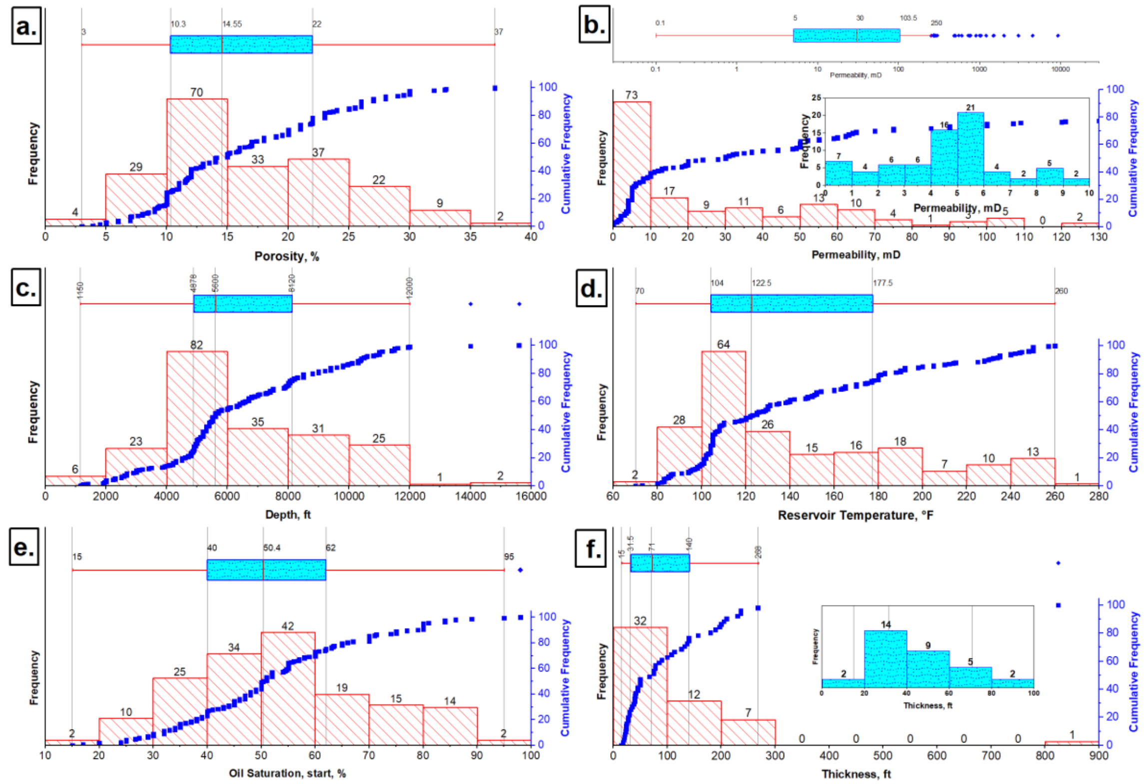

Figure 6. Combination plots representing the ranges, distributions, and cumulative frequencies of (a) porosity, (b) permeability, (c) depth, (d) reservoir temperature, (e) oil saturation, start, and (f) thickness.

4.1.4. Oil Properties. Figure 8 shows the combination plots for oil properties. Based on the classification of oil reservoirs by Meyer et al., CO_2 miscible flooding should be implemented in light-oil reservoirs, which are defined as having an oil gravity greater than 25 °API [93]. The reason is that the molecular weight for light oil is smaller than heavy oil, which makes the value of MMP easier to achieve [94]. Similarly, the oil viscosity is very small since most reservoirs have light oil. Figure 8b depicts that more than 90% of projects have an oil viscosity less than 3.5 cp, and most of the oil viscosities range from 0.5 to 1.5 cp.

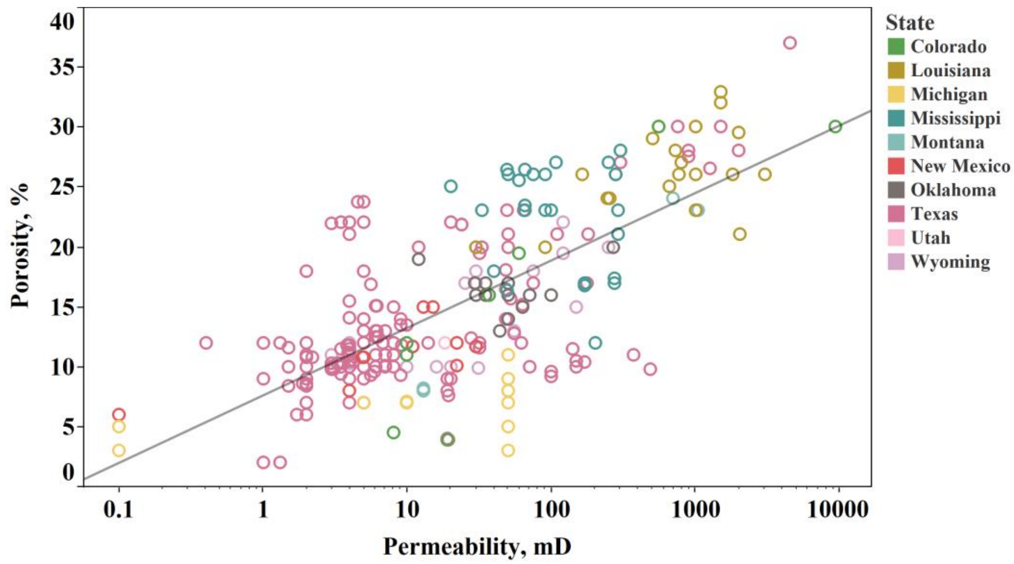

Figure 7. Relationship of permeability and porosity in different states.

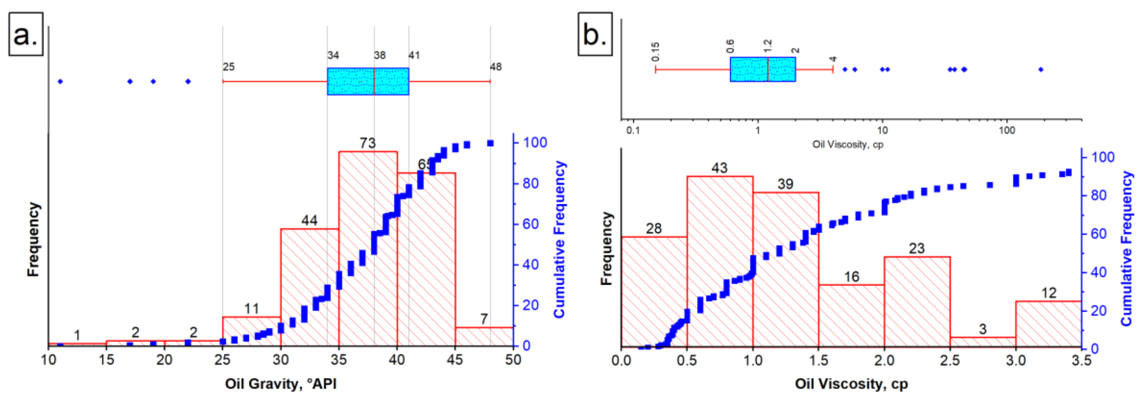

Figure 8. Combination plots representing the ranges, distributions, and cumulative frequencies of oil gravity and oil viscosity.

4.1.5. Operational Property. Minimum miscible pressure (MMP), which is defined as the lowest pressure where oil and injectants achieve miscibility dynamically, is a critical parameter to distinguish miscible/immiscible flooding [95]. Displacements with reservoir pressures higher than MMP are considered as miscible flooding, which could be caused by high reservoir temperatures, high molecular weight (oil composition), and low reservoir pressure [88, 94]. Figure 9 illustrates the ranges of MMP values collected and the relationships between MMP, depth, and reservoir temperature.

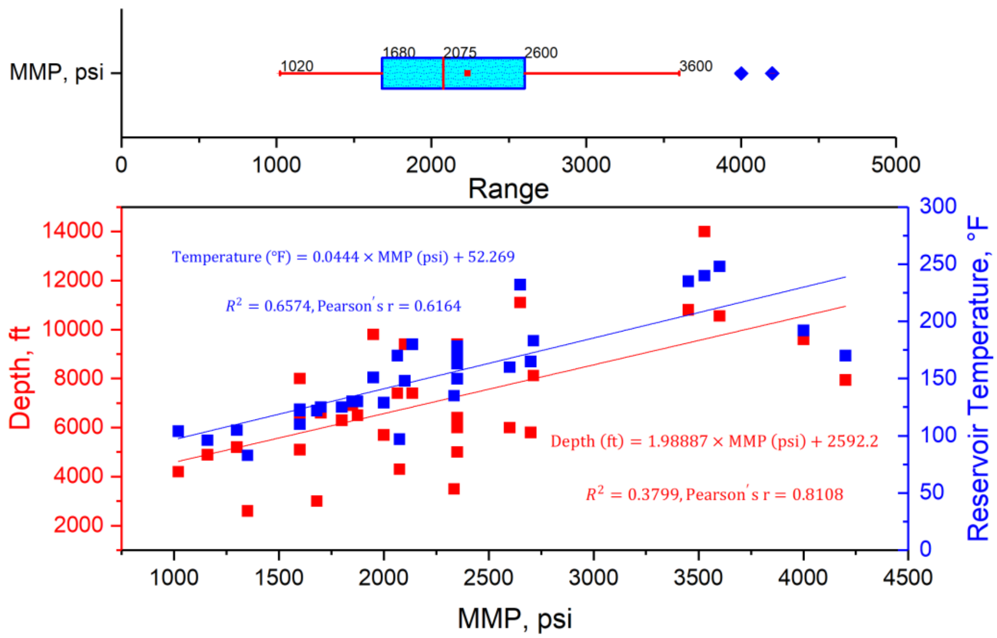

Figure 9. Combination plot of boxplot and scatter plot: ranges of MMP and the relationship between depth, MMP, and reservoir temperature.

In this dataset, only 33 projects provided CO_2 MMP data. MMP ranges from 1020 psi to 4200 psi, most in the range of 1680 to 2600 psi. The CO_2 MMP is generally considered to be greater than 1400 psi, which is well above 1020 psi. The lowest MMP is from the Goldsmith San Andres field. MMP could be lowered by the addition of additive gases, such as SO_2 and H_2S, when the reservoir pressure is insufficient to reach miscibility.

In general, the CO_2 injection pressure is about 200 psi higher than the MMP to ensure that miscibility can be achieved, or the pressure is between the MMP and the fracture pressure. The boxplot shows that the MMP value is normally smaller than 3600 psi, and the two special cases were found in the Farnsworth Field (4200 psi, [4]) and the Paradis Field (4000 psi, [41]). The Pearson's *r* values indicate that the MMP is positively linear related to both depth and temperature (Pearson's *r* >0.5), which is confirmed by the literature [84].

4.2. DESCRIPTIVE GUIDELINES

Table 5 provides a summary of guidelines for CO_2 miscible flooding based on statistical analysis of the cleaned dataset. The total data represents the number of projects that were used for the establishment of guidelines.

Table 5. Guidelines for CO_2 miscible flooding.

	Total Data	Mean	Minimum	Median	Maximum	Standard Deviation
Porosity, %	206	16.3	3	14.55	37	7.3
Permeability, mD	200	290.1	0.1	30	9244	1070.6
Depth, ft	205	6404.2	1150	5600	15600	2700.2
Oil Gravity, °API	205	36.9	25 (special case: 11-22)	38	48	5.5
Oil Viscosity, cp	177	3.8	0.15	1.2	4 (special case: 5-188)	15.6
Temperature, °F	200	141.0	70	122.5	260	50.2
Oil Saturation, start, %	163	52.2	15	50.4	98	16.7
MMP, psi	33	2231.5	1020	2075	3600 (special case: 4000-4200)	790.3
Net Thickness, ft	52	105.6	15	71	824	124.5

Compared with the existing research work reported in Table 1, the differences between these criteria could be explained as follows:

- MMP and net thickness are the first properties that have been considered. The lowest MMP value is 1020 psi, which means that for the implementation of CO_2 miscible flooding, the reservoir pressure should be higher than 1020 psi to achieve miscibility. The thickness of the target reservoir ranges from 15 ft to 824 ft.
- CO_2 miscible flooding could be applied in reservoirs with oil gravity ranges from 11 to 48 °API, and oil viscosities up to 188 cp. Even though the successful projects in heavy-oil reservoirs (oil gravity > °API [93]) extended the application of gravity and viscosity criteria significantly, these heavy-oil projects were excluded with the consideration of the fingering problem between CO_2 and heavy oil.
- The standard deviation of depth reveals that CO_2 miscible flooding could be implemented in a wide range of depth, from 1150 ft to 15600 ft. However, no specific limitation should be set if the miscible phase could be achieved between CO_2 and oil. Namely, the reservoir pressure is higher than the MMP. Because MMP is related to temperature, and the temperature is a function of depth, a higher reservoir temperature results in a higher MMP value, where the deeper location is required to achieve the higher temperature. Therefore, the depth could be any number, and it is not critical for CO_2 miscible guidelines.
- The ranges for permeability and oil saturation are bigger because more projects were included in the dataset for the establishment of guidelines.

5. CONCLUSIONS

- This paper provides the most uniformed CO_2 miscible dataset based on the integration of OGJ Surveys and various publications, and errors in the OGJ EOR Surveys have been corrected based on the best of our knowledge.
- Data from various publications were supplied for MMP and net thickness for each project. Detailed data processing processes were explained to ensure the high data quality before data analysis. The "one field/pay-zone, one project" policy was proposed to remove all duplicate data.
- After data processing, boxplots, histograms and scatterplots were used to present the ranges, distributions, and cumulative frequencies of each reservoir/fluid properties.
- Although the choice of EOR method is never a result of a simple factor, the summarized recommended range can still serve as a reference benefit for field engineers and researchers in the future. The recommended implementation of CO_2 miscible flooding of reservoir and fluid properties can be summarized as follows: reservoir pressure > 1020 psi, porosity > 3%, permeability > 0.1 mD, gravity >25 °API, viscosity < 4 cp, temperature < 260 °F, oil saturation > 15% PV, depth > 1150 ft, and net pay thickness between 15 and 824 ft.

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II. STATISTICAL AND ANALYTICAL REVIEW OF WORLDWIDE CO_2 IMMISCIBLE FIELD APPLICATIONS

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ABSTRACT

CO_2 immiscible flooding is an important enhanced oil recovery (EOR) technology that has demonstrated great potential under varying reservoir and fluid conditions. This paper provides a comprehensive review of worldwide CO_2 immiscible experiences by collecting and analyzing data of 41 field applications from more than 60 publications, including books, DOE reports, AAPG databases, *Oil and Gas Journal* surveys, field reports, and SPE publications. About 100 papers have been reviewed. Two major parts are included in this paper. The first part explores where CO_2 immiscible could be applied, in which screening guidelines have been established and updated by applying statistical methods. Boxplots and histograms were used to detect special cases and to interpret the main distributions of reservoir/fluid properties. The second part discusses the influences of operation to the productions, the performances of each field, and the existing operational problems by using analytical methods, which include injection strategies, gas injection compositions, CO_2 utilization, CO_2 injection efficiency, incremental oil recovery, and incremental oil production rate per well. Results show that CO_2 immiscible flooding could

produce an additional 4.7% to 12.5% of oil with 10.07 Mscf/stb average CO_2 injection efficiency.

1. INTRODCTION

CO_2 miscible flooding is one of the most effective methods for oil recovery enhancement, and this method has provided the highest daily production rate among all EOR methods in the United States since 2012 [1]. However, not all reservoir conditions can meet the miscible requirements due to either technical difficulties or commercial considerations.

Minimum miscible pressure (MMP) is a critical parameter in CO_2 flooding which is defined as the lowest pressure where oil and injectants achieve miscibility dynamically [2]. Numerous slim-tube tests have shown that the reservoir pressure should be greater than 1100 psi to achieve the miscibility between CO_2 and oil [3-8], and the MMP values could be as high as 3970 psi [9], which is mainly caused by high reservoir temperature or high molecular weight (oil composition) [10, 11]. Experimental studies have demonstrated that the CO_2 MMP is directly related to the reservoir temperature [10, 12]. With every increase of 10 °F in temperature, the MMP increases by about 130 psi. When reservoir pressure is less than the MMP due to production or initial reservoir conditions, the displacement is considered as immiscible flooding. Even though the immiscibility between the injected gas and the reservoir fluids leads to fewer interchange components in the mixing zone [13], CO_2 is still highly soluble. As the CO_2 contact with the oil in the formation, the oil swells (10-35%) and reduces its viscosity (up to 10% of original values) [14, 15], which allowing the oil to flow more easily through the interconnected pore spaces towards the production well, and could also assist for pressure maintenance. These benefits give the rise to the implementation of CO_2 immiscible flooding.

The first CO_2 immiscible flooding project was found in Ritchie Field (USA, Arkansas) in 1968 [16]. Motivated by the success of this field application, the second CO_2 immiscible project in United States was conducted in the nearby Lick Creek Field in 1975, where 7.6 Bscf of CO_2 was injected into a reservoir with a net thickness of 8.6 ft and an oil gravity of 17 °API. Over the decades, a considerable amount of CO_2 immiscible projects has been undertaken not only in the United States, but also in China [17-20], Turkey [21-24], Trinidad [25], Malaysia [26-29], Hungary [22, 30, 31], Argentina [32, 33] , Canada [21, 34, 35], and Brazil [36, 37]. Currently, more projects are being planned in oil fields in Thailand and China (Yanchang oil field [38], Shengli oil field [39]). With the global concern of greenhouse gas emission and the development of technologies, more anthropogenic CO_2 sources through carbon capture and storage (CCS) could significantly reduce the cost of CO_2 immiscible flooding, which leads the CO_2 immiscible flooding to become one of the most commercial technology.

Like any other EOR, the successful implementation of CO_2 immiscible flooding requires extensive knowledge and experience from previous successful field applications [40]. CO_2 immiscible screening guidelines are useful for this purpose, and it is considered as a first step in selecting the potential of EOR techniques for given reservoirs, which is crucial at the start of an EOR project [41]. During the past 30 years, many research studies have focused on establishing and updating the screening criteria for different EOR techniques. Table 1 summarizes the screening criteria for CO_2 immiscible flooding that was published by different investigators. Taber et al. proposed one of the earliest technical screening criteria for seven main EOR methods based on oil recovery mechanisms[42]. The researchers updated their work in 1997 since more EOR projects had been conducted in fields [43, 44]. Taber et al. developed the screening criteria for all immiscible gas injections, but no specific investigation has been found for CO_2 immiscible flooding, and reservoir porosity was not considered for all EOR screenings. In addition, formation type, permeability, and temperature are not critical for conducting CO_2 immiscible flooding in their results. Bourdarot and Ghedan presented the EOR screening criteria for offshore carbonate reservoirs [45]. They conclude that application of CO_2 immiscible flooding is suitable for reservoirs with depths greater than 1800 ft and with oil viscosity less than 10 cp because the oil in offshore reservoirs has a low viscosity. Adasani and Bai established EOR screening criteria based on 652 EOR projects gathered from the *Oil and Gas Journal* Biannual EOR Survey [46], but only 16 of them, including duplicate projects were related to CO_2 immiscible flooding. In fact, many CO_2 immiscible projects were conducted in worldwide fields, but these projects data were not well reported or were reported in a variety of formats, which results in the inaccuracy of existing screening guidelines. Therefore, collecting, well-organizing, and analyzing these scattered project information is crucial for establishing guidelines.

As the screening guidelines are mainly related to reservoir and fluids parameters, a better understanding of project performance is also important for each EOR technology to maximize the production benefits. Christensen et al. (1998) reviewed the field WAG experience based on the discussions of well patterns, injectivity, and common problems

[47]. Alvarado et al. (2010) presented a comprehensive review of the status of various EOR methods. However, less research work was found in the review of CO_2 immiscible flooding.

Table 1. Previous screening guidelines for CO_2 immiscible flooding.

Author	**Taber et al.**	**Bourdarot and Ghedan**	**Adasani and Bai**
EOR Method	Immiscible Gases	Offshore CO_2 Immiscible	CO_2 Immiscible
Published Year	1997a	2011	2011
Gravity, °API	>12	>22	Nov-35
Viscosity, cp	<600	<10	0.6-592
Porosity, %			17-32
Oil Saturation, %PV	>35	>20	42-78
Formation Type	NC	Sandstone or carbonate	Sandstone or carbonate
Average Permeability, mD	NC	NC	30-1000
Depth, ft	>1800	>1800	1150-8500
Temperature, °F	NC	>86	82-198
No. of Projects			16
References	[43, 44]	[45]	[46]

The objective of this paper is to provide a comprehensive review for worldwide CO_2 immiscible applications. To fulfill this goal, high-quality worldwide CO_2 immiscible field datasets are established, and both statistical and analytical methods are implemented to find the suitable conditions for the application of CO_2 immiscible displacement. In addition, important operational properties, field performance, and existing operational problems are discussed.

2. DATA COLLECTION AND PREPARATION

The data set was created by collecting information from a variety of data sources, including books, DOE reports, AAPG database, oil and gas biannual EOR surveys, field reports, and SPE publications. All data were extracted from original data sources and saved to the same data collection system. After collecting all the raw data, inconsistent and redundant data have been checked and deleted to keep the data in the high quality. As a result, 41 projects from 36 different oil fields were collected, and the detailed information is presented in Table 2.

Figure 1 and Figure 2 summarize the number and distribution of the projects. In Figure 1, the gap between the two lines represents the total number of projects that have been ceased until that specific year.

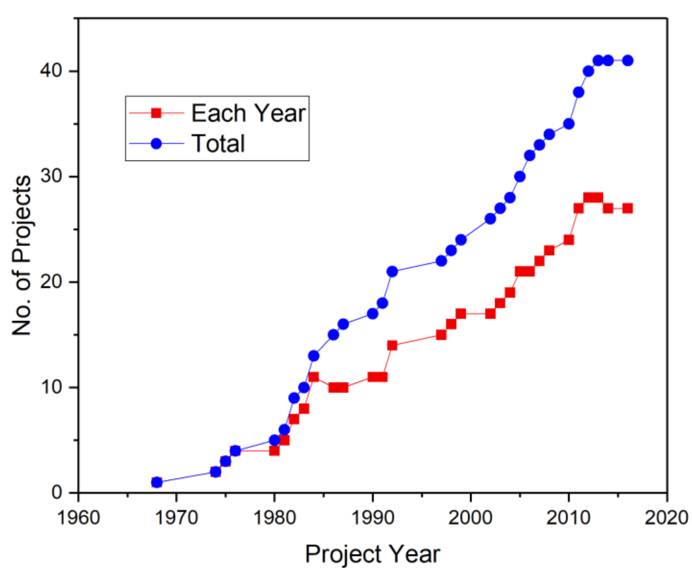

Figure 1. Number of CO_2 immiscible field applications since 1968.

Figure 1 shows that CO_2 immiscible projects increased dramatically in the early 1980s because gas injection techniques (especially in the United States) were considered as a promising but not well understood EOR method [48]. Supported by the Department of Energy (DOE), at that time, not only had more CO_2 immiscible projects come out, but also more gas injection projects had begun (nitrogen, hydrocarbon) [49]. Several projects were ceased in 1985 and 1986 due to the low oil price. After that, the number of projects gradually increased. Figure 2 indicates that the United States is the leader for using CO_2 immiscible techniques, which occupy 46% of all projects. The pie chart in Figure 2 shows the distribution of projects in the United States. Most of the projects were conducted in states with valuable CO_2 sources due to the construction of CO_2 pipelines [50-53].

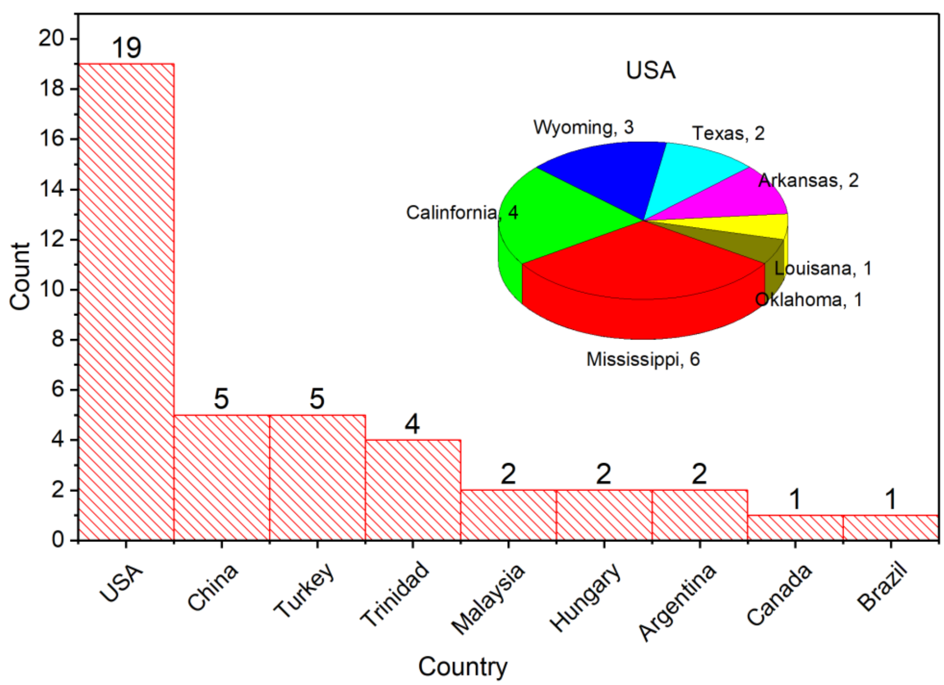

Figure 2. CO_2 immiscible application distribution.

Table 2. CO_2 immiscible applications and references.

Project No.	**Scale**	**Country**	**Field**	**Project Start Date (year)**	**References**
1	Field	USA	Ritchie	1968	[16]
2	Field	Trinidad	Forest Reserve	1974	[25]
3	Field	Trinidad	Forest Reserve	1976	[25]
4	Field	USA	Lick Creek	1976	[54, 55]
5	Field	Hungary	Nagylengyel	1980	[30, 31]
6	Pilot	USA	Wilmington	1981	[56]
7	Field	USA	Huntington Beach	1982	[57, 58]
8	Pilot	Canada	Retlaw Upper Mannville 'V' Pool	1983	[21, 34, 35]
9	Field	Turkey	Camurlu	1984	[21]
10	Pilot	Turkey	Camurlu	1984	[21]
11	Pilot	Turkey	Camurlu	1984	[21]
12	Field	Turkey	Bati Raman	1986	[23, 24]
13	Field	Trinidad	Forest Reserve	1986	[25]
14	Pilot	USA	Paradis	1987	[59, 60]
15	Field	Trinidad	Oropouche	1990	[25]
16	Field	Brazil	Buracica	1991	[36, 37]
17	Field	USA	Halfmoon	1992[a]	[61]
18	Field	USA	Halfmoon	1992[a]	[61]
19	Field	Hungary	Szank	1992	[22]
20	Pilot	Turkey	Ikiztepe	1997[a]	[62]
21	Field	USA	Sho-vel-tum	1998	[63-66]
22	Pilot	Malaysia	Dulang	2002	[26-29]
23	Pilot	Malaysia	Dulang	2002	[26-29]
24	Pilot	China	Changqing	2003	[67]
25	Field	USA	Yates	2004	[68]
26	Field	USA	Salt Creek	2005	[69]
27	Pilot	Argentina	Chihuido de la Sierra Negra	2005	[32, 33]
28	Field	USA	Eucutta	2006	[64-66]
29	Field	USA	Martinville	2006	[64-66]
30	Field	USA	Tinsley	2007	[65, 66]
31	Field	USA	Heidelberg, West	2008	[65, 66]
32	Field	USA	West Hastings	2010	[65, 66]
33	Field	USA	Heidelberg, East	2011	[65, 66]
34	Pilot	China	Yaoyingtai	2011	[18-20]
35	Field	USA	Heidelberg, East	2012	[65, 66]
36	Pilot	China	Tuha	2013[a]	[17]

3. DATA ANALYSIS APPROACH

Descriptive statistical analysis methods were used to analyze the applicability of CO_2 immiscible flooding based on the data collected. Combination plots were generated to better visualize project information, which consists of boxplots, histograms, and scatter plots. Figure 3 illustrates the schematic of a combination plot, where each individual plot has its own presenting purposes.

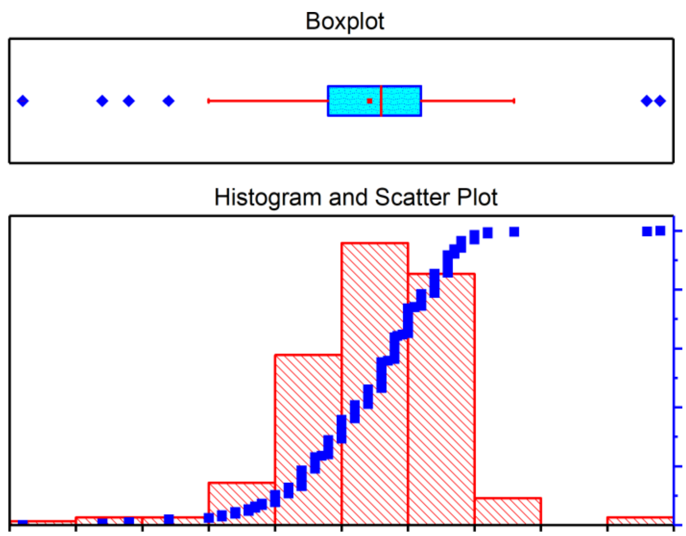

Figure 3. Schematic of combination plot of boxplot, histogram and accumulative frequency (scatterplot).

The purpose of using boxplots was not only to present the ranges but also to detect special cases. As shown in Figure 4, minimum, Q1 (25 percentile), median (50 percentile), Q3 (75 percentile), and maximum observation values are illustrated in the plot, and special cases are detected if the observed parameter is beyond the upper limit, which is calculated as 1.5 times of the interquartile range (IQR, Q3-Q1). Histograms were created to display the distributions for each parameter, and the histograms with local refined information helped to identify the most suitable ranges for each parameter. The purpose of introducing the accumulative frequency curves in theses combination plots was to depict the percentage of CO_2 immiscible flooding projects that implemented in a specific reservoir/fluid properties ranges.

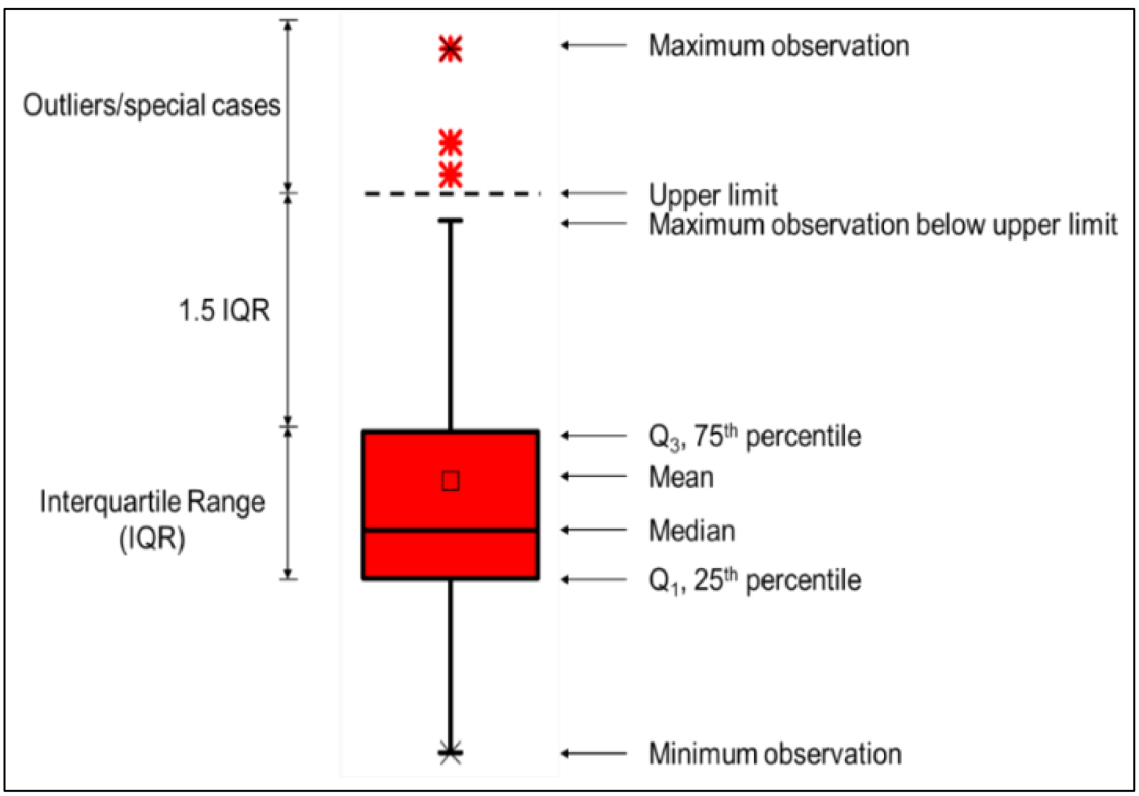

Figure 4. Schematic of boxplots and special cases.

4. TECHNICAL GUIDELINES FOR CO_2 IMMISCIBLE FLOODING

In this section, technical guidelines are provided based on data analysis methods from all CO_2 immiscible flooding applications with both categorical and numerical information. Figure 5 illustrates the distributions of categorical information from all 41 projects, including the scales, locations (on/offshore) of projects, fracture or channeling problems, lithology (formation type), and reservoir initial drive mechanisms.

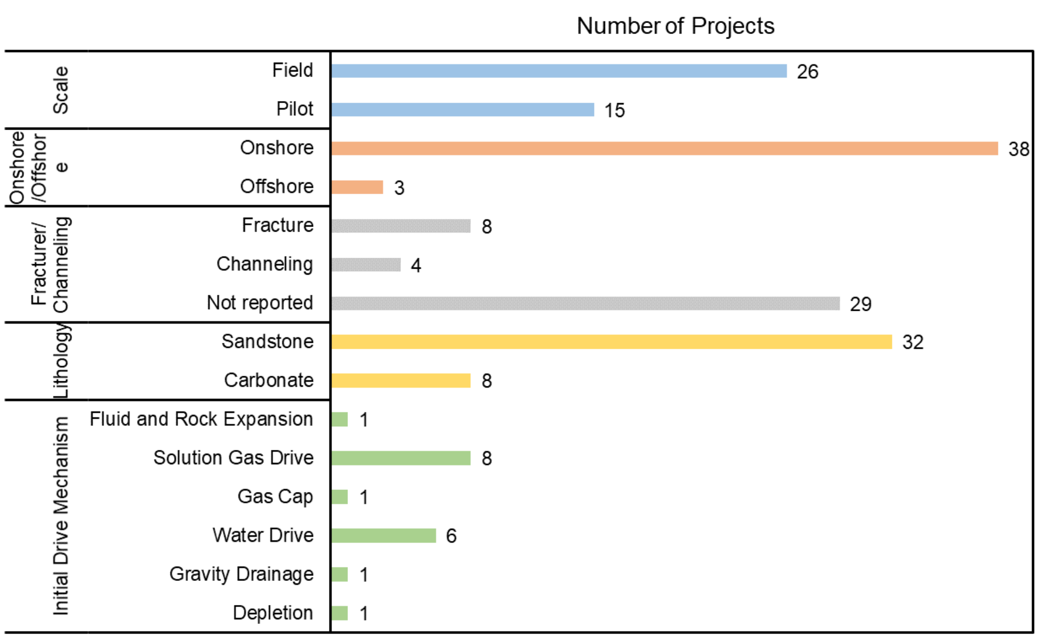

Figure 5. Number of project distributions of project scales, on/offshore, lithology, and initial drive mechanisms.

Figure 5 reveals several important findings. First, most CO_2 immiscible flooding was implemented with the field scale and locates onshore. Only three projects are located offshore, which are in Huntington Beach Field in the United States and Dulang Field (two projects) in Malaysia. Second, eight reservoirs were reported with nature fractures, and four reservoirs had severe channeling problems due to excessive CO_2 injection rates [70]. Twenty-nine projects did not report the fracture and channeling problem, which indicates that CO_2 immiscible flooding could be successfully applied into reservoirs with and without fractures. However, naturally fractured reservoirs are poor candidates for CO_2 flooding (miscible and immiscible flooding). Severe heterogeneity problems were detected in fractured reservoirs which led to the early gas breakthrough and affect the ultimate recovery [71, 72]. Third, although a significant number of different projects for sandstone and carbonate reservoirs were found, the formation type is not critical for CO_2 immiscible flooding because the incremental oil recoveries were close.

Also, the laboratory results from various literature also confirm that CO_2 immiscible flooding could be successfully applied in both sandstone reservoirs [73-75] and carbonate reservoirs [76, 77]. The reason for the skewed distribution could be the fact that there are more sandstone reservoirs compared with the carbonate reservoirs in the world [78]. Lastly, solution gas drive is the most common initial reservoir drive mechanism before the application of CO_2 immiscible displacement, where during the pressure depletion process, the expansion of oil and the solution gas provides the main drive energy [79].

Critical numerical reservoir/fluid parameters were analyzed to propose the screening guidelines for CO_2 immiscible flooding, including reservoir properties, fluid properties, and operational properties.

4.1. RESERVOIR PROPERTIES

Figure 6 presents the combination plots of boxplots, histograms, and accumulative frequency curves to depict the ranges and distributions of important reservoir properties. Figure 6a shows that CO_2 immiscible displacement has been successfully applied not only into shallow reservoirs to 1400 ft (Yates, USA), but also in deep reservoirs to 8500 ft (Martinville, USA). Histogram and the accumulative frequency curve present an even distribution of depth, which reveals that the implementation of CO_2 immiscible flooding could be any depth. Miscibility is difficult to obtain because the reservoir pressure is lower in shallow reservoirs due to the overburden pressure. In deep reservoirs, even though the reservoir pressure is higher, the temperature is high as well. Since MMP is highly related to oil composition and temperature [4, 10, 80], the MMP is hard to achieve. Also, the previous production may lead to the current reservoir pressure to be very low. Therefore, CO_2 immiscible flooding could be implemented for both shallow and deep reservoirs, and the reservoir depth is not critical for the application of CO_2 immiscible displacement.

In the screening guidelines proposed by Adasani and Bai [46], the permeability should be less than 1000 md. The newly collected data revealed that the reservoir average permeability could be up to 2750 md. Figure 6b depicts that 75% of projects are less than 465 md, and the most frequent range is less than 500 md. As indicated in Figure 6c, most reservoir temperatures are from 120 to 160 °F, but the temperature is extremely high in China and Hungary because the formation depths are very high [20, 22, 81]. Figure 6d presents the distributions for porosity. No outstanding application ranges of porosity was detected from the combination plot, but it illustrates that the porosity should be greater than 11.5%. Figure 6e depicts the information for both initial reservoir saturation and the oil saturation when CO_2 immiscible projects were initiated. The initial reservoir oil saturation ranges from 60% to 86%, while the oil saturation at the beginning of projects ranges from 30% to 86%. This information shows that some fields implemented the CO_2 immiscible flooding technology as the first method to produce oil (Martinville Field (86%)), and some fields have used other technology for oil production with a result of low oil saturation at the beginning of project (West Hasting Field (30%), Tinsley Field (30%), etc.).

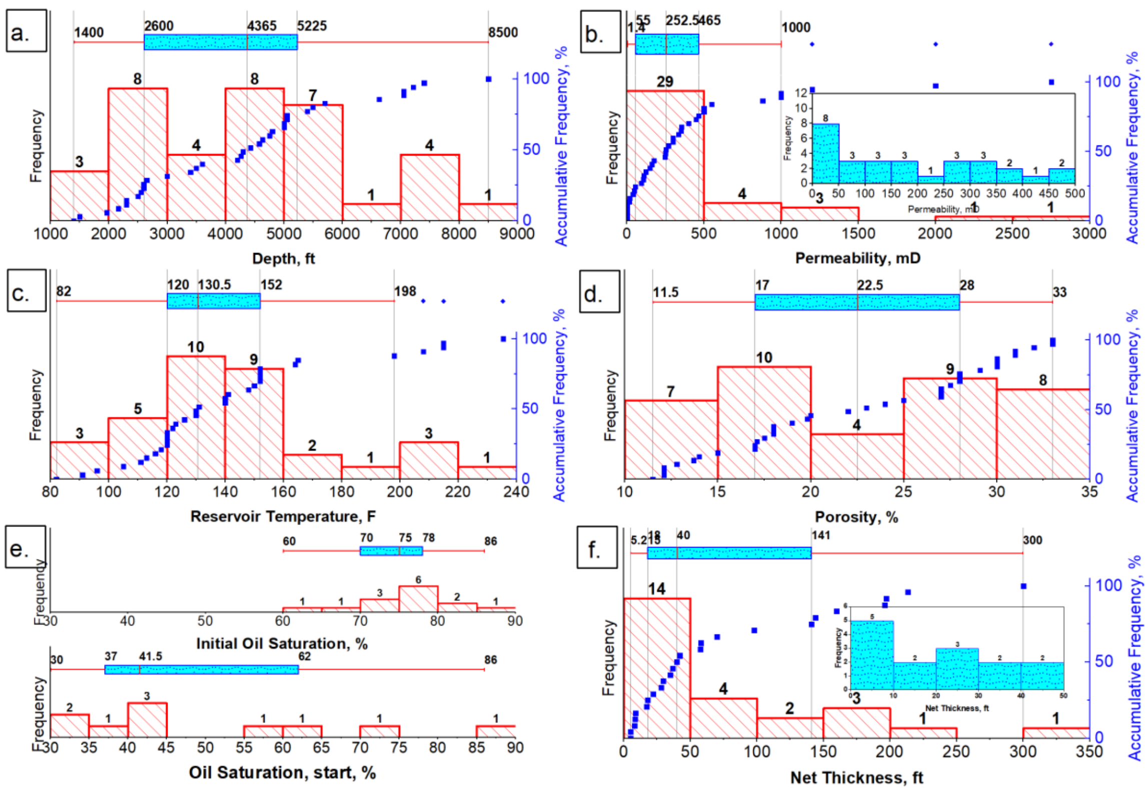

Figure 6. Combination plots for reservoir properties including depth, permeability, reservoir temperature, porosity, oil saturations, and net thickness.

Although reservoir net thickness is not considered as a criterion for CO_2 flooding by previous researchers, it is regarded as a critical parameter for flooding success estimation. Thick net pay is economic and productively beneficial while thin layers could avoid CO_2 gravity segregation to some extent. According to Song (2014), when the net thickness is less than 98.4 ft, the increase of the net thickness would increase the technical efficiency of WAG flooding [82]. The main net thickness for implementing CO_2 immiscible techniques ranges from 18 to 141 ft, as shown in Figure 6f. The thinnest reservoir is in China (Yaoyingtai field), and the thickest reservoir is located in the United States (Huntington Beach Field).

4.2. FLUID PROPERTIES

Based on the classification of oil reservoirs by Meyer et al., light oil reservoirs are defined as having an oil gravity greater than 25 °API, while medium and heavy oil reservoirs have an oil gravity between 20 to 25 °API and smaller than 20 °API [83]. From the boxplots of viscosity and oil gravity, as shown in Figures 7a and 7b, most CO_2 immiscible projects are conducted into the medium to heavy oil reservoirs (10~25 °API), especially in Turkey.

Since MMP is one of the most significant parameters for both miscible and immiscible CO_2 flooding [48], it is critical to know how much difference between current reservoir pressure to MMP. Figure 8 displays the ranges and distributions of MMP for technically successful implementation of CO_2 immiscible projects.

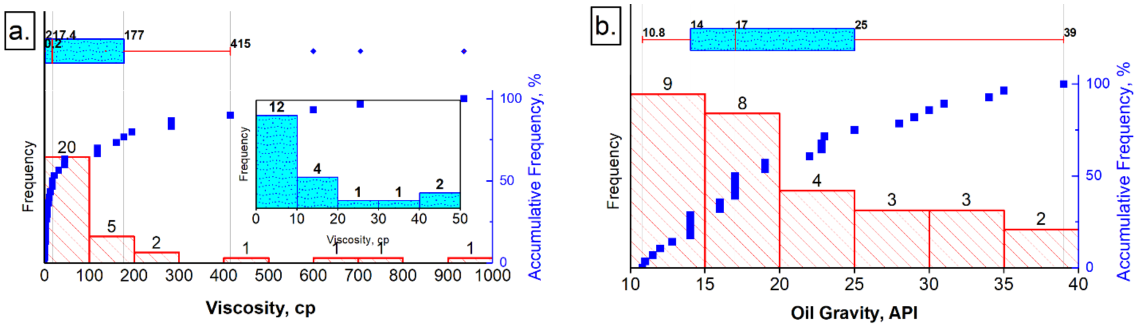

Figure 7. Combination plots for fluid properties including oil viscosity and oil gravity.

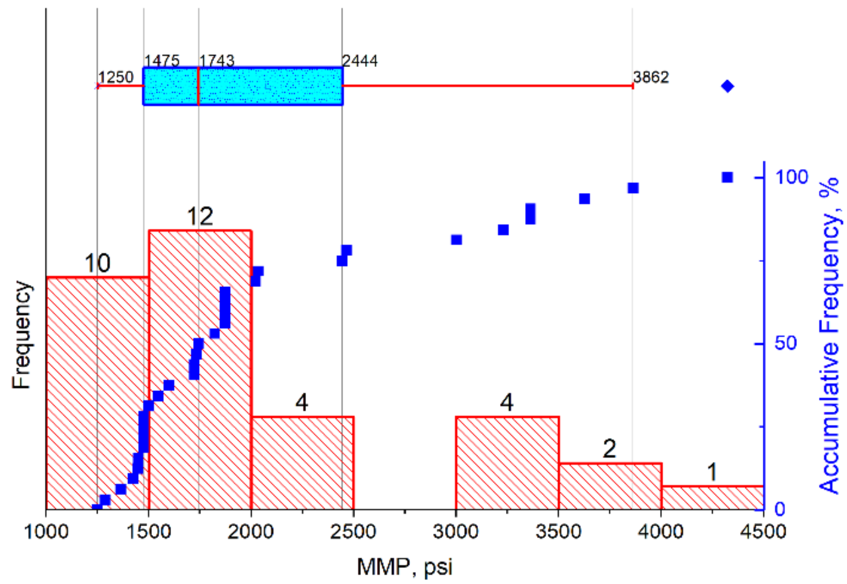

Figure 8. Combination plot for MMP.

The minimum MMP value is 1250 psi, and the maximum value is 4322 psi. Most projects fall into the range from 1250 to 2000 psi. Figure 9 reveals the relationship of MMP with reservoir pressures. Several projects have the original reservoir pressure higher than the MMP; however, during the pressure depletion by production, all current reservoir pressures drop below the MMP. On the other hand, some fields have a very low reservoir pressure (lower than MMP), which makes the miscibility phase unachievable.

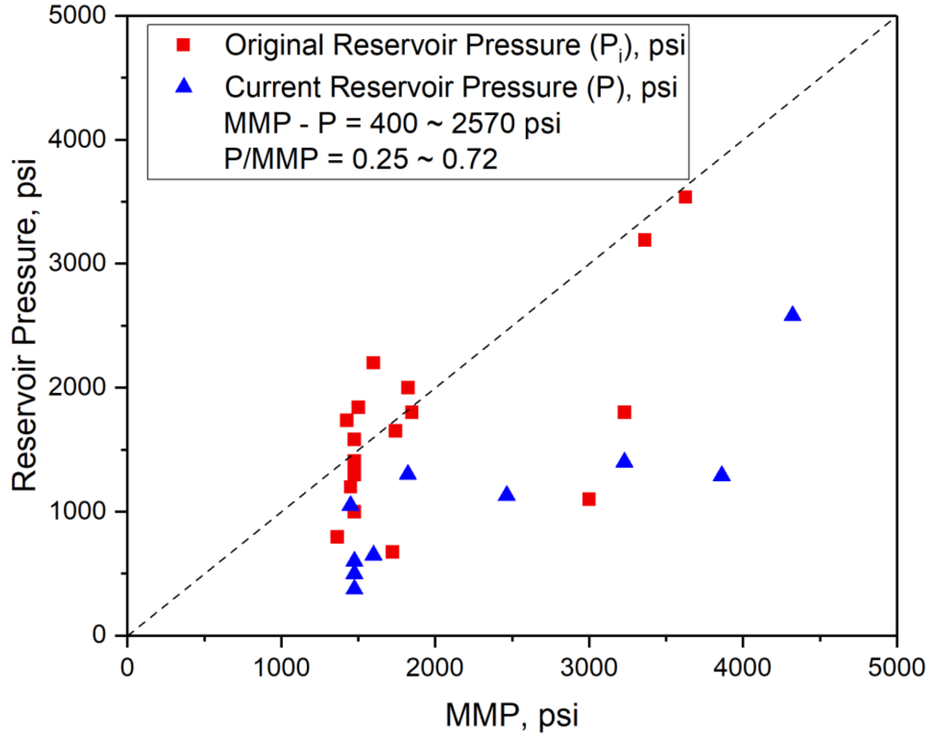

Figure 9. Comparisons of MMP vs. reservoir pressures.

Figure 10 reveals the relationships of MMP with depth and temperature for all CO_2 immiscible projects. From the plot, both depth and reservoir temperatures are positively related to MMP from the Pearson's r value and the R^2 value, which means under the same condition, the deeper the reservoir, the higher the MMP value, and the harder to achieve miscibility. Also, MMP increases with the increase of temperature based on the change of interfacial tension [84-86].

By the default definition of a boxplot, even though the projects beyond the whiskers are declared as outliers [87], these projects should be considered as special cases in the oil industry because they are not biased, and were successfully implemented in the field. From Figure 6 to Figure 8, special cases are found based on boxplots of MMP, permeability, viscosity, and reservoir temperature. Tables 3 and 4 summarize the field names with minimum or maximum observations and the detailed information for all special cases, respectively. As shown in Table 3, the Yates field has the minimum values for both depth and reservoir temperature. The reason for this could be the target formation is a shallow reservoir, which makes the reservoir temperature very low, and the MMP value is lower.

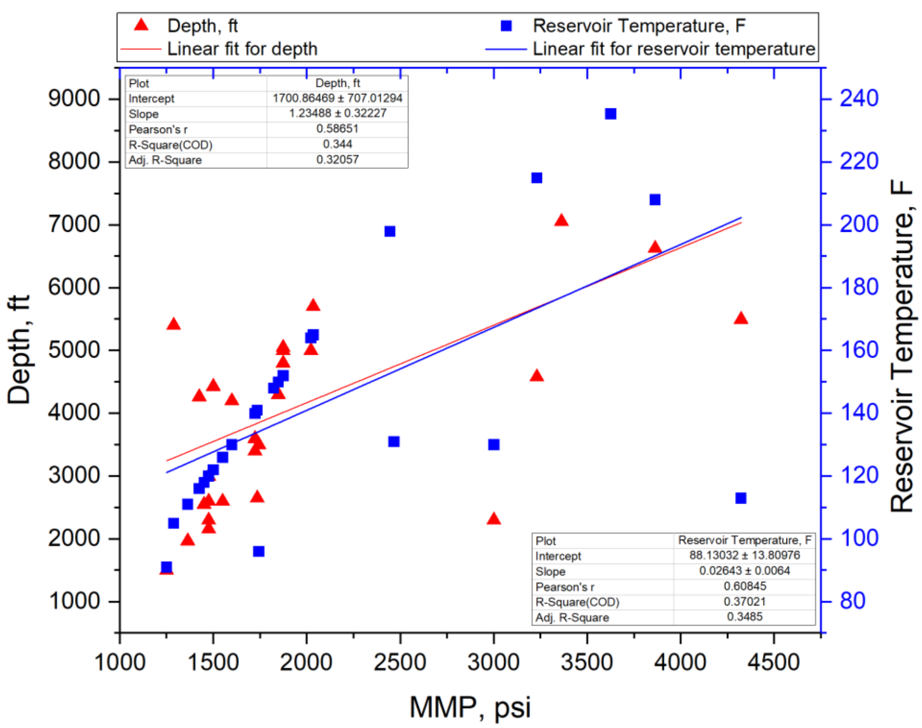

Figure 10. Relationships of MMP vs. depth and temperature.

Table 3. Minimum and maximum field names for each reservoir/fluid parameter.

Properties	Minimum		Maximum	
	Field	Value	Field, Country	Value
Porosity, %	Camurlu	11.5	Paradis, Lick Creek	33
Permeability, mD	Changqing	1.4	Ritchie	2750
Depth, ft	Yates	1400	Martinville,	8500
Net Thickness, ft	Yaoyingtai	5.215	Huntington Beach	300
Temperature, °F	Yates	82	Szank	235.4
Initial Oil Saturation, %	Martinville	30	Tinsley, West Hastings	86
MMP, psi	Salt Creek	1250	Tuha	4322
Oil Gravity, °API	Camurlu	10.8	Salt Creek	39
Oil Viscosity, cp	Dulang	0.2	Ikiztepe, Turkey	936

Table 4. Special cases for CO_2 immiscible flooding.

Country	Field	Start Date Year	Depth ft	Net Thick-ness ft	Perme-ability mD	MMP psi	Oil Visc-osity cp	Tem pera ture °F
USA	Ritchie	1968	2600	9	2750	-	195	126
USA	Paradis	1987	-	17	2000	1823	-	148
USA	Lick Creek	1976	2550	8.6	1200	-	160	118
China	Tuha	2013	5495.5	37	3.4	4322	22.3	113
Turkey	Bati Raman	1986	4300	213.5	55	-	600	150
Turkey	Camurlu	1984	4264	197	351	-	705	116
Turkey	Ikiztepe	1997	4430	57.5	450	-	936	122
China	Yaoyingtai	2011	6627	18	1.9	3862	1.91	208
Malyasia	Dulang	2002	4579	-	112	3230	0.2	215
Hungary	Szank	1992	-	-	255	3626	5.2	235.4

Table 4 depicts that all special cases detected from permeability happened in the United States, while a special case illustrated in MMP boxplot was found in China, and projects in Turkey have the special cases for oil viscosity. It is not a coincidence that special cases for each reservoir parameter (except temperature) are from the same country because the reservoir characteristics in each country are unique. For example, all projects found in China are located at deep reservoirs with the minimum depth of 5495.5 ft. Also, projects in China normally have a high asphalt content (high molecular weight). This special condition leads to a high reservoir pressures which results in a higher MMP value for immiscibility conditions. Meanwhile, all reservoir/fluid information collected from Turkey have heavy to extremely heavy oil, in which the oil gravity is from 10.8 to 12 °API.

Table 5 provides a summary of CO_2 immiscible flooding criteria based on statistical analysis of the main reservoir information collected in the projects, which consists of porosity, permeability, depth, net thickness, reservoir temperature, initial oil saturation, oil gravity, oil viscosity, and formation type.

Table 5. Technical screening guidelines for CO_2 immiscible applications.

	N total	**Mean**	**Minimum**	**Median**	**Maximum**
Porosity, %	37	22.6	11.5	23	33
Permeability, md	37	418.2	1.4	255	2750
Depth, ft	35	4258.3	1400	4300	8500
Net Thickness, ft	24	79.3	5.2	41	300
Reservoir Temperature, °F	33	142.1	82	131	235.4
Initial Oil Saturation, %	16	56.0	30	59.5	86
Oil Gravity, °API	29	20.5	10.8	17	39
Oil Viscosity, cp	30	140.3	0.2	17.4	936
Formation Type	40	Sandstone or carbonate			

In comparison with existing screening guidelines (Table 1) for CO_2 immiscible flooding, the updated guidelines provide the statistical analysis with mean, minimum, median, and maximum values. More field projects are included with comprehensive analysis, and the net thickness is considered for the first time.

4.3. OPERATIONAL PROPERTIES

The design of CO_2 immiscible flooding projects includes the considerations of CO_2 sources, surface facilities, injection strategy, and injection parameters. The injected CO_2 is commonly sourced from large underground deposits and can be captured from sources such as electric power plant emissions. Table 6 summarizes the main CO_2 sources for CO_2 immiscible projects.

Table 6. CO_2 sources for CO_2 immiscible projects.

Field	CO_2 Source
Bati Raman	Dodan Gas Field
Wilmington	Texaco's Wilmington Refinery
Retlaw Upper Mannville 'V' Pool	Turin Gas Plant
Camurlu	On cite
Ikiztepe	Camurlu Field
Yaoyingtai	Songnanqitian
Nagylengyel	Budafa deep horizon
Szank	Budafa deep horizon
Lick Creek	Sterlinton
Buracica	On cite
Chihuido de la Sierra Negra	Puesto Hernandez, Puesto Molina

Most fields were supplied by nearby gas fields, and the Camurlu field and the Buracica Field were sourced from the field itself. The cost of CO_2 is very different from various sources [88]. In the United States, the price for CO_2 is around US$3/ton to US$15/ton from ammonia producers; the price for the anthropogenic CO_2 is US$18/ton; and the price for the pipelined CO_2 is around US$9/ton to US$26/ton, which including the cost of pipeline infrastructure [13, 89-91]. When the CO_2 is captured, it is generally brought to the oil field by pipelines and injected into the reservoir or held in storage tanks. The CO_2 is compressed to a high pressure and injected into the oil reservoir to begin the EOR process.

4.3.1. Injection Strategy. The displacement processes and CO_2 injection strategies have been described in various publications. There are at least six different immiscible CO_2 displacement processes that can be used to enhance oil recovery: (1) continuous CO_2 injection, (2) huff-n-puff, (3) water alternating gas injection (WAG), (4) simultaneous injection of water and CO_2, (5) CO_2 slug process or intermittent injection, and (6) carbonated water injection (CWI). Injection strategy is critical because it affects the CO_2 injectivity and the ultimate oil recovery [92]. Figure 11 presents the project distributions of CO_2 injection strategies.

Water alternating gas (WAG). Water alternating gas is a process where water or oil field brine is injected alternatively with the compressed gas. The WAG method uses the pressure of the water injection to reduce gas channeling, and this increases sweep efficiency and creates a stable force that drives oil to the production well. From field experiences, the WAG ratio is normally from 1 to 1.23 Mscf/STB, and this ratio is dynamically changing with reservoir response [93]. Figure 11 indicates the WAG method is the most popular injection strategy, as this method could assist in mitigating early gas breakthrough and enhancing sweep efficiency. The average incremental oil recovery with the WAG injection strategy is 8.9%, while this value is 8.13% and 6.0% with the continuous and huff-n-puff injection strategies, respectively. These values show that the WAG method is more efficient in recovering oil than other CO_2 injection strategies.

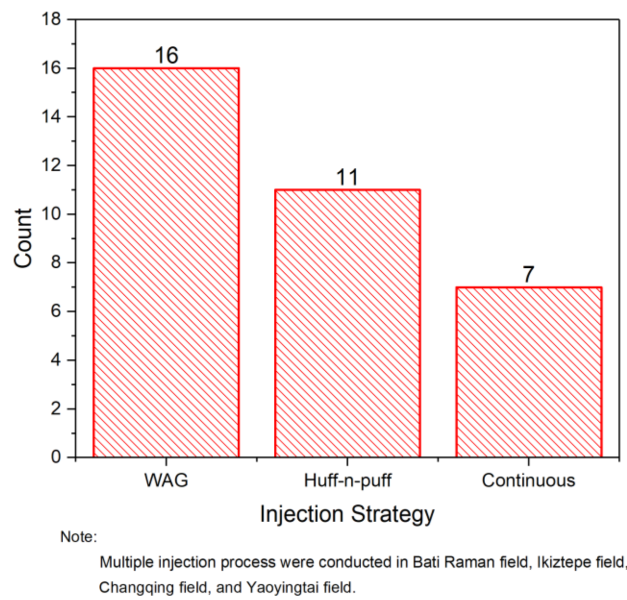

Figure 11. Injection strategies for CO_2 immiscible applications.

Continuous injection. As the name implies, CO_2 is continuously injected until a certain pressure (Bati Field) or until a designated gas volume has been reached. This method is usually applied at the beginning of the CO_2 immiscible flooding process. When CO_2 breakthrough or the produced GOR reaches the designed level, other EOR methods are implemented [94]. Also, this injection process is often combined with the WAG and huff-n-puff processes due to the limited supply of CO_2 and the gas channeling problem induced by gas injection (Changqing Field).

Huff-n-puff. Huff-n-puff is another useful injection strategy in which CO_2 is injected from the production well, the well is shut-in for soaking and for pressure build-up, and then the oil is produced. The scale of applying the huff-n-puff process is smaller than the WAG process, and this process normally runs 3 to 4 cycles [21, 23, 24, 59, 60]. Figure 12 illustrates an example of the durations for the huff-n-puff process.

For each cycle, CO_2 was injected into the production wells for 6 to 63 days, then soaking occurred for 10 to 13 days. After the soaking, the oil was first produced by natural flow due to the pressure build-up for several days (about 10 days, depending on pressure), and then pumps were used to assist the oil production.

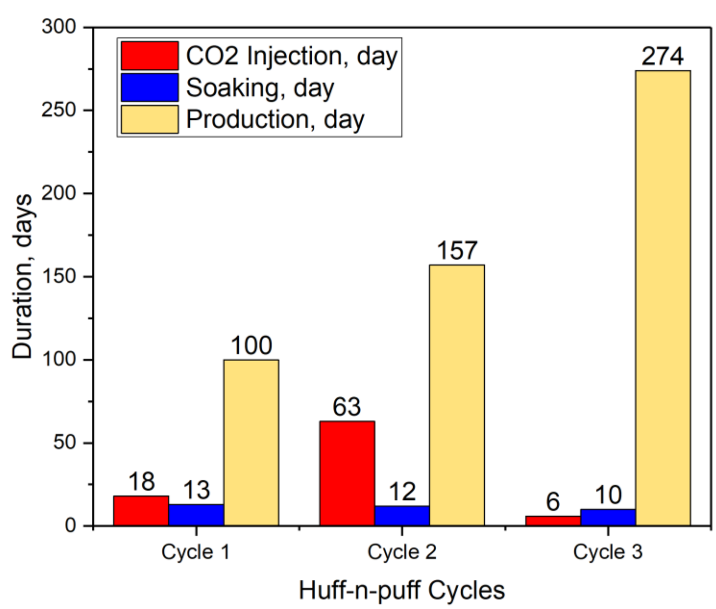

Figure 12. An example of huff-n-puff process from Camurlu field.

4.3.2. Gas Composition. As mentioned before, the sources of CO_2 injected into the field came from the nearby gas field or captured from plant emissions, and these gases are with impurities. Nitrogen and methane are common impurities in CO_2 immiscible project injections. Research studies have shown that the existence of nitrogen content in the injected gas can reduce the effectiveness of CO_2 injection [95]. On the other hand, hydrogen sulfide (H_2S) and C_2^+ are capable to decrease the MMP which could increase the effectiveness of CO_2 injection [11]. Figure 13 depicts the mole percentages of carbon dioxide, nitrogen, methane, and other gas components. Most applications were conducted with 70% CO_2. The sources for Dulang Field contain the least percentage of CO_2 because this is an offshore field and the CO_2 sources were limited.

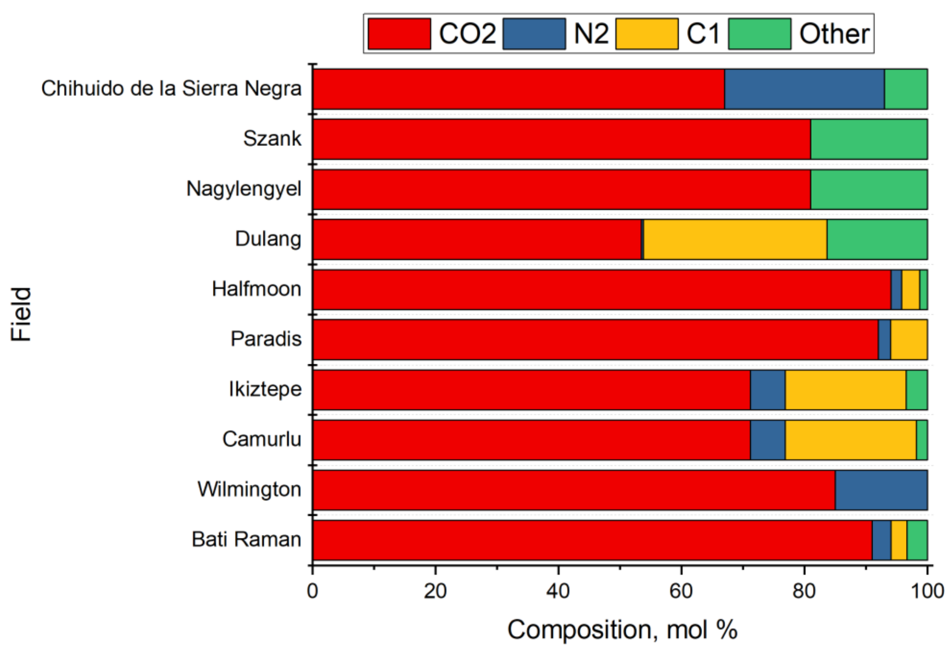

Figure 13. Injection gas composition for CO_2 immiscible applications.

4.3.3. CO_2 Utilization. The volume of CO_2 injection is a key factor to increase the oil recovery both technically and economically. Two methods are commonly used by the evaluation of injection volumes for CO_2 flooding. One is by calculating the percentage of hydrocarbon pore volume (HCPV %), which is used commonly in miscible flooding. Another method is the real volume injected, which is applied for both miscible and immiscible flooding. For CO_2 immiscible flooding, the CO_2 utilization volume is greatly affected by the reservoir size and the number of gas injection wells. The CO_2 utilization volumes are all net values where the recycled CO_2 is excluded. During the production process, CO_2 is produced along with oil and water production, and these produced gases were re-injected into wells to promote economic benefits and to protect the environment. Based on existing data, the average CO_2 utilization is 1.55 Bscf per well, with an average incremental production rate of 23.0 bbl/day per well. Overall, larger reservoir sizes mean greater amount of CO_2 injection volume required and more oil production.

5. PERFORMANCE EVALUATIONS

The purpose of injecting CO_2 is to produce more oil from reservoirs, and the effectiveness of projects could be evaluated from CO_2 injection efficiency, incremental oil recovery, and incremental oil production rate.

5.1. CO_2 INJECTION EFFICIENCY

CO_2 injection efficiency is defined as the ratio of the total gas injected to the cumulative oil produced. The total gas injection only accounts for the net gas utilization volume, and the volume of reinjected gas is not included. The reason for this is for economic evaluation. The amount of total gas usage is considered, which is directly related to how much gas should be purchased. Figure 14 displays the injection efficiency for each field. Higher values indicate lower efficiency because more CO_2 is needed to produce one barrel of oil.

The average injection efficiency among all successful projects is 10.07 Mscf/stb. The Buracica Field and Yaoyingtai Field are the two most effective CO_2 immiscible applications, where the injection efficiencies are 0.45 Mscf/stb and 0.39 Mscf/stb, respectively. These fields are the most effective because of their pure composition of injected gas (100%). In contrast, the injection results in the Ikiztepe Field are the worst because this field has the highest oil viscosity which makes the oil hard to move.

If we assume that the cost for CO_2 is US$20/ton, only US$11.52 need to spend to produce one barrel of oil. Table 7 depicts the details for the economic evaluation of CO_2 immiscible flooding projects.

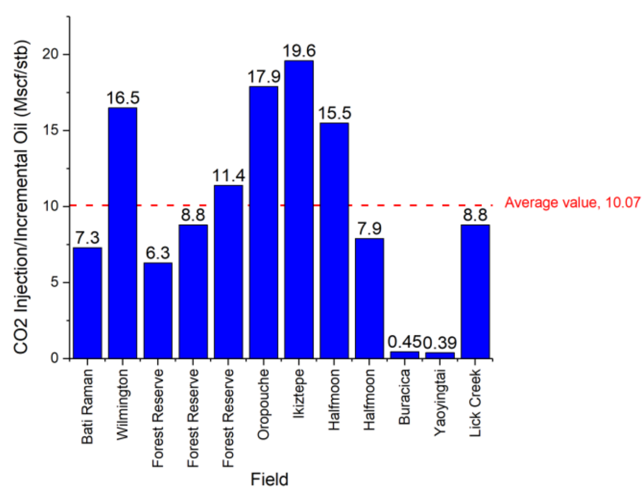

Figure 14. CO_2 injection efficiency for different fields (The field with same name means they are from same field, but different pay-zones.).

Table 7. Economic evaluation based on the injection efficiencies of sandstone and carbonate CO_2 immiscible flooding applications.

	All Projects	Sandstone	Carbonate
Average CO_2 Injection Efficiency, Mscf/stb	10.07	8.72	14.13
Cost for CO_2 Purchase[a], US$/stb	11.52	9.98	16.17
Transportation Cost[b], US$/stb	5.76 - 13.82	4.99 - 11.98	8.09 - 19.40
Operation Cost[c], US$/stb	2 - 3	2 - 3	2 - 3
Total Cost, US$/stb	19.28 - 28.34	16.97 - 24.96	26.26 - 38.57

Conversion:

- 1 ton = 17.48 Mscf [97].

Assumption:

a. The price for CO_2 is US$20/ton.
b. The transportation cost is US$0.5-US$1.2/Mscf.
c. The operation cost is US$2-US$3/stb

The average cost for all CO_2 immiscible flooding is around US$19/stb to US$28/stb with the consideration of transportation and operations, and this cost is a little bit higher than the cost for CO_2 miscible flooding (US$18/bbl) [96], which indicates that CO_2 immiscible is compatible with other EOR technologies. The cost for sandstone reservoir is significantly lower than carbonate reservoir due to the lower injection efficiency, this result shows that the CO_2 immiscible is more commercial in sandstone reservoirs.

5.2. INCREMENTAL OIL RECOVERY

Figure 15 depicts the incremental oil recovery for different fields. It illustrates that CO_2 immiscible displacement is capable to increase oil production by 4.7% to 12.5%, and 8.5% on average. The smaller value does not imply that less oil was produced because the incremental oil recovery relies on the amount of original oil in place and the utilization volume of injection gas. For the biggest CO_2 immiscible flooding project, the Bati Field injected 352.8 Bscf CO_2 into the reservoir, even though only an additional 6% of oil was produced. This project is considered as a great success for the implementation of CO_2 immiscible displacement because it produced an extra 70.4 MMstb oil. This project is still active and has been injecting CO_2 since 1986.

5.3. INCREMENTAL OIL PRODUCTION RATE PER WELL

The incremental oil production rate is another important factor to evaluate the effectiveness of projects. As projects are in various sizes with different numbers of production wells, this value is converted to the average incremental oil production per well for comparisons. Figure 16 shows that the injection of CO_2 could enhance oil production rates by 23.0 bbl/d/well, and the best performance was found in Eucutta Field in the United States.

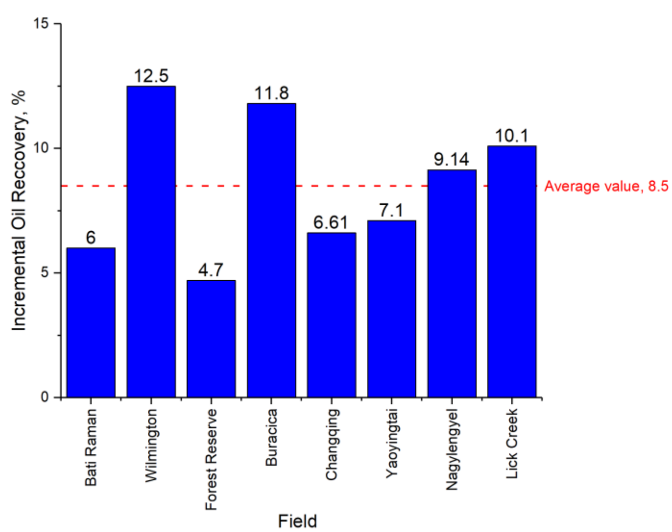

Figure 15. Incremental oil recovery for different fields.

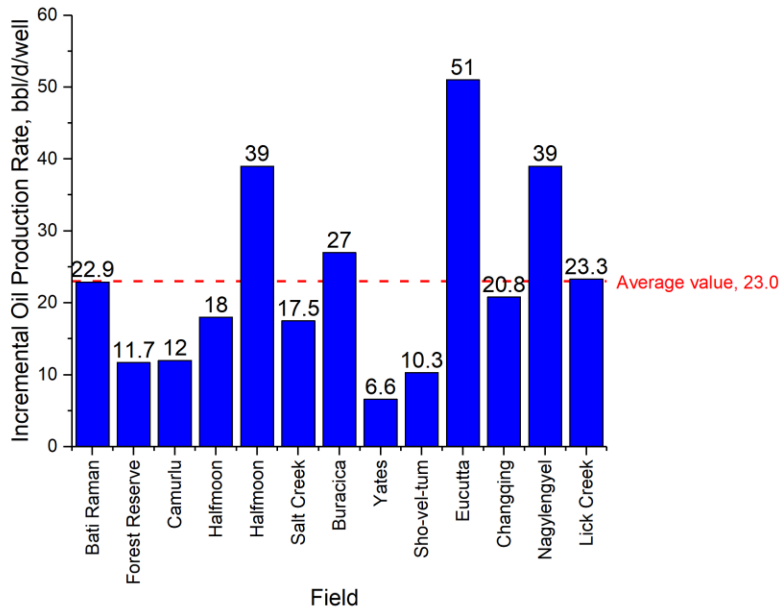

Figure 16. Incremental oil production rate per well for different fields (The field with same name means they are from same field, but different pay-zones.).

6. EXISTING PROBLEMS AND SOLUTIONS

During the production life of oil fields, some operational problems could not be avoided. Table 8 provides an overview of the reported problems along with some useful solutions used in these fields. Overall, these problems could be summarized as: (1) early gas breakthrough/channeling, (2) injectivity reduction, (3) existence of hydrogen sulfide.

The common solutions to avoid the early gas breakthrough and injectivity reduction are to change the well patterns and to adjust injection strategy. For example, the Lick Creek Field converted eight existing producers to injectors to mitigate early gas breakthrough problem and to improve sweep efficiency; The Bati Field changed the injection strategy from continuous CO_2 injection into WAG injection due to the poor conformance sweep of CO_2.

Table 8. Reported operational problems/difficulties and solutions from CO_2 immiscible applications.

Field	**Problems**	**Solutions**
Lick Creek	Early gas breakthrough Low sweep efficiency	Convert eight existing producers to injectors to sweep the reservoir better
Bati Raman	1. Poor conformance sweep of CO_2 2. Existing H_2S in CO_2 3. High gas saturation around the wellbore leads to "gas blockage" formed. 4. Horizontal wells are pumped failures caused by CO_2, especially in the high GOR area.	1. Gel treatments to plug the fracture system within the vicinity of injection wells. WAG 2. The gas is processed in absorption and dehydration units to remove H_2S and water. 3. Give a gas drive application or convert to gas drive. 4. Placing pump intake below the production zone-as deeper as it can. A hybrid configuration of vertical and horizontal wells, which provides the advantages of both well types
Wilmington	1. Excessive gas production in some wells 2. Poor distribution of fluids into the three zones present in this reservoir	Inject foam
Forest Reserve	1. Channeling 2. Severe sand production, many wells lost through failed gravel-pack liners	
Ikiztepe	1. High H_2S concentration 2. Mechanical problems that caused occasional operational interruptions at the wells can be attributed to the inability of the sub-surface sucker-rod pump to handle such heavy and viscous oil	1. Sweetening unit installed. 2. Injecting light oil to decrease the fluid viscosity followed by re-setting of the SSP.

Table 8. Reported operational problems/difficulties and solutions from CO_2 immiscible applications (cont.).

Field	Problems	Solutions
Halfmoon	1. CO_2 injection rate would be limited by production supply. 2. Natural fractures would cause conformance problems. 3. The distribution of remaining oil was unknown, and mobilization of altered oil might be inefficient. 4. The influence of rock type on process response was unknown. 5. Asphaltene precipitation was possible.	A laboratory evaluation was undertaken to alleviate project concerns.
Buracica	CO_2 circulation. Continues expansion of the gas cap (of CO_2) leads to increasing gas production (CO_2).	Connect the tubing-casing annular space of producing wells to production lines; with this, the produced CO_2 was taken to the station facilities to be separated from the oil. Introduce a project of water injection at the gas/oil contact.
Yaoyingtai	Early gas breakthrough, low sweep efficiency	Inject alternatively

Hydrogen Sulfide (H_2S) is a common flue gas in the oil fields, and this gas is one of the reasons that cause the corrosion problem and not good for health. Therefore, the concentration of H_2S should be minimized. In the oil fields, sweetening units are normally installed to remove the H_2S. If the corrosion is so severe that the sweetening unit could not handle, other materials (e.g. glass fiber) are considered for replacement [50].

7. CONCLUSIONS

- A comprehensive review of CO_2 immiscible flooding applications has been presented. Forty-one field cases from 1968 to 2017 are included, and the incremental oil recovery ranges from 4.7% to 12.5% of the original oil in place.
- Statistical analysis from the collected data provides the updated guidelines on the reservoir/fluid conditions for the implementation of the CO_2 immiscible flooding process, and the net thickness is considered for the first time.
- The special cases detected from boxplots reveals the uniqueness of oil field in each country. For example, the oil in Turkey are mainly heavy oil (high viscosity).
- Water alternating gas (WAG) and huff-n-puff are the two most common injection strategies for CO_2 immiscible flooding. Field experiences have showed that the WAG ratio should be flexible with reservoir responses.
- The average cost for CO_2 immiscible flooding is around US$19/stb to US$28/stb, and the economic evaluation reveals that the sandstone reservoir is more commercial for CO_2 immiscible flooding implementations.

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III. A NOVEL EOR SCORING SYSTEM BASED ON CONVENTIONAL SCREENING GUIDELINES AND RANDOM FOREST

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ABSTRACT

Enhanced oil recovery (EOR) selection is an important process to evaluate the potentials about which EOR technology could be performed in a new reservoir candidate. In the literature, the construction of conventional screening guidelines is normally used to assist EOR selection. However, no discriminative screening results could be revealed using this method. In this study, we propose a novel hybrid method to develop a scoring system for EOR selection with the combination of conventional screening guidelines and the random forest algorithm. At first, the screening guidelines were updated by compiling 977 EOR projects from various publications in different languages, including *Oil and Gas Journal (OGJ)* biannual EOR surveys, SPE publications, DOE reports, Chinese publications, etc. Boxplots were used to detect the special cases for each reservoir/fluid property and to present the graphical screening results. Then, the weighting factors for each EOR technology were accomplished through the application of the random forest algorithm, where the EOR types and the oil recovery were regarded as objective functions. The scoring system was then established by the fuzzification of reservoir/fluid property scores and the computation of composite screening scores. A case study was used to

demonstrate that with a simple input of reservoir/fluid information, the novel scoring system could effectively provide recommendations for EOR selection by ranking scores.

1. INTRODUCTION

In the global context of growing energy needs and considering the depletion of oil and gas resources, extending the life of hydrocarbon reservoirs and improving oil recovery is a challenge for all petroleum engineers, especially for reservoir engineers. To improve oil recovery, more than 20 enhanced oil recovery (EOR) techniques have been developed over years [1]. Generally, by applying various EOR technologies to the different oil fields, an additional up to 30% of crude oil could be produced from the reservoir. Therefore, EOR technologies are vitally important in the oil industry, and these technologies have been used worldwide.

EOR selection is a complex process that involves reservoir characterization, technology feasibility, and commercial evaluations. In the oil industry, the EOR screening process has been considered as the first step for EOR selection. Since the 1970s, a variety of EOR screening methods have been proposed to find the suitable EOR method for a new candidate reservoir. In 1978, Poettman and Hause proposed the screening guidelines for micellar-polymer based on reservoir properties [2], which is the first publication found for EOR screening. After that, especially since the late 1990s, EOR screening criteria for broader EOR processes have been discussed by more researchers, and more methodologies have been developed. By far, EOR screening could be classified as conventional and advanced methods.

The conventional EOR screening is also called the "go/no-go" approach, which generally uses the ranges or intervals of reservoir/fluid properties to filter out the applicable EOR technologies. Look-up tables coming from the statistical analysis of the existing EOR projects are provided with different property intervals for each EOR method. One famous and well-acknowledged EOR screening guideline was proposed by Taber et al. in 1997, which provides screening criteria based on the EOR projects conducted from 1974 to 1996 [1, 3]. Six important parameters were considered in the proposed screening process with suitable ranges, including oil gravity, oil viscosity, oil saturation, average permeability, depth, and temperature. Al-Adasani and Bai updated the Taber's screening guidelines by including data from 1998 to 2010. Miscible and immiscible flooding were distinguished for all gas injection technologies, and the porosity guidelines were newly added in their work [4]. Even though both Taber and Al-Adasani provide useful guidelines for each EOR technology, updating screening guidelines along with the dramatic increase of EOR projects is crucial since the conventional screening guidelines are constructed based on existing projects and expert knowledge, especially the projects conducted after 2010. Furthermore, no discriminative results are presented in the conventional screening methods, so further studies are required.

Advanced EOR screening includes all of the methods that apply artificial intelligence (AI) techniques to assist engineers for EOR selection. Alvarado et al. proposed a methodology by utilizing the machine learning algorithm to draw the rules for EOR screening [5]. Six clusters were classified based on the dataset, and each cluster has its own rules for applications. Siena et al. developed a methodology for target reservoirs analog by applying the Bayesian hierarchical clustering algorithm [6]. Although the advanced EOR screening methods provide discriminative results, the reliability and accuracy of the prediction models need further investigation and validation by using simulation and pilot tests.

The objective of this study is to propose a novel EOR selection methodology, which could retain the advantages of both conventional and advanced EOR screening methods while avoiding the disadvantages. To fulfill the goal, the conventional screening guidelines is updated by integrating all OGJ biannual EOR surveys with various publications. The quantitative net thickness guidelines are provided for the first time, and the applicable ranges are presented based on formation types. Then, the weighting factor matrix is determined for each EOR technology by implementing the random forest algorithm. Finally, the scoring system is developed based on the computation of composite screening scores.

2. DATA PREPARATION AND ANALYSIS

Figure 1 presents a graphical flow chart of the proposed EOR screening process. Four stages are included in this study: (1) preparing worldwide EOR project dataset; (2) constructing conventional screening guidelines; (3) computing weighting factors for each EOR technology; (4) analyzing the screening results based on the composite screening scores. The first stage includes EOR data collection/integration from various sources and data pre-processing for further analysis. After data preparation, boxplots are applied to reveal the ranges and to detect the special cases for each reservoir/fluid property. To provide discriminative screening results, the weighting factors are introduced in each EOR technology, where the weighting factors are computed with the objective functions of EOR types and the additional incremental oil recovery factor by the implementation of EOR technology. The last stage is to establish a scoring system that calculates the screening scores and provides visualized results for EOR selection.

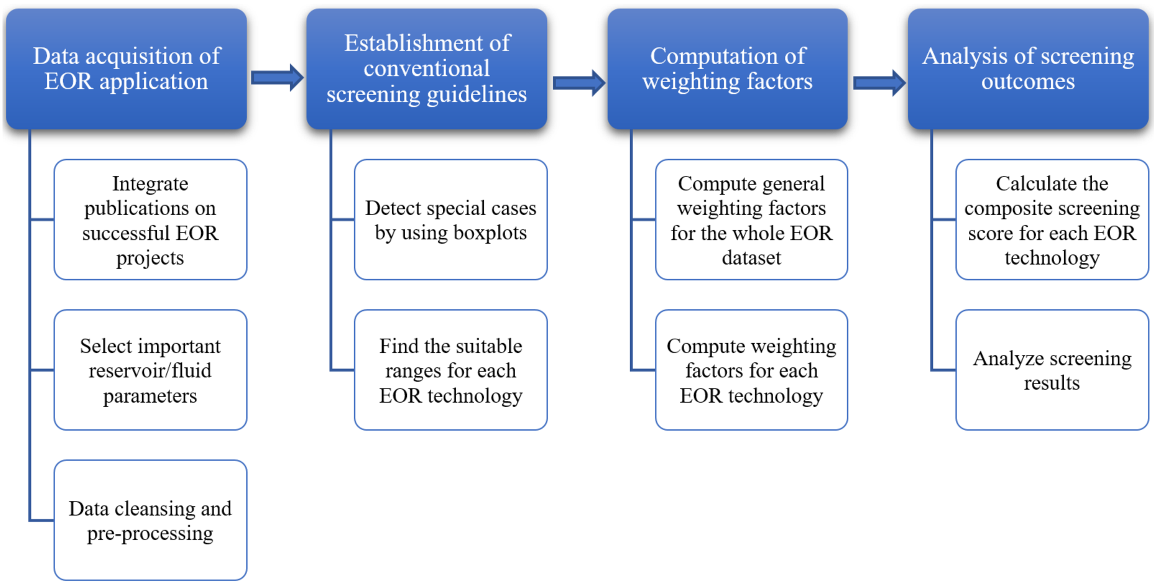


Figure 1. Flow chart of worldwide EOR screening process.

2.1. DATASET PREPARATION

Establishing a worldwide EOR dataset is a great challenge because EOR projects are scattered and are reported in a variety of publications in different languages. To establish the screening guidelines for EOR applications, a dataset with 977 successful EOR projects was created. Figure 2 depicts the process for dataset construction with references.

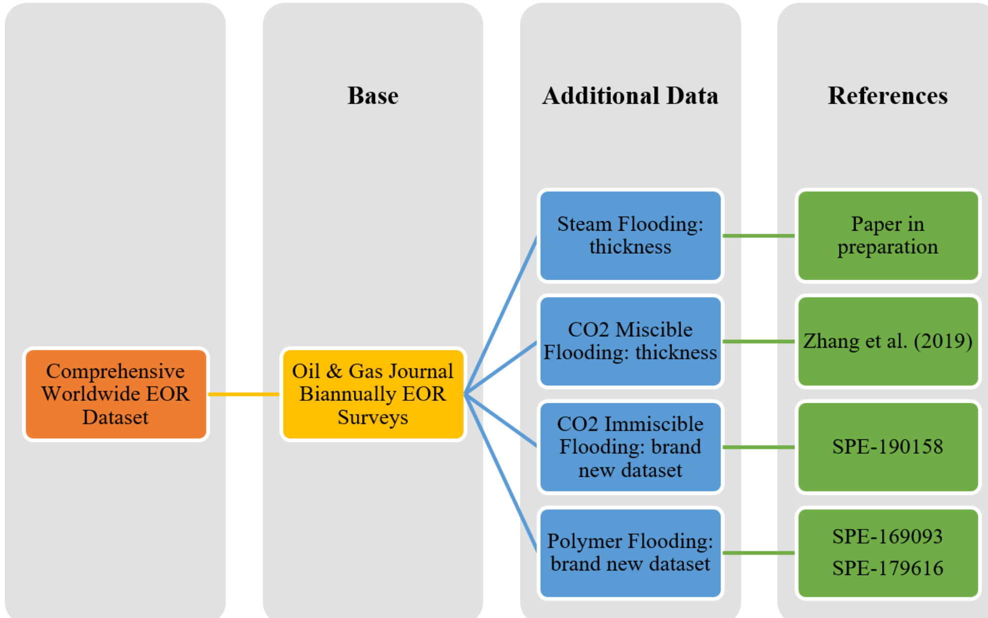


Figure 2. Dataset construction process and references.

The original dataset was established based on all OGJ biannual EOR surveys published before 2018. Due to the fact that several important reservoir/fluid properties were not included and some operators did not report and update to the OGJ, the supplemental information gathered from books, DOE reports, AAPG databases, field reports, Chinese publications, and SPE publications are used to fill in for missing EOR projects and reservoir/fluid properties. For example, the CO_2 immiscible projects were barely presented in the EOR surveys, and the Chinese government only published the EOR projects (mostly polymer flooding) information in 1996, brand-new datasets with the most up-to-date and comprehensive CO_2 immiscible flooding and polymer flooding projects were created in which most projects were extracted from Chinese publications and SPE publications. Important operational properties (e.g., CO_2 utilization, injection rate, well pattern, etc.) and performance evaluations (incremental oil recovery, injection efficiency, enhanced production rate, etc.) are also included in these datasets. For steam flooding dataset, additional information for formation net thickness was collected as it is crucial for economic evaluation.

2.1.1. Data Pre-processing. Data pre-processing is a critical process for data analysis that ensures the high quality of the dataset by detecting/removing errors and inconsistencies (Cite my CO2 miscible paper). With the integration of various OGJ biannual EOR surveys and different publications, the need for data processing increases significantly because the combined surveys and publications consist of severe duplicate data with different representations. To improve the quality of the dataset, all the duplicated projects were deleted by following the “one field/pay-zone, one project” policy proposed in the previous paper (Cite my CO2 miscible paper). All special cases revealed by the boxplots were double-checked and corrected based on relevant publications. Meanwhile, all EOR projects were consolidated into the same format, and only successful EOR projects were considered for further data analysis.

2.2. WORDWIDE EOR PROJECT DISTRIBUTIONS

The established worldwide EOR dataset consists of 977 projects from more than 10 countries, including the United States (563), Canada (155), China (70), etc. The colored countries in Figure 3 illustrate the locations and number of EOR projects in the world. Countries with less than 5 EOR projects are characterized under the “other” category and are not presented in the world map due to the limited space. Such countries include Argentina (4), Hungary (4), Indonesia (4), Congo (2), Malaysia (2), Norway (2), Russia (2), Colombia (1), Egypt (1), Holland (1), Libya (1), Oman (1), Suriname (1), and United

Kingdom (1). Most EOR projects were conducted in North and South America. Figure 4 presents the project distributions for each EOR technology in different countries. As shown in Figure 4, most of the thermal EOR projects were applied in the United States, Canada, Venezuela, Trinidad, and Germany, which occupies 94.7% of the thermal projects. Besides steam flooding, CO_2 miscible flooding is also a well-developed EOR technology in the United States due to sufficient CO_2 sources with 30 years of CO_2 pipeline constructions. In contrast, hydrocarbon miscible flooding technology has been mostly used in Canada because of the rich existence of natural gas.

Reservoir lithology is one of the most important properties for EOR applications. Sandstone and carbonate reservoirs are the common formation types based on existing worldwide EOR dataset. Figure 5 depicts that hot water, hydrocarbon immiscible flooding, surfactant, and microbial flooding have only been successfully applied in sandstone reservoirs.

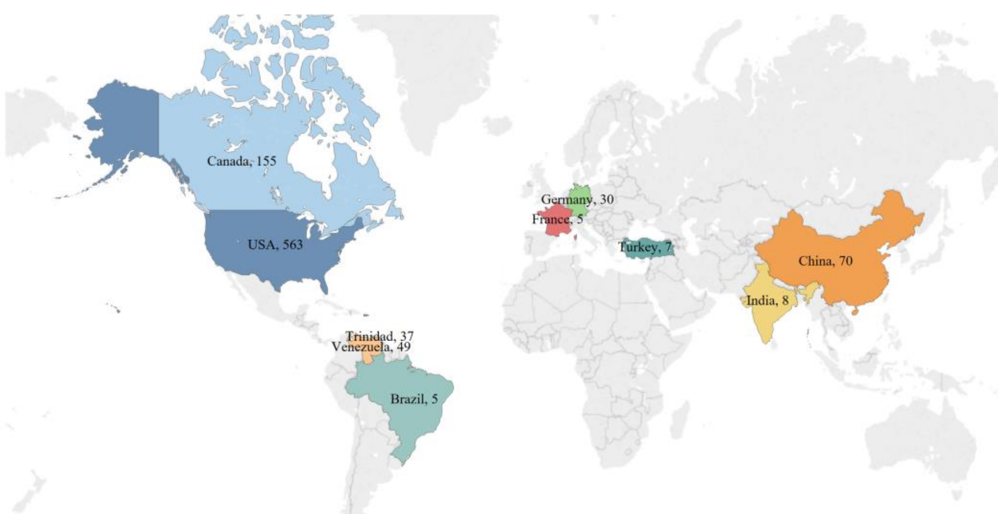


Figure 3. Locations of EOR project implementations (Data sources: [9-32]).

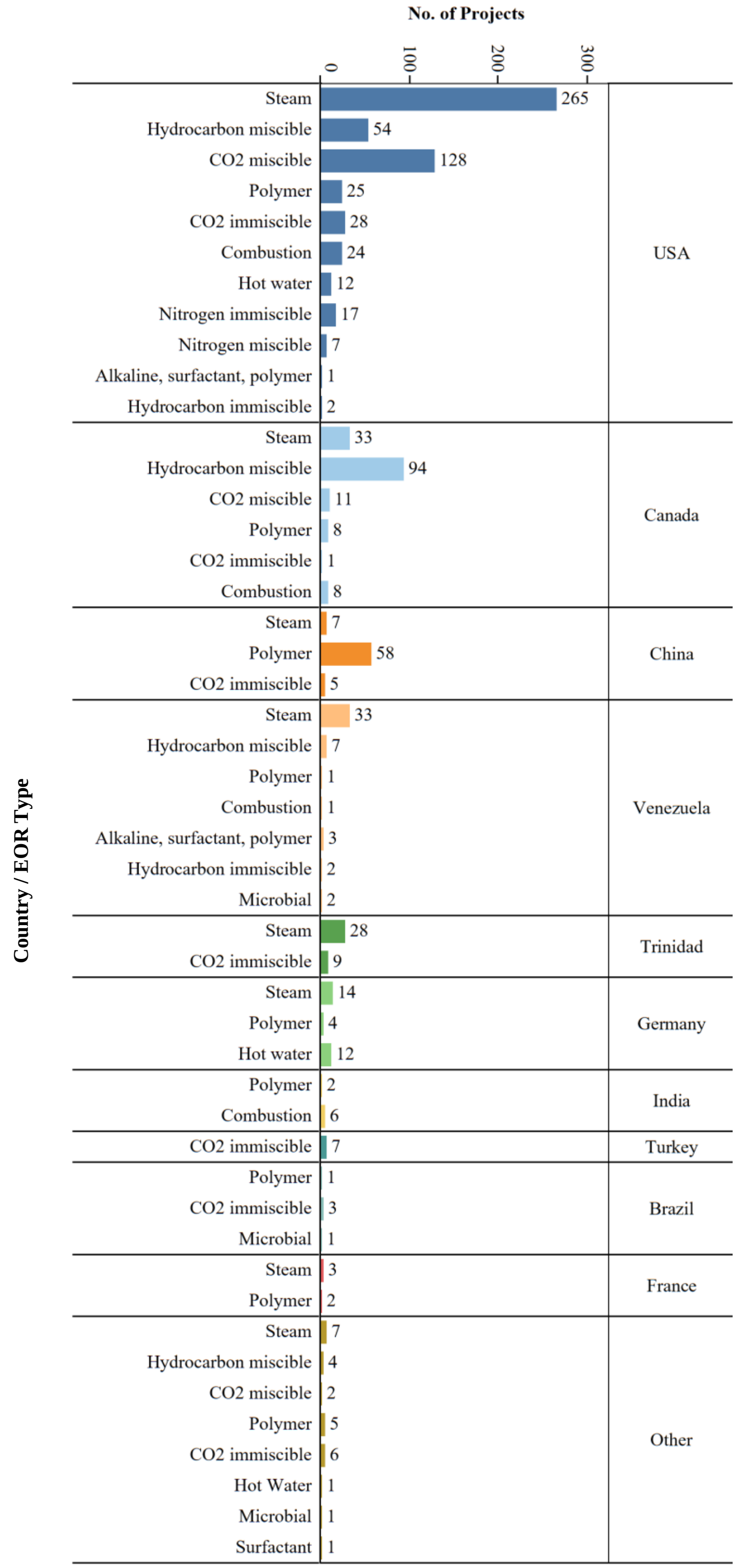


Figure 4. EOR type distributions in different countries.

Most thermal and chemical EOR projects were conducted into the sandstone formation, while gas injection projects have been widely applied in both sandstone and carbonate reservoirs. Based on the established EOR dataset, 79% of the EOR projects were applied in sandstone reservoirs because most of the proven petroleum reservoirs are in sandstones [7] and most of the technologies have been evaluated or tested at the pilot stage in these formations [8].

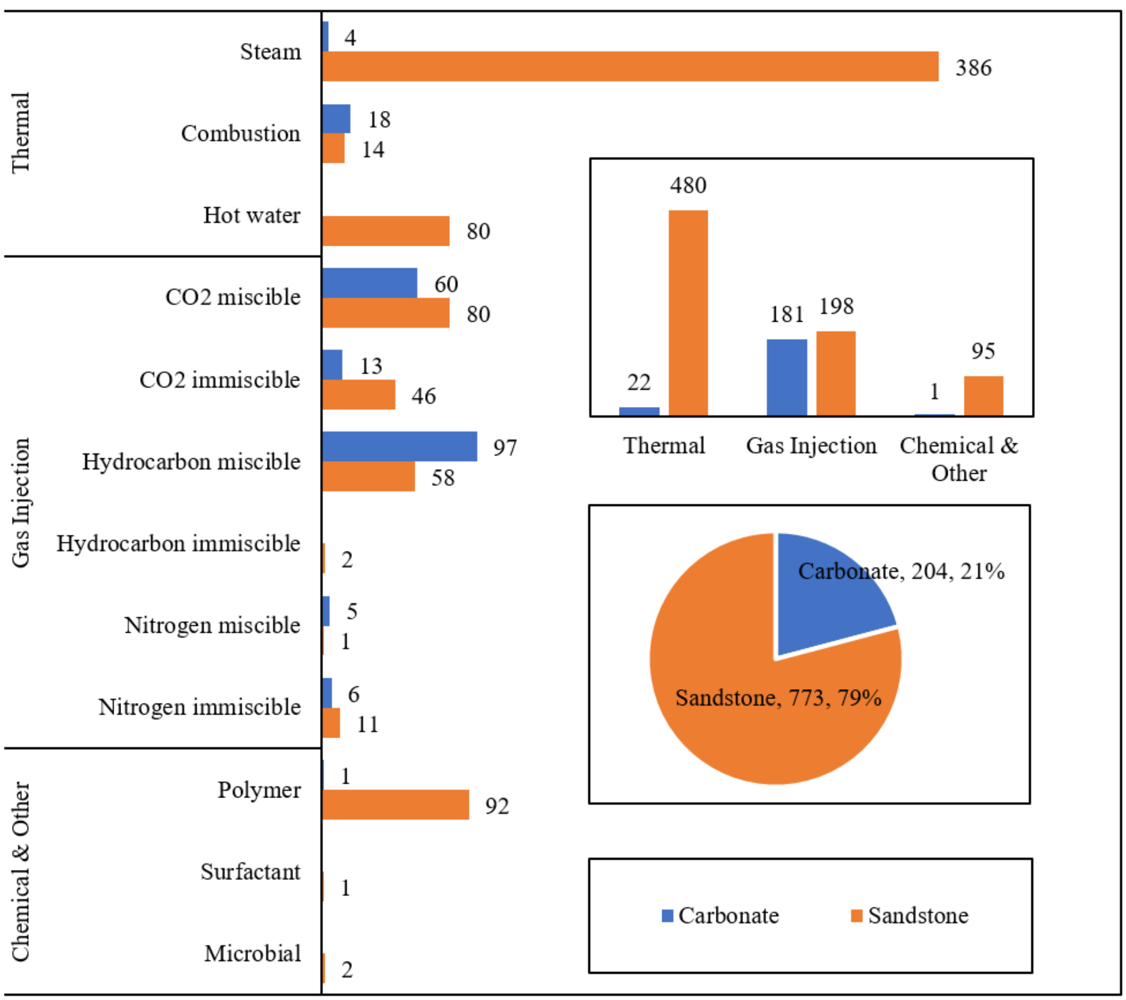


Figure 5. EOR applications by EOR methods and lithologies (based on a total of 977 projects).

3. CONVENTIONAL SCREENING GUIDELINES

Figure 6 illustrates a modified graphical screening guideline that was created by Taber et al. for depth and viscosity based on the newly established worldwide EOR dataset. Regions enclosed within the ellipse represent the applicable ranges for each EOR technology. The figure suggests that the thermal methods could be successfully applied in shallow reservoirs with heavy oils (viscosity up to 1,000,000 cp), while the gas injection methods need to be used in deep reservoirs with light oil (viscosity less than 3 cp).

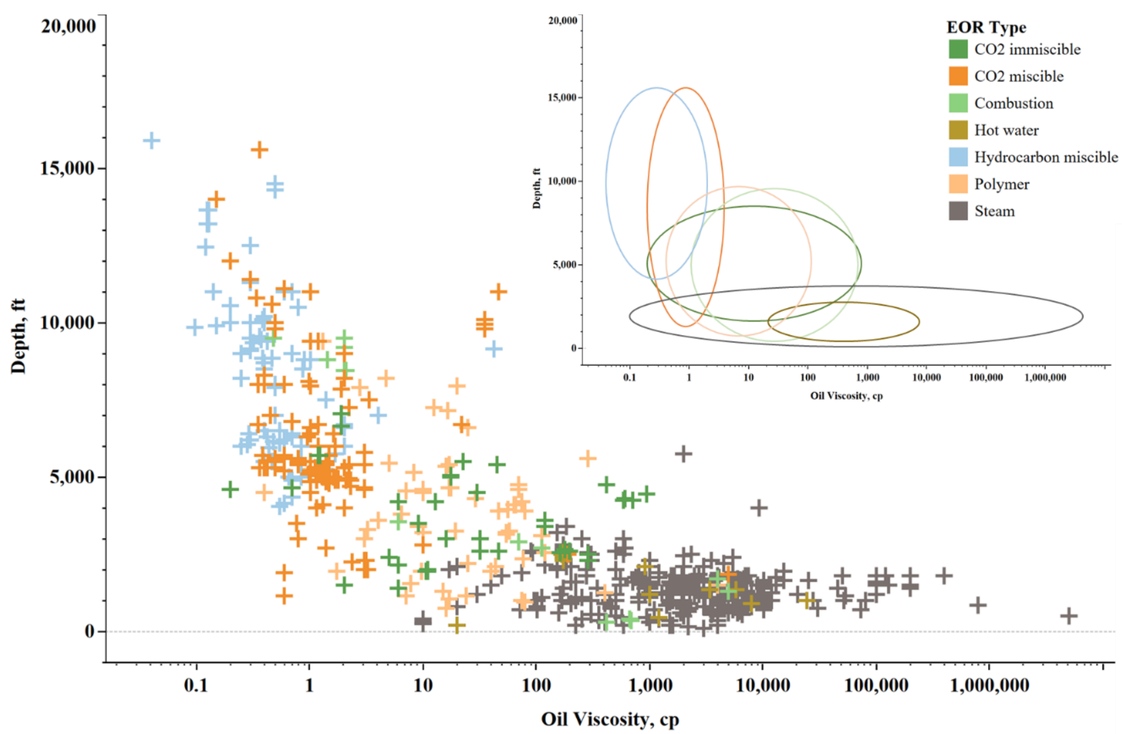


Figure 6. Modified conventional screening guidelines by Taber et al. [1, 3]. (EOR technologies with less than 20 projects are excluded in this figure (Data sources: [9-32]).

To provide an easy, straightforward, and comprehensive screening guideline, a boxplot matrix is created to visualize all the ranges for reservoir/fluid properties. Figure 7 displays the schematic for a boxplot under two conditions, which reveals the minimum, 25th percentile (Q1), median, 75th percentile (Q3), maximum, lower limit (2.5Q1-1.5Q3), and upper limit (2.5Q3-1.5Q1). Figure 7A depicts the condition when the lower and upper limits are within the minimum and maximum values. In statistics, when the value is smaller than the lower limit or greater than the upper limit, those projects will be considered as outliers in statistics. However, for the construction of screening guidelines, the detected outliers are regarded as special cases after data cleansing that could not be ignored because each case represents either an extreme reservoir/fluid situation or a new development for the implementation of an EOR technology. Figure 7B illustrates the condition when the lower and upper limits are outside the minimum and maximum values. No special cases are revealed as no project falls into the range between lower limit and minimum value, or between maximum and upper limit.

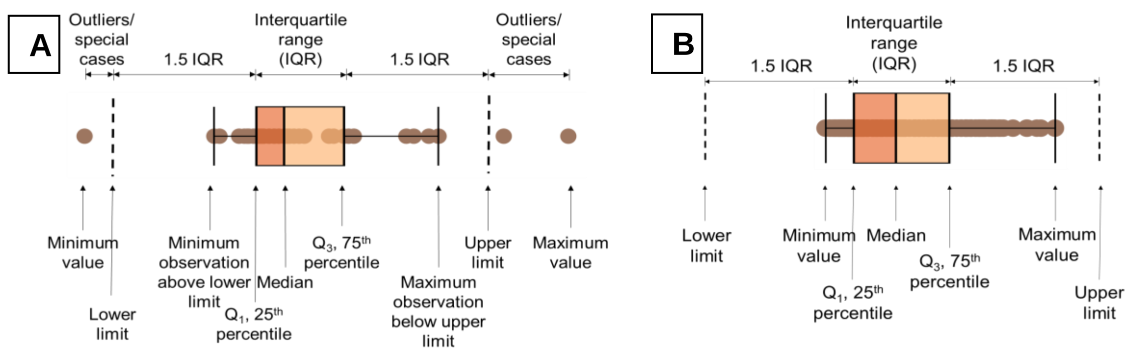


Figure 7. Schematic of boxplots with lower/upper limit within minimum/maximum values (A) and lower/upper limit outside minimum/maximum values (B).

The graphical EOR screening guidelines are presented in Figure 8. Each boxplot represents the ranges for one EOR type, one lithology, in one property. The boxplots for the same property are generated at the same scale under different EOR technologies and lithologies, which facilitate the screening process significantly. For example, for a given porosity of 20%, the feasibility of EOR technologies could be revealed directly in the boxplots by drawing a vertical line in the boxplot matrix (porosity equal to 20). The intersection points between the vertical line and the boxplot(s) indicate which EOR technique is feasible to the given porosity situation, and vice versa.

Table 1 provides the updated quantitative worldwide EOR screening guidelines based on sandstone and carbonate formation types, which shows the conditions about which EOR technology could be used. The bar charts in the table depict the proportion of each formation type to a specific EOR technology, which is a direct indication of formation type distributions. The bar charts show that steam flooding and chemical flooding have been mostly applied in sandstone reservoirs, while the gas injection technologies have been widely conducted in both formation types. Table 1 also presents the descriptive statistical ranges (minimum, maximum, average values) for each reservoir/fluid property. Special cases beyond the lower limit and the upper limit that are detected from boxplots are also illustrated in the table to show the boundaries for EOR technologies.

4. SCORING SYSTEM

Although the constructed conventional screening guidelines provide a useful recommendation list for EOR selection, no discriminative screening results are presented for the comparison between EOR technologies. In other words, the conventional screening guidelines have no indication of which EOR method is the best for given reservoir/fluid conditions. To solve this problem, weighting factor and reservoir/fluid property scores are introduced into the conventional screening guidelines to establish a hybrid scoring system to rank all the EOR methods.

4.1. WEIGHTING FACTORS COMPUTATION USING THE RANDOM FOREST ALGORITHM METHOD

Determination of weighting factors for EOR screening is crucial as it provides the relative importance of reservoir/fluid properties for a particular EOR technology. The expert's domain knowledge and the statistical method are two approaches that could define the weighting factors. In the oil industry, the former approach is normally used to decide the importance of properties for each EOR technology because the latter requires a large quantity of data. However, the domain knowledge may not be always reliable, as the interesting results from special cases may be ignored [33].

In this study, the random forest algorithm is implemented in the worldwide EOR dataset to find the importance of properties for each EOR technology. Using random forest is advantageous because it not only provides high predictive accuracy even at high-dimensional problems but also considers the impact of individual predictors as well as the multivariate interactions between predictors [34]. In the random forest, permuting out-of-bag (OOB) error is the general rule to estimate the importance of one predictor variable, where the importance measures how much mean square error (MSE) and impurity increase for regression problems when that variable is randomly permuted.

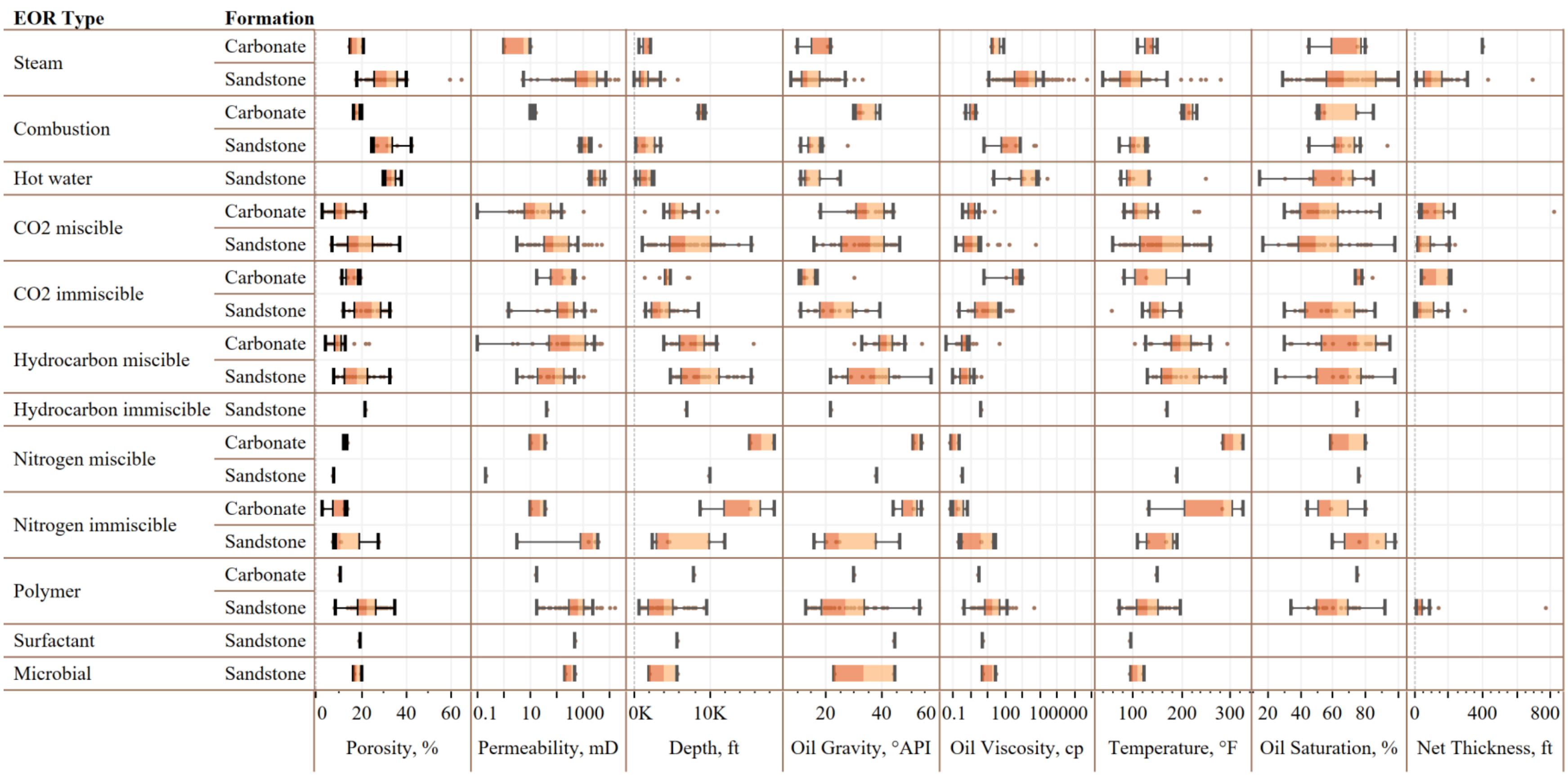


Figure 8. Assembled graphical conventional screening guidelines.

Table 1. Updated EOR screening guidelines (Data sources: [9-32])

EOR Type	Formation Type	No. of Projects	Porosity, %	Permeability, mD	Depth, ft	Oil Gravity, °API	Viscosity, cp	Temperature, °F	Oil Saturation. Start, % PV	Thickness, ft
Thermal Methods										
Steam	Carbonate	4	15-21 avg. 16.5	1-10 avg. 4	700-2101 avg. 1725.3	10-22 avg. 18.8	17-72 avg. 32.3	110-150 avg. 137.5	45-80 avg. 61.3	400
	Sandstone	386	18-40.3 (65) avg. 32.4	5-6700 (20000) avg. 2617.9	100-3400 (5740) avg. 1365.5	8-27 (33) avg. 13.8	10-15000 (5000000) avg. 24046	40-170 (280) avg. 100.7	29-98 avg. 67.8	9-700 avg. 194.8
Combustion	Carbonate	18	17-20 avg. 18.2	10-15 avg. 11.2	8450-9500 avg. 8991.7	30-39 avg. 33.7	1-2.1 avg. 1.8	200-230 avg. 216.2	50-85 avg. 57.5	
	Sandstone	14	25-42.6 avg. 30.3	650-1790 (4000.6) avg. 1325	300-3550 avg. 2071.4	11-19 (28) avg. 17.5	6-675 (50000) avg. 1163	74-130 avg. 106.5	45-77 (94) avg. 67.8	
Hot water	Sandstone	80	30-38 avg. 31.7	1500-6000 avg. 3928.6	200-2560 avg. 1794.2	11-25 avg. 19.1	20-8000 (24000) avg. 2771.7	75-135 (250) avg. 105	15-85 avg. 57	
Gas Injection										
CO2 miscible	Carbonate	60	3-22 avg. 11	0.1-140 (1000) avg. 38.3	(1400) 4000-8500 (11100) avg. 5642.3	18-44 avg. 35.8	0.4-3 (22) avg. 1.8	82-151 (237) avg. 119.2	30-89 avg. 53.4	27.9-824 avg. 154.9
	Sandstone	80	7-37 avg. 19.9	3-550 (4500) avg. 394.4	1150-15600 avg. 6952.4	16-46 avg. 37.5	0.2-3 (5000) avg. 89.4	60-260 avg. 159.5	17-98 avg. 51.7	18-236 avg. 87.3
CO2 immiscible	Carbonate	13	11.5-19.8 avg. 16.8	17-1000 avg. 251.4	(1400) 4265-4756 (7401) avg. 4041.4	10.8-17 (30) avg. 17.8	6-936 avg. 397.6	82-213.5 avg. 127.1	74-78 (84.5) avg. 77.4	40-213.5 avg. 127
	Sandstone	46	12.1-33 avg. 25	1.4-2750 avg. 415.3	1500-8500 avg. 4120.5	11-39 avg. 23.1	0.2-45 (283) avg. 45.7	(58) 120-198 avg. 142.4	30-86 avg. 415	5.2-300 avg. 69.7
Hydrocarbon miscible	Carbonate	97	4.3-12.7 (23.9) avg. 9.6	0.1-2400 (5000) avg. 721.7	4040-11000 (15900) avg. 7422	(30) 34-48 (54) avg. 40	0.04-1 (42) avg. 1.8	(105) 125-260 (293) avg. 192.9	30-95 avg. 78.5	
	Sandstone	58	8-33 avg. 20	3-420 (1000) avg. 270.6	4900-15600 avg. 9255.8	22-57 avg. 35.9	0.1-2 (4) avg. 0.8	131-290 avg. 197.2	25-98 avg. 64.4	
Hydrocarbon immiscible	Sandstone	2	22	40	7000	22	4	170	75	
Nitrogen miscible	Carbonate	5	12.4-14 avg. 13	10-35 avg. 20	15400-18500 avg. 17260	51-54 avg. 52.8	0.1-0.2 avg. 0.1	285-325 avg. 309	59-80 avg. 74.8	
	Sandstone	1	7.5	0.2	10000	38	0.3	190	76	
Nitrogen immiscible	Carbonate	6	3-14 avg. 11.1	10-35 avg. 15	8835-18500 avg. 16372.5	44-54 avg. 51.8	0.1-0.6 avg. 0.2	132-325 avg. 286.2	43.8-80 avg. 70.5	
	Sandstone	11	7.5-28 avg. 24.6	3-3400 avg. 2190.3	2500-12000 avg. 5275.5	16-46 avg. 25.2	0.2-25000 avg. 164	110-190 avg. 159.4	60-98.5 avg. 73.8	
Chemical & Other Methods										
Polymer	Carbonate	1	10.4	16	7900	30	2.8	150	75	
	Sandstone	92	8-35 avg. 23.9	17-2107 (15000) avg. 1138.2	750-9600 avg. 3948.9	15-53 avg. 27.5	0.4-120 (4000) avg. 96.4	72-198 avg. 133.4	34-92 avg. 61.5	10-779 avg. 64.3
Surfactant	Sandstone	1	20	475	5740	44.3	5	95		
Microbial	Sandstone	2	17-20 avg. 18.5	200-465 avg. 332.5	1970-5740 avg. 3855	23-44.3 avg. 33.7	5-28 avg. 16.5	95-122 avg. 108.5		

Note:

(Lower special cases) Range (Higher special cases)
Average value

If one randomly permutes a variable that does not gain anything in prediction, then predictions will not change much and small changes in impurity and MSE could be observed. On the other hand, the important variables will change the predictions significantly if randomly permuted, and therefore, bigger changes should be observed. Similarly, for classification problems, the mean decrease accuracy (MDA) and the mean decrease Gini (MDG) are the two indices that are calculated to represent the importance, where the higher the indices are, the more important the properties are. For both regression and classification problems, the permutation variable importance measurement is based on an arbitrary error measure E, which is defined as

$$VIM_j^E = \frac{1}{ntree}\sum_{t=1}^{ntree}\left(EP_{tj} - E_{tj}\right)$$

where:

ntree = Number of trees in the forest.

E_{tj} = OOB error on tree t before permuting the values of X_j.

EP_{tj} = OOB error on tree t after randomly permuting the values of X_j.

Table 2 displays the general weighting factors for the worldwide EOR dataset by normalizing the mean decrease Gini indices from 0 to 1 for the straight importance comparisons of reservoir/fluid properties for each EOR technology. The EOR types were used as an objective function in the model for classifications. The results show that the oil viscosity and depth are the two most important properties for the determination of EOR types, which confirms the results in Figure 6. As the reservoir/fluid properties should have different importance for each EOR technique instead of a universal value, the weighting factors are determined by feeding the incremental oil recovery factors into each EOR model (e.g., steam flooding, CO_2 miscible flooding). The universal weighting factors for EOR selection are used for hydrocarbon immiscible, surfactant, and microbial EOR process due to insufficient data to build different models.

Table 2. General weighting factors for the whole EOR dataset (objective function: EOR type).

Reservoir/fluid parameters	**Weighting Factor**
Oil Viscosity	0.31
Depth	0.23
Temperature	0.12
Oil Gravity	0.11
Permeability	0.09
Start Oil Saturation	0.08
Porosity	0.06

Table 3 presents the combined weighting factor matrix for each EOR technology. The higher the value is, the more important the property is for a particular EOR method. For example, the results demonstrate that the oil gravity is the most important parameter for the performance of combustion, while the permeability and reservoir temperature are not critical for gas injections. All the results in Table 3 agree with the well-accepted domain knowledge by Taber et al. [1], which validates the effectiveness of using random forest for the determination of weighting factors.

4.2. COMPOSITE SCREENING SCORES

After the computation of weighting factors for each EOR technology, the composite screening scores are calculated as

$$Composite\ Screening\ Scores = \sum_{i=1}^{n} w_i\, P_i$$

where:

w = Weighting factors for each parameter.

P = Reservoir/fluid properties' score.

Table 3. Weighting factor matrix for each EOR technology.

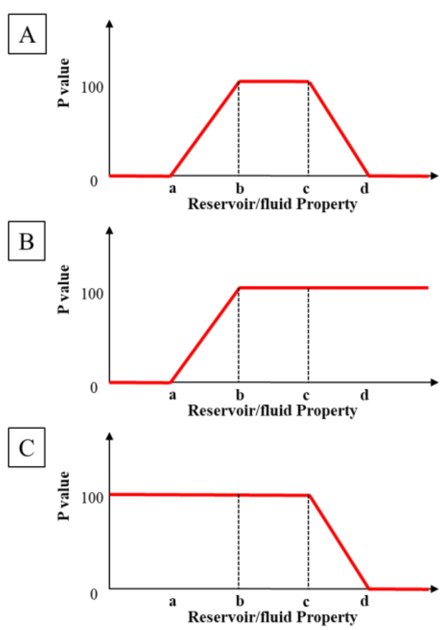
EOR Type	**Thermal**			**Gas Injection**						**Chemical & Other**		
	ST	CB	HW	CM	CI	HM	HI	NM	NI	PL	SF	MB
Porosity	0.16	0.16	0.14	0.09	0.18	0.08	0.06	0.01	0.16	0.01	0.06	0.06
Permeability	0.15	0.1	0.22	0.09	0.07	0.17	0.09	0.3	0.13	0.17	0.09	0.09
Depth	0.11	0.15	0.15	0.15	0.15	0.16	0.23	0.19	0.16	0.34	0.23	0.23
Oil Gravity	0.09	0.18	0.18	0.21	0.1	0.2	0.11	0.13	0.19	0.07	0.11	0.11
Viscosity	0.12	0.15	0.11	0.15	0.2	0.06	0.31	0.01	0.16	0.02	0.31	0.31
Temperature	0.11	0.1	0.01	0.07	0.05	0.07	0.12	0.09	0.17	0.31	0.12	0.12
Oil Saturation	0.18	0.16	0.19	0.14	0.19	0.26	0.08	0.27	0.03	0.08	0.08	0.08
Net Thickness	0.08			0.1	0.06							
Note: ST=steam, CB=combustion, HW=hot water, CM=CO2 miscible, CI=CO2 immiscible, HM=hydrocarbon miscible, HI=hydrocarbon immiscible, NM=nitrogen miscible, NI=nitrogen immiscible, PL=polymer, SF=surfactant, MB=microbial												

The reservoir/fluid properties' score (P) is determined by conventional screening guidelines and the fuzzification of membership under different conditions. Compared with the traditional method of assigning P values with hard boundaries based on minimum and maximum values (either 0 or 100), this study presents a new method to evaluate the P values, which ranges from 0 to 100. If the calculated lower/upper limit are between the minimum/maximum values (case Figure 7A), the conventional screening results will be applied, where the P values are defined as

$$P(x) = \begin{cases} 0 & x < minimum, or\ x > maximum \\ 100 & minimum \le x \le maximum \end{cases}$$

where x is the reservoir/fluid property value. If the property falls into the range from minimum to maximum values, a score of 100 will be received for that property; otherwise, no score will be given for that property.

Figure 9 illustrates the fuzzification memberships of P values for different properties if the lower/upper limit for a given property falls outside the minimum/maximum values (case Figure 7B). Figure 9A displays the trapezoidal shape of P values for property of reservoir depth and temperature. Both lower limit and upper limit are used for the determination of P values because the influence of depth and temperature are not monomial to different EOR techniques. For example, the thermal methods are more feasible at shallow reservoirs due to the upward transportation of heavy oil, while the gas injection techniques are more applicable at deep reservoirs because the miscibility between injected gas and oil are easier to achieve. Higher reservoir temperature is preferred in thermal methods, while chemical flooding (especially polymer flooding) are more applicable at lower temperature. Figure 9B shows monomial increasing of P values with the increase of porosity, permeability, oil gravity, and the oil saturation at the starting point of EOR techniques. When the candidate reservoir property is greater than the minimum value from existing EOR projects, a score of 100 will be assigned. With the decrease of property values from the minimum value to the lower limit, the score will reduce from 100 to 0 with a linear function. If the property reaches the threshold value (lower limit), no score will be received. Under the same reservoir/fluid condition and EOR process, the higher values of porosity and oil saturation mean that more oil existing in the reservoir, which result in more additional oil could be produced from the reservoir. Reservoirs with high average permeability represents the less resistance for the oil to flow. Also, the higher the oil gravity illustrates the easier the oil to flow towards the production well. Similarly, Figure 9C presents the decreasing of P values with the increase of oil viscosity. Low oil viscosity is more favorable as the oil is easier to flow, and more oil could be extracted from the reservoir. Hence, if the oil viscosity is greater than the maximum value, the P value for oil viscosity will gradually reduce from 100 to 0 until reaches the threshold upper limit value.



$$P(x) = \begin{cases} 0 & x \le a, or\ x \ge d \\ \dfrac{100(x-a)}{b-a} & a < x < b \\ \dfrac{100(d-x)}{d-c} & c < x < d \\ 100 & b \le x \le c \end{cases}$$

$$P(x) = \begin{cases} 0 & x \le a \\ \dfrac{100(x-a)}{b-a} & a < x < b \\ 100 & x \ge b \end{cases}$$

$$P(x) = \begin{cases} 0 & x \ge d \\ \dfrac{100(d-x)}{d-c} & c < x < d \\ 100 & x \le c \end{cases}$$

Figure 9. Determination of P values under different conditions when the lower/upper limits are outside the minimum/maximum values (a: lower limit, b: minimum value, c: maximum value, d: upper limit).

5. CASE STUDY

A case study is used to demonstrate the usage and effectiveness of the established methodologies, including (1) construction of conventional EOR screening guidelines, (2) computation of weighting factors for each EOR method, and (3) definition of P values. Table 4 illustrates the normally available related reservoir/fluid properties for EOR screening in the Midway-Sunset oil field.

Table 4. Reservoir/fluid properties in Midway-Sunset oil field.

Field Name	Φ, %	K, mD	D, ft	OG, °API	μ, cp	T, °F	S_o, %PV	h, ft
Midway-Sunset	24	1500	1000	11.3	24000	220	40	205

Table 5 and Figure 10 present the direct results by simply inputting the given reservoir/fluid properties into the scoring system. The individual score for each property indicates the screening result for a specific EOR technology. The results show that the steam flooding, combustion, and nitrogen immiscible are promising EOR technologies that could be used in the Midway-Sunset oil field because no red circle is present, meaning that all reservoir/fluid properties fall into the applicable ranges based on established conventional screening guidelines. Most gas injection methods are not feasible due to the given reservoir location at shallow formation (depth) and the heaviness of oil (oil gravity, oil viscosity). Low reservoir temperature is the other main reason that cause the gas injection inapplicable. As indicated in Figure 8 and Table 1, most gas techniques were conducted with reservoir temperature greater than 110 °F.

Table 5. Computation of P values and composite screening scores (Red circle-not applicable, yellow circle-applicable, green circle-good candidate).

EOR Type	P_{Φ}	P_k	P_D	P_{OG}	P_{μ}	P_T	P_{S_o}	P_h	Composite Scores
ST	100	100	100	100	100	100	100	100	100
CB	100	100	100	100	100	100	75.0	100	96
HW	0	100	100	100	100	100	100	100	86
CM	100	100	95.4	48.6	0	100	100	100	73.5
CI	100	100	83.6	100	0	0	100	100	72.5
HM	100	49.1	10	0	0	100	100	100	50.9
HI	0	0	0	0	0	0	0	100	0
NM	100	100	0	0	0	100	0	100	40
NI	100	100	83.7	81.2	100	100	81.9	100	93.3
PL	100	100	100	79.9	0	10	100	100	68.8
SF	0	0	0	0	0	0	100	100	8
MB	100	100	100	63.4	0	0	100	100	53

Even though the conventional screening guidelines filter out the steam flooding, combustion, and nitrogen immiscible EOR techniques are more applicable in the Midway-Sunset oil field, it is hard to know which EOR methods may present the best performance. In this case, the weighting factors assist the comprehensive evaluation of each EOR technology based on all reservoir/fluid properties. The composite scores are calculated with the integration of conventional screening guidelines, weighting factors, and P values to provide the discriminative screening results for EOR selection. Higher composite scores represent higher applicability of EOR technology. The bar charts in Figure 10 provide visualized discriminative screening results for the Midway-Sunset oil field, which depicts the composite scores for each technology by three main categories (thermal, gas, and chemical and others). The results in Table 5 and Figure 10 illustrate that the steam flooding technique receives a score of 100, which indicates that steam flooding is the most favorable EOR technology in the Midway-Sunset oil field. The next two recommending technologies are combustion and nitrogen immiscible flooding, which have scores of 96 and 93.3, respectively.

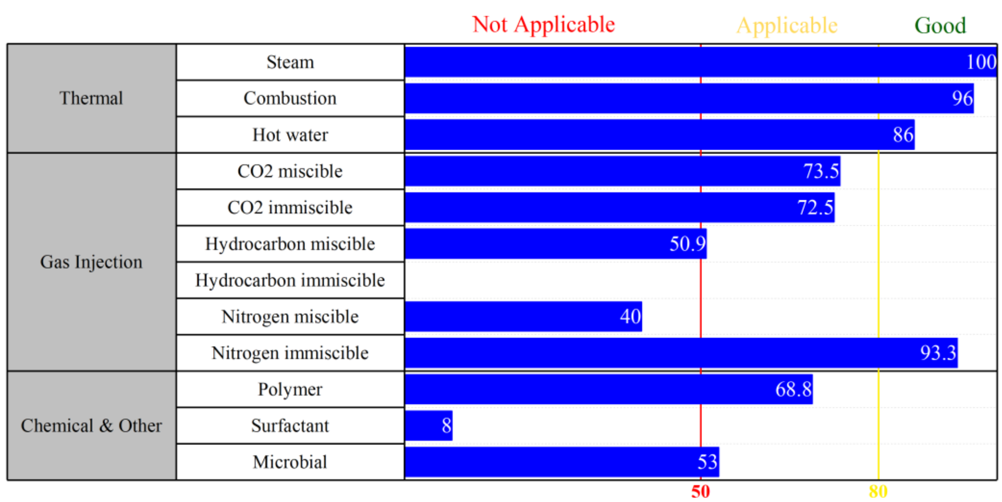


Figure 10. Discriminative EOR screening results for the Midway-Sunset oil field.

6. CONCLUSIONS

- A new dataset with 977 worldwide EOR projects has been established based on the data collection and integration from all OGJ EOR surveys and numerous publications in different languages.

- The updated conventional screening guidelines not only provide a graphical visualization application but also add quantitative guidelines for net thickness for the first time. The guidelines for each reservoir lithology are also distinguished.
- Random forest is a popular statistical method for both regression and classification problems. The results have demonstrated that the random forest algorithm could effectively determine the weighting factors for each EOR technology.
- The case study illustrates that the established novel hybrid scoring system could provide discriminative screening results by integrating the conventional screening guidelines with the random forest algorithm.

NOMENCLATURE

EOR =	Enhanced Oil Recovery
OGJ =	Oil and Gas Journal
AI =	Artificial Intelligence
IQR =	Interquartile Range
OOB =	Out-of-bag
MSE =	Mean Square Error
MDG =	Mean Decrease Gini
MDA =	Mean Decrease Accuracy
ST =	Steam Flooding
CB =	Combustion
HW =	Hot Water

CM =	CO2 Miscible
CI =	CO2 Immiscible
HM =	Hydrocarbon Miscible
HI =	Hydrocarbon Immiscible
NM =	Nitrogen Miscible
NI =	Nitrogen Immiscible
PL =	Polymer
SF =	Surfactant
MB =	Microbial
Φ =	Porosity
K =	Permeability
D =	Depth
OG =	Oil Gravity
μ =	Oil Viscosity
T =	Temperature
S_o =	Start Oil Saturation
H =	Net Thickness

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IV. PATTERN RECOGNITION AND ANALOGUE RESERVOIR FOR STEAM FLOODING FIELD APPLICATIONS

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ABSTRACT

Steam flooding is a complex process that has been considered as an effective enhanced oil recovery (EOR) technique in both heavy oil and light oil reservoirs. Many studies have been conducted on different sets of steam flooding projects using the conventional data analysis methods while the implementation of machine learning algorithms to find the hidden patterns is rarely found. In this study, a hierarchical clustering algorithm coupled with principal component analysis is used to analyze the steam flooding projects worldwide. The goal of this research is to group similar steam flooding projects into the same cluster so that valuable operational design experiences and production performance from the analog case can be referenced for decision-making. Besides, hidden patterns embedded in steam flooding applications can be revealed based on data characteristics of each cluster for different reservoir/fluid conditions. In this research, all reservoir/fluid properties were first normalized to the same scale to ensure the same importance of properties. Principal component analysis is applied to reduce the dimensions from 8D to 2D but still retain almost 90% of the variance. After the data pre-processing process, the hierarchical clustering algorithm is implemented with the optimized design of

five clusters, Euclidean distance, and Ward's linkage method based on the computation of 30 indices, linkage coefficients, and clustering structures. The results of the hierarchical clustering depict that each cluster detects a unique range of each property, and the analog cases present that fields under similar reservoir/fluid conditions could share similar operational design and production performance.

1. INTRODUCTION

Steam flooding is the oldest and most successful commercial enhanced oil recovery (EOR) technique for oil reservoirs having been used since the 1960s, and it is recognized as one of the most efficient oil recovery techniques for depleting the oil in various types of reservoirs since steam flooding results in higher ultimate oil recovery compared to other EOR techniques [1, 2].

The mechanisms of steam flooding are intimately related with the thermal effects on the reservoir rock and fluid properties. Mechanisms that benefit the ultimate oil recovery include (1) increasing rock and fluid temperature from heat convection and conduction, (2) reduction in reservoir fluid (e.g., oil and water) viscosities, (3) increasing reservoir rock and fluid volumes that serving as a depletion drive energy, (4) vaporization of the light fraction of crude oils (often called distillation), (5) reduction of interfacial tensions and change of the relative permeability to oil and water, (6) gravity segregation, (7) solution gas drive, and (8) emulsion drive. These thermal effects are typically not applied uniformly to the whole reservoir, usually resulting in several temperature-fluid flow regions [3]. When steam flooding is applied to reservoirs with different characteristics, The relative importance of these EOR mechanisms change [2]. It is evident that oil viscosity reduction is a dominating factor for heavy oil recovery that significantly increases the oil mobility in the improved reservoir conditions; however, for light oil reservoirs, thermal expansion and distillation are of greater importance than other EOR mechanisms.

Steam flooding has been widely used for the production of heavy crude oil in shallow, thick sandstone formations [4]. Most of steam flooding projects have been implemented in sandstone formations because most of the EOR techniques have been tested at the pilot and commercial scale in this type of lithology [5]. However, steam flooding is also one of the EOR techniques that can be applied to various reservoir and fluid conditions with improved operational techniques. There is an increasing number of steam flooding projects in carbonate reservoirs [6, 7], light oil reservoirs [1, 2, 8-10], thin heavy oil reservoirs [11-13], and offshore developments [14]. Before the implementation of steam flooding at full field scale, a series of detailed preliminary studies, including laboratory tests, reservoir characterization, simulation, and pilot tests, are preformed to reduce the uncertainties and to minimize the risks [15]. However, these evaluation studies are expensive and time-consuming. The reservoir/fluid properties change under different conditions, which brings the challenge of decision-making to operational design and production performance prediction.

In recent years, artificial intelligence (AI) has become a hot topic with more and more AI techniques being implemented in the oil industry for advanced data analysis. Both supervised and unsupervised learning algorithms have been employed in literature to assist the decision-making of EOR techniques. Implementation of AI in the oil industry could be classified as the prediction of the efficiencies/parameters and analog analysis. In machine learning, the predictions are normally treated as regression problems (supervised learning), where objective functions are required in the establishment of models. In contrast, no objective function is needed to feed the model in the analog analysis because the main reason for using analog analysis is to find hidden patterns, which is a classification problem (unsupervised learning). Artificial neural network (ANN), particle swarm optimization (PSO), and support vector machine (SVM) have been widely used in prediction models in the oil industry. For example, Zhang et al. proposed to implementation of SVM and multiple regression (ML) methods to predict the recovery factor and the CO_2 injection efficiency for CO_2 immiscible flooding [16]. Shafiei et al. developed models for the prediction of the steam flooding recovery factor and the cumulative steam-oil ratio by the implementation of ANN-PSO [17].

However, only the clustering algorithm has been applied in the oil industry for analog analysis, which focuses on EOR method selection. The main idea of the clustering algorithm is to detect hidden patterns in the dataset so that a recommendation can be provided after the characterization of the proposed patterns. Siena et al. applied Bayesian clustering and principal component analysis to build a model for EOR selection based on six reservoir/fluid properties, where the EOR selection result is revealed by the analogy projects [15]. Alvarado et al. present a 2D graphical expert map to visualize the percentage of each EOR method included in the clusters for inspection [18], where the EOR method recommendation depends on the cluster the new project merged with.

In this paper, we implement the hierarchical clustering algorithm (HCA) to worldwide steam flooding projects that were collected from existing EOR surveys and publications to find the hidden patterns within steam flooding projects since the steam flooding techniques have been conducted under various conditions. Based on the patterns revealed from the HCA, the analog assessment for new candidate steam flooding projects enables us to find the most similar cases from the existing projects, which assists in the decision-making process of risk reduction by providing recommendations for operational design and production performance.

This paper is organized as follows. The data preparation section describes the establishment of the worldwide steam flooding dataset that we used for pattern recognition and analog reasoning. The methodologies section details the approaches included in this work followed by the results received from each method. The analog reasoning section presents three field case applications to examine the effectiveness of the proposed methodologies for which the operational design and production performance have been well documented. Final remarks are then summarized in the conclusion section.

2. DATA PREPARATION

Figure 1 illustrates a graphical workflow of the steam flooding analog process. Four steps are integrated into this work: (1) data preparation of the worldwide steam flooding dataset; (2) data cleansing and pre-processing; (3) design and implementation of hierarchical clustering for pattern recognition; (4) data analysis for clustering results. The first step relies on extensive review and examination of successful pilot/field steam flooding projects that were published in *Oil and Gas Journal* biannual EOR surveys (from 1980 to present), SPE publications, DOE reports, and AAPG databases. Eight main reservoir/fluid parameters are selected and extracted as these parameters are commonly available and used for EOR project data analysis [19]. These parameters include porosity, average permeability (matrix permeability and fracture permeability), depth, net thickness, oil viscosity, oil gravity, temperature, and oil saturation before steam flooding started.

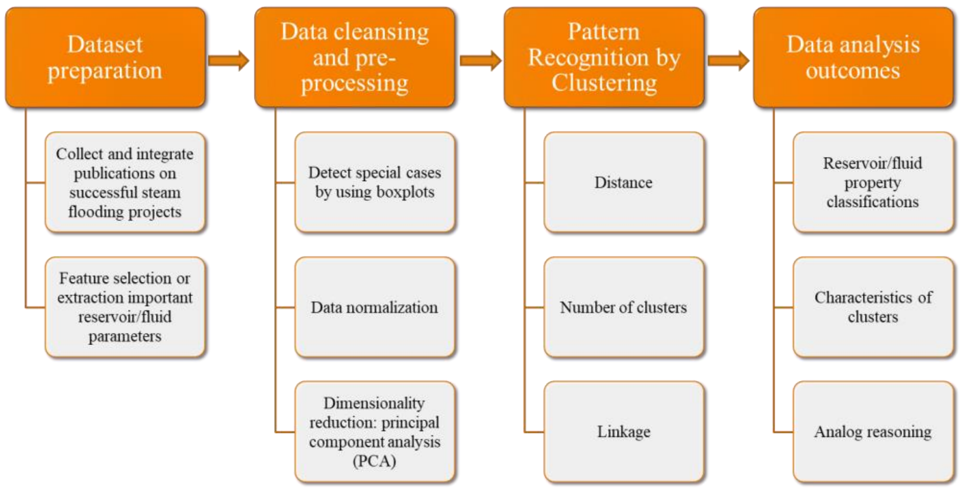

Figure 1. Workflow of steam flooding analog procedures.

The second step ensures the data quality and clustering analysis meet requirements. In this study, all projects with missing values are deleted to avoid biased results if the missing properties could not be found from supplemental publications or reports. A severe duplicate data problem is revealed in the steam flooding dataset as the dataset is formed with the integration of various sources, so identical projects are removed. Senseless or incorrect data are detected from boxplots and scatterplots as explained in previous studies [20-22] where incorrect data are erased or corrected based on literature. After cleansing for data quality enhancement, 384 projects are retained in the dataset. Figure 2 presents the location of oil fields and the number of projects in each country that applied steam flooding technology. The United States, Venezuela, Canada, and Trinidad are the leaders for the conduction of steam flooding, which makes up 93% of the total projects. Only one to three oil fields in other countries has been successfully implemented the steam flooding technology, and the main reason is caused by the reservoir/fluid properties.

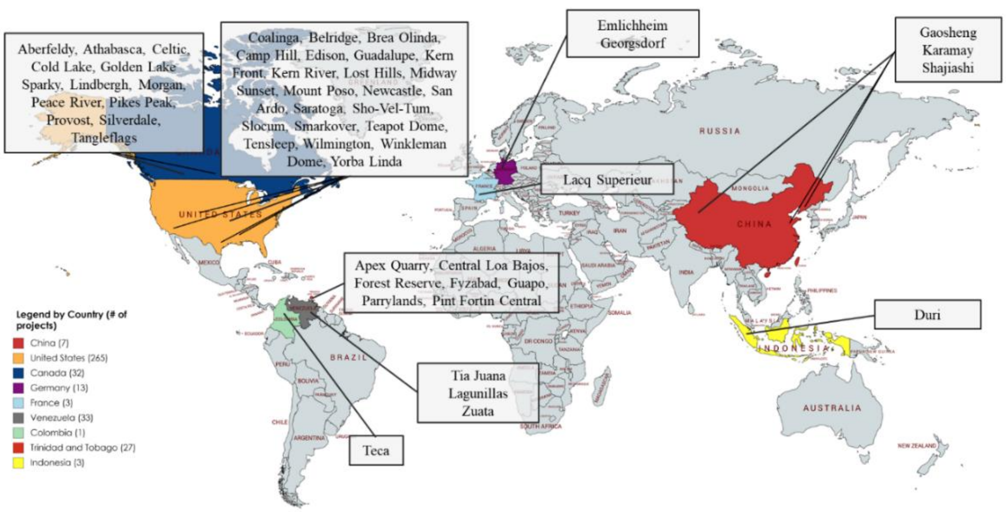

Figure 2. Country/field distribution and number of steam flooding projects onto a world map.

3. METHODOLOGIES

After we finalize the dataset, a series of robust data transformation techniques and data analysis methodologies are applied to assist the pattern recognition process, and is also applied to analog steam flooding projects, which are detailed in the following subsections.

3.1. NORMALIZATION

To ensure the selected or extracted eight reservoir/fluid properties have the same importance, we applied normalization transformations on our dataset to force the properties into the same scale. The type of normalization used is called the min-max normalization or unity-based normalization, which is defined as

$$X' = \frac{X - X_{min}}{X_{max} - X_{min}},$$

where,

X' = transformed value,

X = original value,

X_{min} = minimum value in a reservoir/fluid property,

X_{max}= maximum value in a reservoir/fluid property.

The main advantage of using the min-max normalization method is not only bringing all properties into the range from 0 to 1, but also preserving all relationships among properties [23].

3.2. PRINCIPAL COMPONENT ANALYSIS (PCA)

In the implementation of machine learning techniques, a phenomenon called "the curse of dimensionality" has been widely observed. Machine learning techniques perform well with a low dimensionality of data; however, with the increase of dimensionality of the analyzed data, the algorithm works badly [24]. In statistics, a method called PCA has been commonly used to solve the high-dimensional data problem by reducing the dimensionalities of the dataset while retaining the main variances. The goal of PCA is to find directions/vectors that project the dataset with minimized projection error. The primary mechanism of PCA is a series of orthogonal transformations that are applied to convert a set of observations into linear unrelated variables (principal components (PC)) with each principal component representing a combination of all input variables, which reveals the associations between reservoir/fluid properties. After the data is transformed by PCA, the original dataset with high dimensions can be effectively reduced to two dimensions (2D) or three dimensions (3D) without losing much information. Typically, a good PCA result should retain more than 90% variance from the original dataset.

3.3. HIERARCHICAL CLUSTERING ALGORITHM (HCA)

Clustering is considered one of the most crucial unsupervised learning algorithms that deals with finding a structure in a collection of unlabeled data. The goal of clustering is to determine the intrinsic grouping or hidden pattern in a dataset by computing the pairwise distance. In this study, we apply the agglomerative hierarchical clustering technique to the steam flooding dataset because this method allows for a fully customized design in the algorithm (e.g., number of clusters cut off, distance, linkage) and prevents the "black-box" processing information from being stored as in other algorithms (like artificial neural network (ANN)). The structure and outcomes of HCA can be presented in a dendrogram and scatterplot, which depicts the closeness among all projects, reveals the hidden pattern in the dataset, and enables the analog process by computing the distances. The framework of the implementation of HCA in this work is made up of six main steps:

1. Perform data preprocessing
2. Define distance function
3. Determine the linkage method by the computation of linkage coefficient

4. Find the optimized value of the number of clusters
5. Use HCA with the defined distance function, linkage method, and number of clusters
6. Analyze clustering result

Figure 3 presents the process for the implementation of an agglomerative HCA with a bottom-up structure. The agglomerative HCA starts with each data point (project) being a single cluster, and then merges the data points that are closest (smallest distance). The merging process ends when all objects are forced in one superior cluster. The root node represents the whole dataset, and each leaf of the tree represents a sample. The intermediate nodes describe the clusters at that level, and the height of the dendrogram usually displays the distance between each paired cluster.

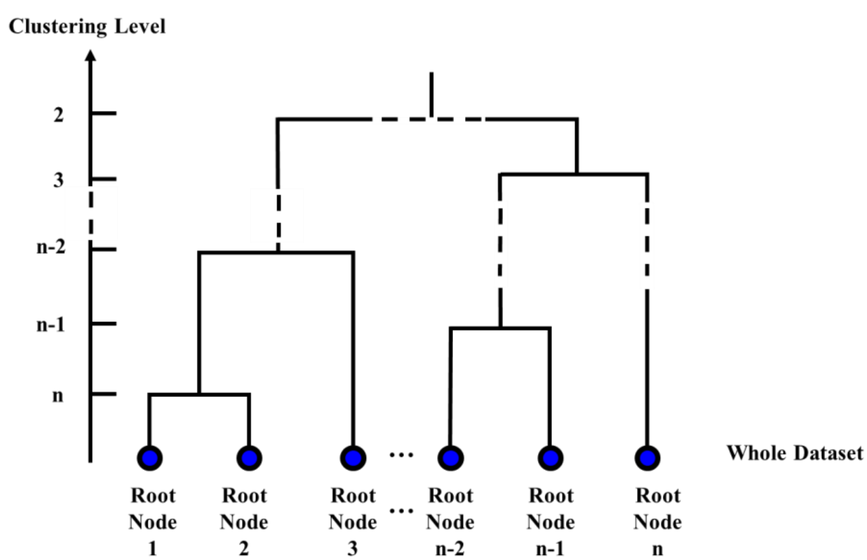

Figure 3. Illustration of the agglomerative hierarchical clustering process.

In mathematics, numerous methods exist to define the distances between objectives. As the HCA is a distance-based algorithm, the definition of distance is critical for the design of HCA because by using different methods, the computation results will be different, which determines how clusters/projects are merged together. In this research, the Euclidean distance is used to determine the closeness between projects and clusters because this method has been most commonly utilized for numerical features. Average, single, complete, and Ward linkage methods have been considered in the design of HCA to define how clusters are merged to a higher level. The number of clusters is another required parameter in the implementation of HCA. Thirty indices are employed to find the optimal number of clusters. This was proposed by M. Charrad et al. because they present a comprehensive evaluation and combination of the majority of existing methodologies in literature, including Silhouette, elbow, gas statistic, etc. [25].

3.4. RESERVOIR/FLUID PROPERTY CLASSIFICATION

The classification of reservoir/fluid properties is essential as they are closely associated with the driving mechanisms that affect the performance of steam flooding. Based on the oil viscosity at reservoir condition, oil has been commonly classified as a viscous oil ($\mu < 100$ cp), heavy oil (100 cp $\leq \mu \leq$ 10000 cp), and extra heavy oil ($\mu > 10000$ cp) [17, 26, 27]. A similar oil classification based on oil gravity has also been well-accepted by the oil industry [26, 27]. The reservoir depth is also an important parameter for steam flooding applications, which are generally classified as either a shallow reservoir or a deep reservoir. In the oil field, the criterion for the classification of depth is ambiguous. For example, most steam flooding projects were conducted in shallow reservoirs because deep reservoirs have more heat loss and have higher requirements for the insulating tubing leading to higher costs. However, no specific value was given in the literature to define the specific depth of a shallow or deep reservoir. In this study, we classify the reservoir depth for steam flooding based on the collection of numerous publications that mentioned “shallow reservoir” or “deep reservoir”. For the rest of the reservoir/fluid properties (porosity, permeability, start oil saturation, temperature, and net thickness), we employ a statistical method by using boxplots to classify the properties as shown in Figure 4. The goal of applying a boxplot is to display the range and distribution of each property for the existing projects, which not only facilitates the classification of properties, but also presents the feasibility of steam flooding applications. Minimum, Q1 (25^{th} percentile), median (50^{th} percentile), mean (average), Q3 (75^{th} percentile), and maximum values are illustrated in the boxplot. A property is classified in a low category when the value is smaller than Q1 (25^{th} percentile), which means that more than 75% of the existing steam flooding projects were conducted with a higher value. Similarly, the high category is defined as when the property value is greater than Q3 (75^{th} percentile), which indicates that only less than 25% of the existing projects are greater than the given property value. The range from Q1 to Q3 is categorized as a medium category since this range represents most projects.

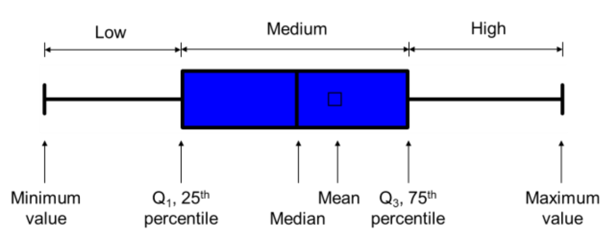

Figure 4. Illustration of reservoir/fluid ranges and classification method by a boxplot.

4. RESULTS

4.1. DIMENSIONALITY REDUCTION

Since eight reservoir/fluid parameters are selected for pattern recognition (clustering), PCA transforms the eight-dimensional data into eight principal components (PCs). The column chart in Figure 5 illustrates the variance expressed by each PC based on the input data, and the red dotted line denotes the cumulative variance explained by the first several PCs. The results depict that the first two PCs retained about 90% of the variance, which proves that the PCA could be effectively used in the steam flooding dataset for dimensionality reduction. Therefore, a two-dimensional PCA results in a high variance explained from the original data are used to feed into the clustering algorithm for pattern recognition. A visualized comparison of the clustering results with and without PCA pre-processing process will be presented in the discussion section.

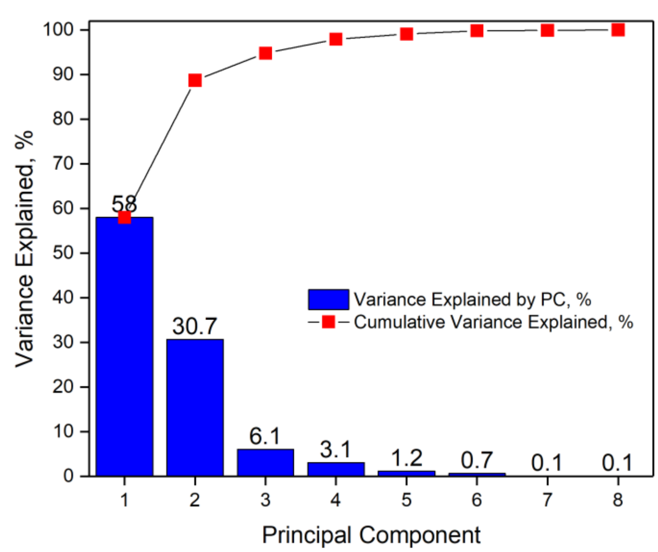

Figure 5. Variance explained by each principal component (PC).

4.2. HIERARCHICAL CLUSTERING

Agglomerative coefficient has been commonly used for the evaluation of different linkage method based on clustering structure. Table 1 presents that the Ward linkage method, which is based on the optimization of error sum of squares (minimum variance) is selected as a criterion to choose the paired clusters in each step.

Table 1. Comparison of clustering linkage coefficients.

Linkage	**Average**	**Single**	**Complete**	**Ward**
Coefficient	0.976	0.943	0.984	0.995

Figure 6 presents the frequency distributions of 24 out of 30 indices that recommend having less than 10 clusters. The other six indices elucidate that the dataset should be split into more than 10 clusters. The horizontal axis in Figure 6 shows the number of clusters, while the vertical axis illustrates the total number of indices/methods that recommend each value of the number of clusters. For example, five indices suggest splitting the original data into two clusters/groups, while three indices agree to divide the data into three clusters based on (1) the maximum/minimum value of the index, (2) the maximum/minimum difference between hierarchy levels, (3) the maximum/minimum second differences between hierarchy levels, (4) critical values such as in the gap statistic, and (5) the significant local change in the measurement [28]. The results recommend that five clusters with seven supporting indices are the optimal value in the steam flooding dataset.

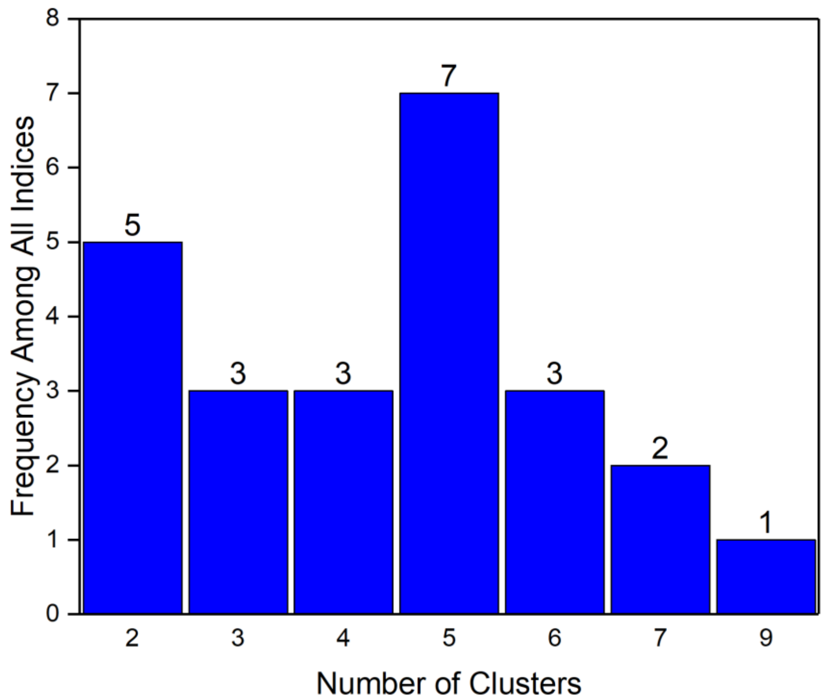

Figure 6. Frequency distribution among 30 indices to determine the optimized number of clusters.

Figure 7 illustrates the visualization of PC1 and PC2 with five clusters by retaining about 90% of the variance from the original steam flooding dataset. The number of steam flooding projects in each cluster is shown in Table 2, where cluster 1 (C1) is the biggest group containing 126 projects, followed by C2 (105 projects), C4 (82 projects), C3 (47 projects), and C5 (24 projects). The results in Figure 7 elucidates the clear boundaries between clusters, which means that five clusters are distinguished from each other by including significantly different reservoir/fluid properties. In contrast, Figure 8 shows a messy distribution with the same HCA design (distances, linkages, number of clusters) where PCA did not pre-process the original dataset. The main reason for the unclear boundaries between clusters is the high dimensionality of data, where the dimensions of the original data were reduced from 8D to 2D. Therefore, data transformation with PCA is essential for steam flooding projects.

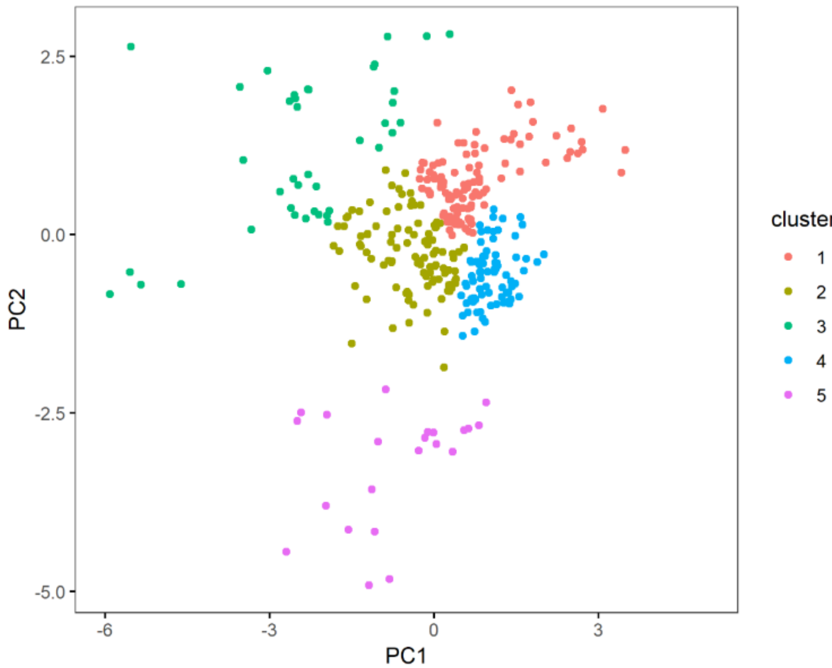

Figure 7. Hierarchical clustering visualization with PCA in data pre-processing.

Table 2. The number of steam flooding projects in each cluster.

Cluster Number	**Number of Projects**
C1	126
C2	105
C3	47
C4	82
C5	24

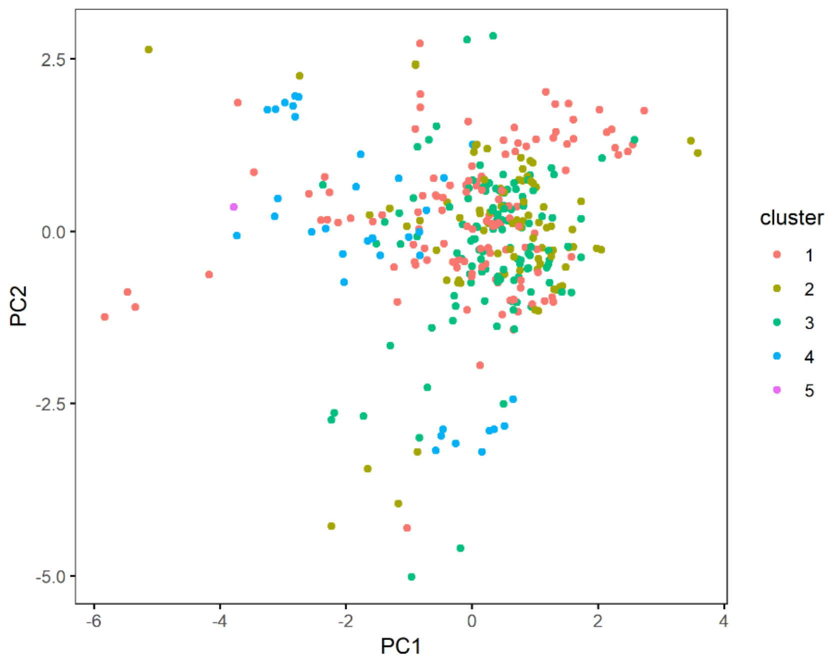

Figure 8. Hierarchical clustering visualization without PCA in data pre-processing.

4.3. CHARACTERIZATION OF CLUSTERS

As the purpose of HCA is to recognize the hidden patterns in steam flooding datasets that cannot be seen from direct observations, the characterization of clusters is critical for studying reasons why the clusters are distinguished from each other. Blue boxplots in Figure 9 demonstrate comparisons between five clusters for each reservoir/fluid property.

Figure 9a indicates that C3 and C5 include the special reservoirs (2 projects) that have high porosity (up to 65%), which is caused by the lithologies in the reservoirs. Most of the steam flooding projects have been implemented in sandstone formations because most of the EOR techniques have been tested at the pilot and commercial scale in this type of lithology [29]. The normal porosity for the sandstone reservoirs is less than 35%. The projects with extremely high porosities are found in the Midway-Sunset field and South Belridge field and in diatomite formations, where the diatomite reservoirs generally have low matrix permeability (less than 1 mD) with a high porosity (40% to 70%) [30, 31]. Figure 9b illustrates the average permeability ranges based on the matrix and fracture permeabilities. Although C1 is the biggest cluster, most of the projects in C1 fall into a well-concentrated range of permeability from 2000 mD to 3000 mD, which reveals that C1 had been effectively grouped with projects with similar permeability. Also, permeability boxplots for C4 and C5 show that the permeability of these two clusters is condensed from 2000 mD to 3500 mD and from 2000 mD to 3000 mD, respectively.

Figure 9c displays that most steam flooding projects were applied in reservoirs with a depth less than 2500 ft, with the deepest project being conducted in a reservoir 5740 ft deep, which is shallower than other EOR methods. A detailed discussion will be presented in the following subsection for why steam flooding is normally presented in shallow reservoirs. The ranges of formation net thickness are presented in Figure 9d. Most of the steam flooding projects were applied with a thickness less than 200 ft. However, C4 detected most of the projects that the reservoir is thicker than 200 ft. Normally, steam flooding could not be applied in thick reservoirs so as to avoid the steam overriding problem, which reduces the sweep efficiency.

Figures 9e and 9f display the ranges for reservoir temperature and the oil saturation, respectively, before the application of steam flooding. C1 contains most of the projects with reservoir temperatures less than 90 °F and an average oil saturation of 65%, while C5 containes a broader range of temperatures (>90 °F) with a small range of oil saturation. The boxplots demonstrate that most projects are conducted in lower reservoir temperatures compared to other EOR techniques [22, 34, 35]. The shallower burial depth is one of the reasons for the lower temperature, where the temperature is positively related to the depth with an average geothermal gradient of 2 °F/100 ft [36]. Another reason is that lower reservoir temperatures may cause a greater temperature difference when the same amount of steam is injected with the same temperature, which results in a more significant reduction of oil viscosity, especially in heavy oil reservoirs. Also, boxplots in C2, C3, and C4 elucidate similar ranges for both temperature and oil saturation, which means that other reservoir/fluid properties may have significant differences between C2, C3, and C4 (e.g., porosity, permeability).

Figures 9g and 9h summarize the ranges for both oil gravity and oil viscosity. In Figure 9g, only cluster 3 detected the light oil projects from the steam flooding dataset, which includes the projects with oil gravity greater than 25 °API. The projects in other clusters illustrate a condensed range from 12 to 14 °API, which means most of the projects in C1, C2, C4, and C5 are heavy oil reservoirs. Figure 9h shows that C1 captured the projects with extremely heavy oil (μ > 100000 cp), and that C4 grouped the projects with high oil viscosity ranging from 4000 to 10000 cp, which is higher than the ranges in C2, C3, and C5.

4.4. CLASSIFICATION OF RESERVOIR/FLUID PROPERTIES

Table 3 shows the classification results of all reservoir/fluid properties for steam flooding. As described in the previous section, the classification results for porosity, permeability, net thickness, reservoir temperature, and start oil saturation are based on the yellow boxplots illustrated in Figure 9, where a property value less than Q1 is considered a low value, a value greater than Q3 is in the high category, and a value between Q1 and Q3 is in the medium category. The domain knowledge is applied for the classification of oil gravity and oil viscosity based on previous studies from experts [17, 26, 27]. For the classification of depth, we find that the 3000 ft burial depth is the critical value for steam flooding applications. Many studies have showed that heat loss is the main reason for why steam flooding technique is applied mostly in shallow reservoirs [32, 33]; however, it is essential to point out that the temperature of injected steam is more important. Based on the pressure-enthalpy phase diagram of water, the lower reservoir pressure requires a lower steam temperature to provide the same amount of energy (enthalpy). For a naturally pressured reservoir with a burial depth of 3000 ft, the reservoir pressure is about 1350 psi, which requires the steam temperature to reach about 600 °F. Uniquely designed downhole equipment is needed to meet the requirements of high temperature. Therefore, 3000 ft is a threshold depth for steam flooding projects, where reservoirs with a depth greater than 3000 ft are considered deep reservoirs. Otherwise, they are shallow reservoirs.

Table 4 contains the rules for all clusters based on the characteristics shown in Figure 9, while the classification results are displayed in Table 3. Each category in the table represents most of the projects (> 50%) in the specified cluster share the same property category. For example, more than 50% of the projects in C1 have medium porosity, which ranges from 30% to 50%. Similarly, C5 detected the projects with high reservoir temperature. Therefore, by compiling the rules of clusters, the hidden patterns in the steam flooding dataset are revealed. C4 and C5 are the two unique clusters that detected the projects with concentrated ranges for all reservoir/fluid properties. Also, C1 found six concentrated ranges, and the rules imply that the reservoir temperature may be the primary reason to group the projects in C1. Only four concentrated reservoir/fluid properties are found in C2 and C3, which indicates the existence of special cases.

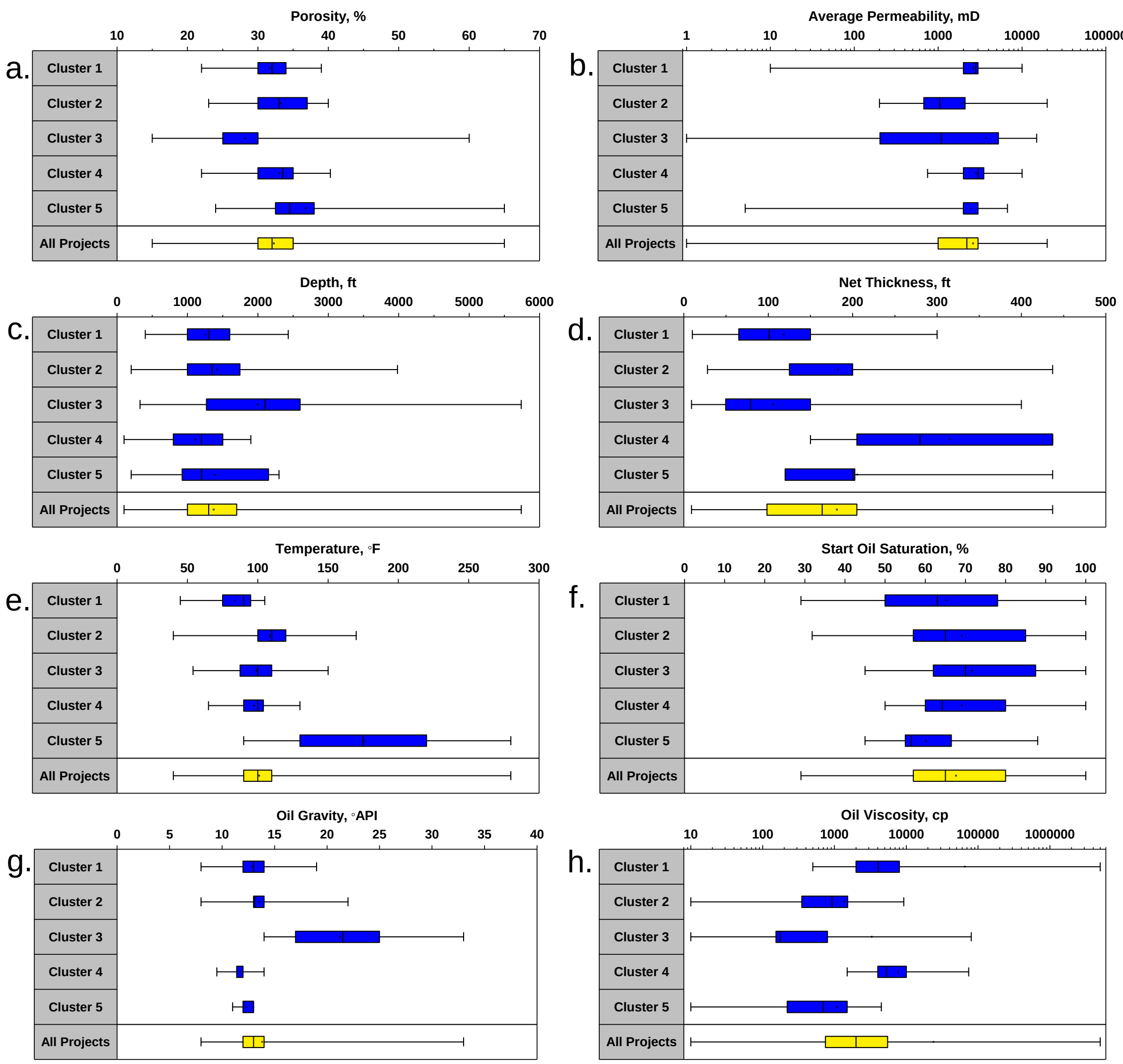

Figure 9. Characteristics of clusters for each reservoir/fluid property.

Table 3. Classification results of reservoir/fluid properties based on worldwide steam flooding projects and domain knowledge.

Property	Category	Value Range	References
Porosity, %	Low	<30	Based on worldwide steam data
	Medium	[30,35]	
	High	>35	
Permeability, mD	Low	<1000	Based on worldwide steam data
	Medium	[1000,3000]	
	High	>3000	
Depth, ft	Shallow	≤3000	[37-39]
	Deep	>3000	
Net Thickness, ft	Thin	<98.4	Based on worldwide steam data
	Medium	[98.4,205]	
	Thick	>205	
Temperature, °F	Low	<90	Based on worldwide steam data
	Medium	[90,110]	
	High	>110	
Oil Gravity, °API	Light Oil	>25	[26, 27]
	Medium Oil	[20,25]	
	Heavy Oil	[10,20)	
	Extra Heavy Oil	<10	
Oil Viscosity, cp	Viscous Oil	<100	[17, 26, 27]
	Heavy Oil	[100,10000]	
	Extra Heavy Oil	>10000	
Start Oil Saturation, %	Low	<57	Based on worldwide steam data
	Medium	57-80	
	High	>80	

Table 4. Rules of clusters based on the classification of reservoir/fluid properties.

	Porosity	Permeability	Depth	Net Thickness	Temperature	Start Oil Saturation	Oil Gravity	Oil Viscosity	Number of Concentrate Feature
C1	Medium	Medium	Shallow	-	Low	-	Heavy	Heavy	6
C2	-	-	Shallow	Medium	-	-	Heavy	Heavy	4
C3	Low	-	Shallow	-	-	-	Light	Heavy	4
C4	Medium	Medium	Shallow	Thick	Medium	Medium	Heavy	Heavy	8
C5	High	Medium	Shallow	Medium	High	Medium	Heavy	Heavy	8

Note:

- Every categorized reservoir/fluid property for each cluster represents more than 50% of the projects in that cluster are within the range as specified in Table 3
- "–" stands for no specific concentrate range for that reservoir/fluid property

5. ANALOG

The goal of analog is to examine the effectiveness of the established PCA/HCA method and find the most similar project to the new candidate steam flooding project. The analog process is carried out by the computation of Euclidean distances that were embedded in the hierarchical clustering process between new candidate steam flooding project(s) and the existing steam flooding dataset. A project with minimal distance to the candidate field is considered as being the closest case to the new project. Figure 10 illustrates the visualized analog results of three new candidate projects. As shown in Figure 10, three cases fall into different patterns/clusters that were revealed by the PCA and HCA. The first case is allocated to C2, and case 2 is merged with C1, while case 3 is integrated with C3. Each case represents a scenario of the analog result, which includes (1) analog to a foreign oil field, (2) analog to the same field, and (3) analog to an adjacent field. Table 5 depicts the comparison of reservoir/fluid properties between the testing cases and the analog cases.

The analog of case 1 from the established PCA and HCA methods reveals that the reservoir/fluid properties of the Forest Reserve field from Trinidad are the most similar project to the Shanjiashi field from China. Both fields applied the cyclic steam flooding technology with an averaged soaking period of 3 to 4 days in each cycle. Although the well schemas are so different in the two fields, where 280 production wells were drilled in the Shanjiashi field compared to 70 production wells in the Forest Reserve field, the averaged enhanced oil production after the implementation of steam flooding for each well is similar, which are 32.6 (Shanjiashi field) and 30.9 bbl/d/well (Forest Reserve field), respectively

[42, 45-47]. Besides, the conduction of steam flooding was the first attempt to enhance the oil recovery for both fields. Thinner insulating tubing than that in Shanjiashi field was installed in the Forest Reserve field with a more insulated cement sheath to reduce the drilling cost and to ensure the steam quality [39]. The analog results from case 1 imply that the design and performance are similar when the reservoir/fluid properties are close. Therefore, the analog assessment could assist in predicting the effectiveness of steam flooding for new candidate steam flooding projects based on existing experiences from a similar field, especially when the field data is limited.

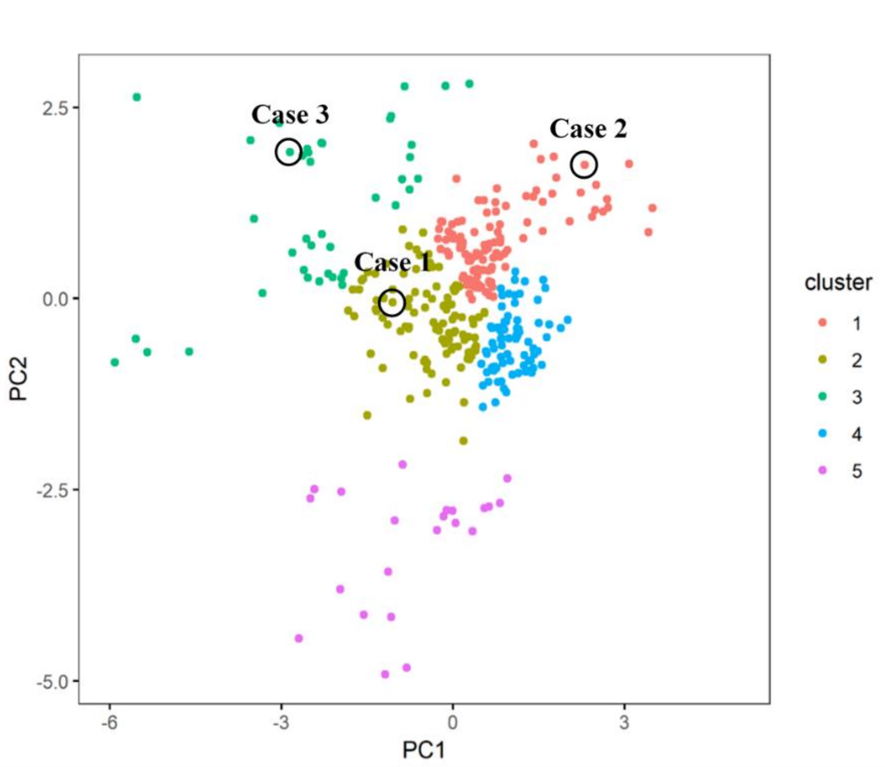

Figure 10. Analog visualization with three new steam flooding testing projects in a scatterplot.

Table 5. Reservoir/fluid properties of testing cases and analog results.

Case #	**Case 1**	**Analog 1**	**Case 2**	**Analog 2**	**Case 3**	**Analog 3**
Field Name	Shanjiashi	Forest Reserve	Wolf Lake	Wolf Lake	Ruehlertwist	Emlichheim
Country	China	Trinidad and Tobago	Canada	Canada	Germany	Germany
Cluster	Cluster 2		Cluster 1		Cluster 3	
Net Thickness	82	95	75	75	49	79
Porosity	30	31	31	33	28	30
Permeability	5000	205	3000	3000	5000	6000
Depth	3983	3000	1398	1400	2650	2400
Oil Gravity	19	19	10	10	25	24.5
Oil Viscosity	9200	32	10000	45000	175	175
Temperature	131	120	60	60	100	95
Start Oil Saturation	60	57	65	78	51	62
References	[37]	[39]	[40]	[40]	[41-43]	[42-44]

The second case is the Wolf Lake field from Canada, which implemented steam flooding in 1985 and consisted of 187 production wells. The analog result presents that the most similar existing project is located in the same field, which applied steam flooding in 1982 with one production well. In fact, case 2 is the expansion of the analog project, so the reservoir/fluid properties are almost the same except the viscosity [40]. Since oil viscosity reduction is the main mechanism for steam flooding, especially in bitumen reservoirs, the oil viscosity decreased significantly after steam injection from the pilot test, which caused viscosity reduction compared with the analog case. The analog result proves that the proposed PCA/HCA methodology is still capable of detecting the similar cases from the same field because all the reservoir/fluid properties were normalized before the implementation of HCA.

Case 3 represents a scenario which finds an adjacent oil field. Oil fields with close geographical locations normally share similar reservoir/fluid properties because the depositional environments are the same, which results in smaller distances between the analog project and the candidate case. The third case is selected from the Ruehlertwist field from Germany in Lower Saxony, and the analog results show that the nearby Emlichheim field is the most similar and is only 13.4 miles away from the Ruehlertwist field.

6. CONCLUSIONS

In this paper, a combination of principal component analysis and hierarchical clustering algorithms is applied to identify the hidden patterns in worldwide steam flooding projects and to examine the effectiveness of the proposed method via the analog reasoning process. Based on the computation of 30 indices and the clustering structure, we detected that the optimum number of clusters is five, which indicates five stabilized cluster patterns among all steam flooding projects. We further characterized the clusters and to study the patterns revealed by the HCA. We found the reservoir/fluid properties C1, C4, and C5 have small concentrated ranges, while the projects in C2 and C3 contains special cases for porosity, permeability, depth, and oil gravity. The comparison with/without PCA before the implementation of HCA illustrates that the HCA associated with PCA transformation provides clear clustering boundaries and reduces the dimensionalities from 8D to 2D while still retaining about 90% of the variance. In addition, the reservoir/fluid properties are classified based on domain knowledge from literature and the values of Q1 and Q3 as revealed by the boxplots. The threshold depth for the implementation of steam flooding is 3000 ft due to the limitation of infrastructure. Most of the steam flooding projects were applied with the burial depth less than 3000 ft and are classified as the shallow reservoir.

A blind test of the proposed method was performed by considering three field cases. The analog results demonstrate that the established method is capable of capturing the most similar existing steam flooding projects that share similar reservoir/fluid properties. The operational designs and performance of steam flooding are close even though the candidate case and the analog field are from different countries. Therefore, the analogy based on the PCA/HCA not only provide assistance for operational design decision-making in new steam flooding candidate fields, but also provides a prediction for the future performance based on existing projects.

NOMENCLATURE

EOR =	Enhanced Oil Recovery
PCA =	Principal Component Analysis
PSO =	Particle Swarm Optimization
SVM =	Support Vector Machine
PC(s) =	Principal Component(s)
PC1 =	First Principal Component
PC2 =	Second Principal Component
HCA =	Hierarchical Clustering Algorithm

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SECTION

2. CONCLUSIONS

EOR selection is a complex process that involves reservoir characterization, technology feasibility, and commercial evaluations. In this dissertation, the conventional, advanced, and hybrid methods have been applied to facilitate the process of EOR screening. Meanwhile, reservoir analog technology have also been design and evaluated to find the most similar case in steam flooding dataset. The overall conclusions of this dissertation could be summarized as follows:

1) This research work presents the most uniformed and comprehensive dataset for worldwide EOR projects by collecting the data from scattered publications and sources. Duplicate, missing, and inconsistent data problems have been detected and resolved for the enhancement of data quality.
2) Critical parameters (e.g. MMP and net thickness) are augmented in the datasets for the construction of screening guidelines, especially for CO_2 miscible and immiscible flooding.
3) Statistical methods including boxplots, histograms and scatterplots were used to present the ranges, distributions, and cumulative frequencies of each reservoir/fluid properties.
4) The conventional screening guidelines for 12 EOR technologies have been updated. For example, the recommended implementation of CO_2 miscible flooding of reservoir and fluid properties can be summarized as follows: reservoir pressure >

1020 psi, porosity > 3%, permeability > 0.1 mD, gravity >25 °API, viscosity < 4 cp, temperature < 260 °F, oil saturation > 15% PV, depth > 1150 ft, and net pay thickness between 15 and 824 ft.

5) The distributions of important reservoir/fluid properties are presented in assembled boxplots to provide a better understanding of existing successful EOR projects, which lay the foundation for further analysis.

6) For the implementation of CO_2 immiscible flooding, water alternating gas (WAG) and huff-n-puff are the two most common injection strategies, and the average cost for CO_2 immiscible flooding is around US$19/stb to US$28/stb.

7) A hybrid EOR screening system has developed and tested for EOR selection by combining the conventional screening guidelines and the random forest algorithm which retains the advantages of both conventional and advanced EOR screening methods while avoiding the disadvantages.

8) Random forest algorithm is applied for both regression and classification problems, where the EOR type and incremental oil recovery are used as objective functions. The expert domain knowledge and the results from the case study have demonstrated that the random forest algorithm could effectively determine the weighting factors for each EOR technique.

9) The fuzzy membership was introduced in the definition of reservoir/fluid property scores for the first time in the literature, which avoids the crisp values and makes the scoring system realistic.

10) The blind test of the proposed hybrid screening methodology was performed on the Midway-Sunset oil field. The case study results illustrate that the established novel

hybrid scoring system could provide discriminative EOR screening results for the selected field.

11) Five hidden patterns were revealed and characterized by the implementation of hierarchical clustering and principal component analysis in the steam flooding dataset.

12) The clustering results illustrate that the reservoir/fluid properties C1, C4, and C5 have small concentrated ranges, while the projects in C2 and C3 contains special cases for porosity, permeability, depth, and oil gravity.

13) The comparison with/without PCA before the implementation of HCA illustrates that the HCA associated with PCA transformation provides clear clustering boundaries and reduces the dimensionalities from 8D to 2D while still retaining about 90% of the variance.

14) The classification of reservoir/fluid properties was proposed in this research study for the first time based on domain knowledge from literature and statistical method. The threshold depth for the implementation of steam flooding is 3000 ft due to the limitation of infrastructure. Most of the steam flooding projects were applied with the burial depth less than 3000 ft and are classified as the shallow reservoir.

15) A blind test of the proposed method was performed by considering three field cases. The reservoir analog results demonstrate that the established method is capable of capturing the most similar existing steam flooding projects that share similar reservoir/fluid properties. The operational designs and performance of steam flooding are close even though the candidate case and the analog field are from different countries.

3. RECOMMENDATIONS

This research work applies both conventional and advanced data analysis methodologies to study the characteristics, hidden patterns, applicabilities (EOR screening), and analogous of EOR technologies. However, further studies are need to better facilitate the decision-making process, which are summarized as follows:

1) Detailed examination/evaluation (e.g. external indices) of the hierarchical clustering is needed to the implementation in the worldwide EOR dataset.
2) For the determination of P value in the hybrid scoring system, other fuzzification membership functions could be tested and verified (e.g. sigmoid, Gaussian function).
3) The reservoir analog technology could be applied other EOR technologies with different similarity matrices based on the reservoir/fluid characteristics (e.g. CO_2 miscible flooding, polymer flooding, hydrocarbon miscible flooding, etc).
4) Further comparison of different EOR selections is needed to find the best method.
5) More domain knowledge need to be used for the implementation of machine learning techniques.

VITA

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