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A New CO_2-EOR Methods Screening Model Based on Interdependency Parameters

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Abstract: The successful implementation of carbon dioxide-enhanced oil recovery (CO_2-EOR) is crucial in increasing oil production and reducing carbon emissions. For this reason, screening criteria are needed for the initial characterization of a suitable CO_2-EOR reservoir. The existing screening model treats the screening parameters independently. Therefore, each parameter has its criteria limit and does not relate to the others. However, in reality, several screening parameters are interdependent, so we need a method that treats the interdependent parameters simultaneously. This research develops a new simultaneous screening model using the interdependency of the parameters. Quantitative and actual data were collected from CO_2-EOR field documentation worldwide with a comprehensive analysis. A statistical approach with a correlation analysis method was used to determine the interconnected screening parameters. The results were synchronized with the expert domain to match actual physical conditions. The limit of simultaneous screening criteria was acquired by multivariate quality control (MQC) based on the principal component analysis (PCA) method. The proposed screening model was compared with 13 actual projects, and demonstrated improvements to previous models. The results match actual operations and follow the expert domain rules. If the miscible CO_2-EOR is met, then the immiscible should also be appropriate but not vice versa. Nevertheless, four different immiscible projects are predicted to be slightly optimistic as miscible or immiscible.

Keywords: screening; CO_2-EOR; principal component analysis; multivariate quality control

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1. Introduction

One of the enhanced oil recovery (EOR) methods is carbon dioxide injection, which directly utilizes CO_2 from unwanted industrial operations because of its harmful impact on climate change. Currently, this method has attracted the attention of petroleum industries because it provides dual benefits. Firstly, it prevents the release of excess CO_2 in the atmosphere by re-injecting it into reservoirs. Secondly, it increases the oil recovery to meet energy needs [1]. Correspondingly, CO_2-EOR has been considered as one of the primary EOR methods in the US [2]. The CO_2-EOR projects in the US have increased in the last than 20 years, despite oil prices fluctuation. Therefore, they have good prospects for continuous implementation [3].

In the oil recovery process, CO_2 is injected into the reservoir, and it creates an interaction with the rock and the oil. This interaction alters the oil and rock properties with its mechanism including oil swelling, reduction in oil viscosity and CO_2-oil interfacial tension, extraction of light/intermediate oil components, and wettability changes [4]. The high solubility of CO_2 in the oil causes swelling and consequently reduces the oil viscosity and density [5]. Oil swelling is the main recovery mechanism for miscible and immiscible CO_2-EOR [6]. Miscible CO_2-EOR results in a greater ability to produce incremental oil from the reservoir than immiscible CO_2-EOR. However, the miscible CO_2 can only be achieved at higher reservoir pressure than minimum miscible pressure (MMP) [7]. The value of MMP depends on many factors such as pressure, reservoir temperature, and oil and gas-injected compositions [8].

A CO_2-EOR project consists of stages, starting with the screening phase, laboratory analysis, simulation, pilot test, and finally, full-scale field injection [9]. Screening is the first stage in identifying the suitability of the reservoir for CO_2-EOR. The successful implementation of the project is highly dependent on the screening process and its results, making the stage is very crucial. Previous studies have widely introduced the CO_2-EOR screening process as part of the EOR screening. Existing screening criteria for miscible and immiscible CO_2-EOR are given in Tables 1 and 2, respectively. For instance, Taber et al. [10] popularized the famous EOR screening by summarizing its criteria in the form of simple descriptive statistics using minimum, maximum, and mean values. Their data was collected from 1974 to 1996. The essential aspects of screening parameters depend on reservoir rock and fluid properties: gravity, oil saturation, viscosity, formation type, net thickness, average permeability, depth, and temperature. Later, Al Adasani and Bai [11] updated this screening guideline with data collected from successful EOR projects carried out from 1998 to 2010. They also added porosity as a screening parameter. Zhang et al. [5] improved their findings and completed a screening guideline for miscible CO_2 injection by including parameters with a significant effect, namely MMP and net thickness. The projects carried out from 2010 onwards are provided as the database for this screening.

Table 1. Existing screening criteria for miscible CO_2-EOR.

	Taber et al. [10]	Al Adasani and Bai [11]	Zhang et al. [5]				
			Minimum	Mean	Median	Maximum	Standard Deviation
Porosity, %	-	3–37	3	16.3	14.55	37	7.3
Permeability, mD	NC	1.5–4500	0.1	290.1	30	9244	1070.6
Depth, ft	>2500	1500–13,365	1150	6404.2	5600	15,600	2700.2
Oil Gravity, °API	>22	22–45	25 (special case: 11–22)	36.9	38	48	5.5
Oil Viscosity, cp	<10	0–35	0.15	3.8	1.2	4 (special case: 5–188)	15.6
Temperature, °F	NC	82–257	70	141	122.5	260	50.2
Oil Saturation, %	>20	15–89	15	52.2	50.4	98	16.7
Net Thickness, ft	Wide Range	Wide Range	15	105.6	71	824	124.5
MMP, psi	-	-	1020	2231.5	2075	3600 (special case: 4000–4200)	790.3
Compositions	High percent of C2 to C12	-	-	-	-	-	-
Formation Type	Sandstone or carbonate	Sandstone or carbonate	-	-	-	-	-

Table 2. Existing screening criteria for immiscible CO_2-EOR.

	Taber et al. [10]	Al Adasani and Bai [11]	Zhang et al. [12]			
			Minimum	Mean	Median	Maximum
Porosity, %	-	17–32	11.5	22.6	23	33
Permeability, mD	NC	30–1000	1.4	418.2	255	2750
Depth, ft	>1800	1150–8500	1400	4258.3	4300	8500
Oil Gravity, °API	>12	11–35	10.8	20.5	17	39
Oil Viscosity, cp	<600	0.6–592	0.2	140.3	17.4	936
Temperature, °F	NC	82–198	82	142.1	131	235.4
Oil Saturation, %	>35	42–78	30	56	59.5	86
Net Thickness, ft	NC	-	5.215	79.3	41	300
MMP, psi	-	-	-	-	-	-
Formation Type	NC	Sandstone or carbonate	Sandstone or carbonate			

The screening model in the previously mentioned research analyzed the parameters independently. Therefore, they did not affect one another. As a result, each parameter has its respective criteria limit in this individual screening model. For example, porosity has its screening criteria limit, as do permeability and other parameters. However, in reality, these parameters are interdependent because they influence and relate to one another. Therefore, a screening model capable of considering these parameters simultaneously is needed. A new screening model utilizing the interdependency among the parameters called the simultaneous screening model was developed in this research.

Essentially, the present research aims to develop a combined screening model that is between simultaneous and individual models for the CO_2-EOR methods. Two approaches were simultaneously applied to achieve this purpose, namely statistics and expert domain. The statistical approach is used to model physical phenomena. The expert domain approach is used to correct the results of statistical correlations adjusted to the real physical phenomena. The updated data on the miscible and immiscible CO_2-EOR was the basis for supporting this goal. Nine significant screening parameters were used, including porosity, permeability, oil viscosity, oil gravity, depth, temperature, oil saturation, net thickness, and MMP.

2. Materials and Methods

Based on the collected data set, this research developed a screening model for miscible and immiscible CO_2-EOR. The database was collected and documented according to references of actual fields worldwide to develop an improved and more realistic screening model. Data reference sources were taken from the Worldwide EOR Surveys reported by Oil and Gas Journal (OGJ) from 1986 to 2014, SPE publications, Elsevier publications, technical field reports, and AAPG bulletin. The workflow of the screening model is shown in Figure 1, which is divided into three stages.

Stage 1: Data preparation. The quality of the data greatly affects the final result. Therefore, this stage plays an essential role in controlling data quality. This stage was carried out by collecting, sorting, and filling in missing data. For the sorting phase, only the successful and profitable CO_2-EOR project data were chosen for miscible CO_2-EOR. However, this was not the case for immiscible CO_2-EOR due to limited published data.

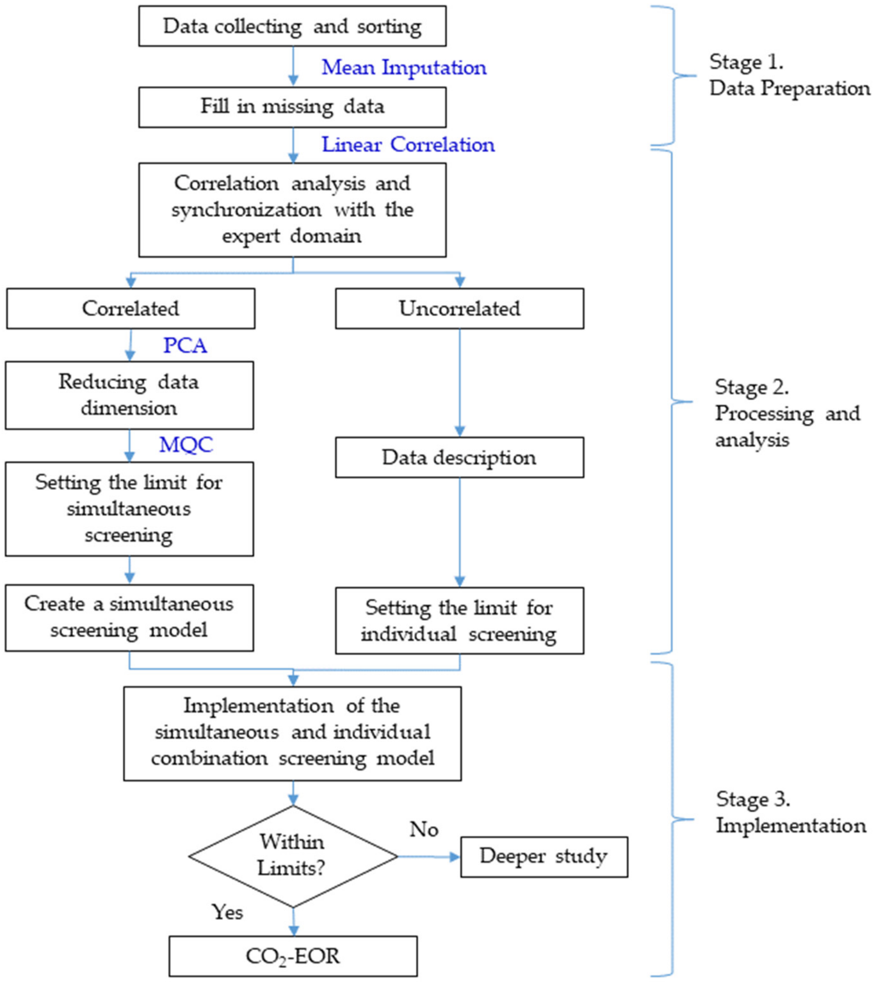


Figure 1. CO_2-EOR screening model workflow.

The collected data also had to be reorganized because of duplications and typos in unit measurements reported in the data source. For the incomplete data due to missing values, mean imputation based on the same type of formation was applied for screening parameters other than MMP. A fully expert domain approach of Yellig–Metcalfe empirical correlation as a function of temperature (T), as shown in the following, was used for determining MMP [13,14].

$$MMP\ (MPa) = 12.6472 + (0.01553 \times T) + \left(1.24192 \times 10^{-4} \times T^2\right) - \frac{716.9427}{T} \quad (1)$$

Stage 2: Processing and analysis. These are the main steps in developing the screening model in this research. The data required for the process was collected in Stage 1. Then, a correlation analysis was carried out to determine the relationship between screening parameters with the Pearson linear correlation method. The results of the correlation analysis were synchronized with the expert domain rules to match the fundamental physical phenomena. Furthermore, the PCA method reduced the data dimension into several principal components (PCs). The PCs were the input for the MQC method in determining the screening limit simultaneously. For uncorrelated screening parameters, the screening limit was determined by simple descriptive statistics to obtain the individual screening limit for each parameter. Stage 2 results in a simultaneous and individual combination screening model as a new screening model for CO_2-EOR.

Linear assumptions were adopted in the statistical calculation methods, including Pearson correlation, PCA, and MQC. Figure 2 describes the relationship among the statistical methods used to create a simultaneous screening model. The first calculations on the covariance matrix measured changes in the two related variables linearly. The normalized covariance produced a correlation matrix that showed the strength and direction of the relationship among the screening parameters in a linear manner. The t-statistic test was used to check the significance of the correlation coefficients [15].

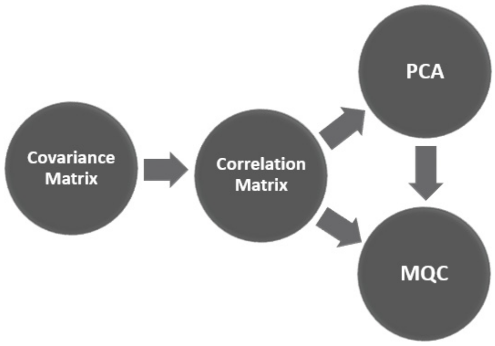


Figure 2. Relationship of statistical methods for simultaneous screening.

MQC is a method for simultaneously monitoring the variability of a multivariate case of two or more related quality characteristics. MQC method is suitable for a small number of process variables since the covariance matrix of MQC method will become singular when implemented in large and intercorrelated process variables [16]. A popular approach for reducing the dimensions of this variable is PCA [17]. The PCA method expresses information by constructing new variables in linear combinations called principal components (PC) without eliminating the original variables to minimize the excessive loss of information [18].

The condition is presumed to be statistically controlled, supposing the process variable is within the limit as specified in the control chart. This research uses the Hotelling T^2 control chart and, when associated with PCA, it is equivalent to:

$$T^2 = \sum_{i=1}^{A} \frac{PC_i^2}{S_{PC_i}^2} \tag{2}$$

where PC_i^2 is the ith principal component score, S_{PCi}^2 is the variance of PC_i, and A is the number of PC retained in the PCA model [16]. The upper and lower limits of the Hotelling T^2 control chart have an F distribution as follows [16].

$$T_{UCL}^2 = \frac{(n-1)(n+1)q}{n(n-q)} F_{1-\alpha(q,n-q)} \tag{3}$$

When the number of samples n is large, i.e., $n > 100$, many practitioners use an approximate control limit given by [17]:

$$T_{UCL}^2 = \frac{(n-1)q}{(n-q)} F_{1-\alpha(q,n-q)} \tag{4}$$

$$T_{LCL}^2 = 0 \tag{5}$$

The symbol T_{UCL}^2 is the upper control limit, T_{LCL}^2 is the lower control limit, n is the number of samples, q is the number of variables, and $F_{1-\alpha(q,n-q)}$ is the $100(1-\alpha)\%$ of the F-distribution with q and $n-q$ degrees of freedom. This control chart limit is further used as the simultaneous screening limit. An ellipse can represent multivariate control limits for two variables.

Subsequently, the individual screening model examines the parameters independently, indicating that these parameters are uncorrelated to each other. Individual screening criteria limits use simple descriptive statistical methods for quantitative calculations. The box plot gives some information on value of the minimum, mean, median, maximum, and quartiles. The swarm plot describes the data distribution in the box plot. Integrating the box and swarm plots then provides information more clearly as shown in Figure 3.

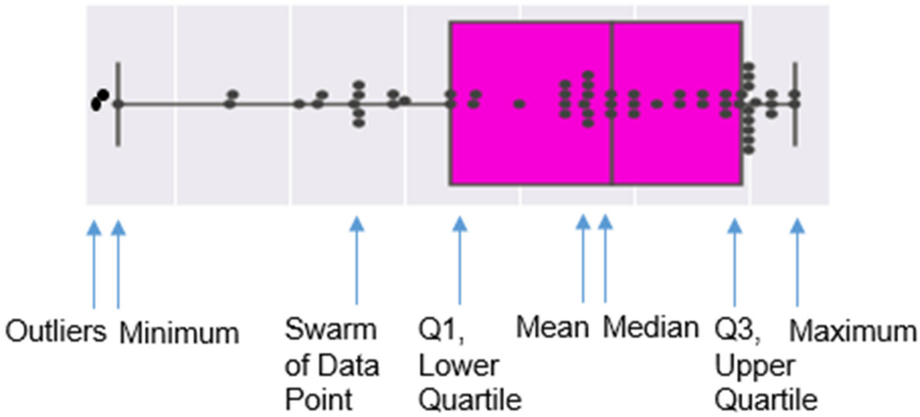
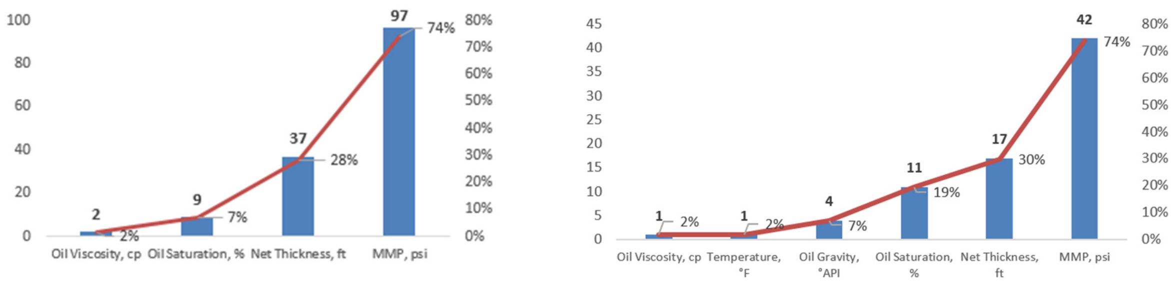


Figure 3. Integration of box plot and swarm plot.

Stage 3: Implementation. The final stage involved the implementation of the combined simultaneous and individual screening model on the CO_2-EOR field data asides from those analyzed data. If the reservoir parameters are appropriate for the screening criteria, then the field is a suitable target for applying the CO_2-EOR methods.

3. Results and Discussion

A total of 131 datasets on miscible CO_2-EOR projects in the US were sorted from 1100 duplicating datasets into 145 datasets on project success and, finally, into 131 datasets for successful and profitable projects. There were some missing data in oil viscosity, oil saturation, net thickness, and MMP, as shown in Figure 4a.



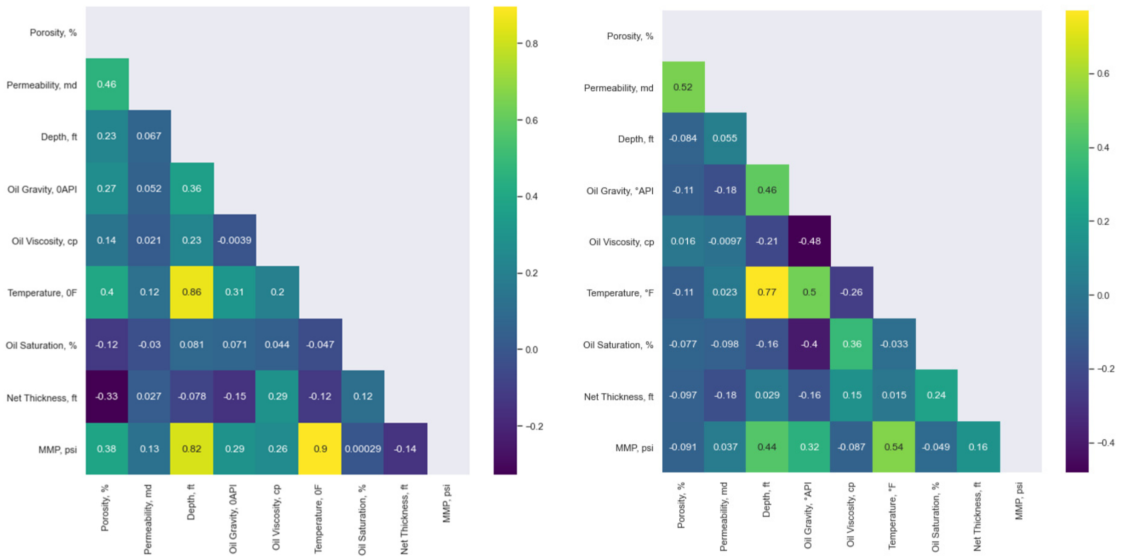
(**a**) (**b**)

Figure 4. Amount of missing data: (**a**) miscible CO_2-EOR, (**b**) immiscible CO_2-EOR.

Moreover, 37 project datasets of immiscible CO_2-EOR were obtained from OGJ by constructing, extracting, and sorting 164 duplicated initial datasets. Furthermore, an additional 27 project datasets were collected from SPE and Elsevier publications, bringing a total of 64 project datasets originating from several countries. Afterward, 57 datasets from 1986 to 2020 were analyzed, and the remaining 7 datasets were used to implement the newly established screening model. Missing data in Figure 4b were identified for several screening parameters, including oil viscosity, temperature, oil gravity, oil saturation, net thickness, and MMP. The mean imputation and Yellig–Metcalfe empirical correlation were applied to fill the missing data.

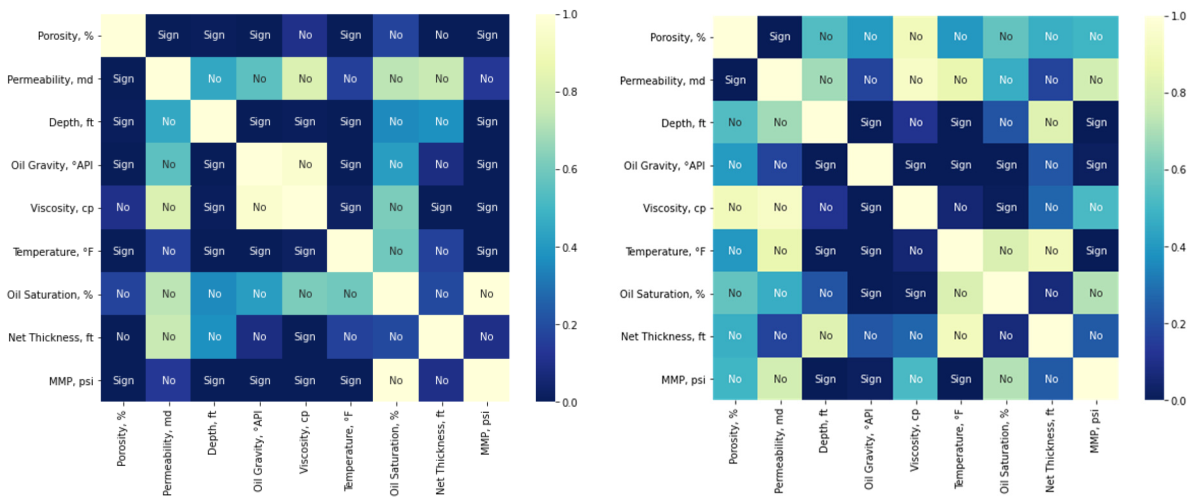
The coefficients of correlation among screening parameters are shown in Figure 5a for miscible CO_2-EOR and Figure 5b for immiscible CO_2-EOR. A high coefficient value tends to have a significant correlation based on a p-value smaller than 5% of the t-statistic test shown in Figure 6. Statistically, the MMP screening parameter was significantly correlated to porosity, depth, oil gravity, viscosity, and temperature. Permeability was related substantially to porosity. Oil gravity correlated with porosity, depth, viscosity, and temperature. Oil saturation had an insignificant correlation with all the screening parameters and so, the net thickness. Combining statistical methods and expert domains was needed to match the results from the correlations to the actual physical phenomena. Besides, the expert domain approach served as the basis for determining the correlation and dependency of the screening parameters shown in Figure 7 with the following explanation:

1. MMP correlates with temperature, oil gravity, and depth, whereas oil gravity correlates with oil viscosity. Therefore MMP, temperature, oil gravity, depth, and oil viscosity are intercorrelated and depend on each other.
2. Porosity correlates with permeability based on reservoir rock properties.
3. Oil saturation and net thickness insignificantly correlate to other screening parameters.



(**a**) (**b**)

Figure 5. Heatmap of Pearson correlation: (**a**) miscible CO_2-EOR; (**b**) immiscible CO_2-EOR.



(**a**) (**b**)

Figure 6. Heatmap of correlation significance test: (**a**) miscible CO_2-EOR; (**b**) immiscible CO_2-EOR.

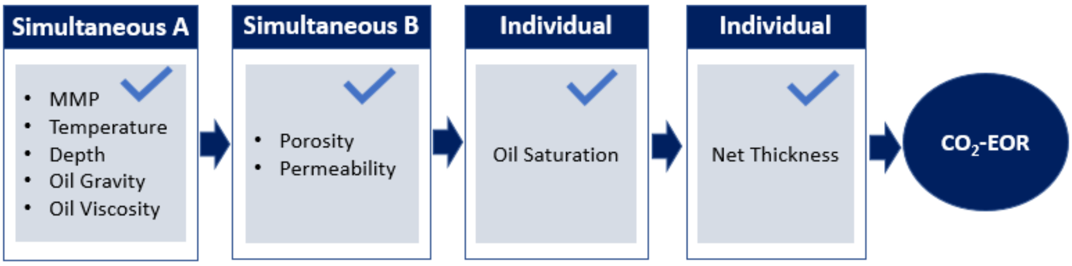


Figure 7. CO_2-EOR simultaneous and individual combination screening model.

Figure 7 shows four processes in the resulting screening model. The first calculation is done with the simultaneous model A, then, if appropriate, the process moves to the simultaneous model B and finally to the two individual models. If the four processes meet all the criteria, the reservoir is suitable for implementing CO_2-EOR.

As mentioned, this research focused on developing a screening model for miscible and immiscible CO_2-EOR. These two models are significantly different and have their own uniqueness. The following sections discuss the development and implementation of the screening model for different miscibility conditions of CO_2-EOR.

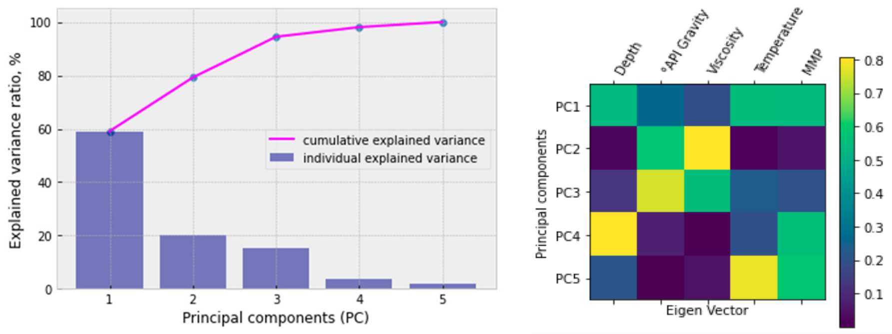
3.1. Miscible CO_2-EOR Screening Model

The summary of simultaneous and individual combination screening models for miscible CO_2 is provided in Table 3. Simultaneous screening model A includes five parameters: MMP, temperature, depth, oil gravity, and oil viscosity. Although the grouping only concerns the limits or boundary of data values, to the best of our knowledge, the model may relate to mixture miscibility and the fluids' composition, where the mixture, in this case, stands for oil mixed with CO_2 within the reservoir during the injection. Indeed, the miscibility is sensitive to the pressure-related properties, i.e., MMP and depth, and also temperature. Furthermore, the composition of oil dictates the specific gravity and the viscosity, and affects the miscibility of CO_2 into the oil as well. Based on this, those five parameters were grouped into the corresponding model.

Table 3. Summary of the miscible CO_2-EOR screening model.

	Screening Model			
Simultaneous A: • MMP, psi • Temperature, °F • Depth, ft • Oil Gravity, °API • Oil Viscosity, cp	$T_A^2 = \left(0.335911 \times PC1^2\right) + \left(0.985883 \times PC2^2\right)$ If $T_A^2 < 11.13$ Then Miscible CO_2-EOR $PC1 = (0.000233 \times Depth) + (0.05839 \times API) + (0.037014 \times Visc) + (0.011362 \times Temp) + (0.000713 \times MMP) - 6.4375053$ $PC2 = -(0.0000113 \times Depth) - (0.127728 \times API) + (0.157454 \times Visc) - (0.000327 \times Temp) + (0.0000639 \times MMP) + 4.407477$			
Simultaneous B: • Porosity, % • Permeability, md	$T_B^2 = \left(1.259 \times X^2\right) - (1.142 \times X \times Y) + \left(1.259 \times Y^2\right)$ If $T_B^2 < 11.13$, then miscible CO_2-EOR $X = \frac{\text{Por} - 14.29}{5.839}$ and $Y = \frac{\text{Perm} - 88}{428.77}$			
Individual: Oil saturation, %	Minimum Maximum Mean Standard Deviation	=17 =89 =48.54 =14.14	Q1 (25th percentile) Q2 (50th percentile) Q3 (75th percentile)	=38 =47 =55
Individual: Net Thickness, ft	Minimum Maximum Mean Standard Deviation	=9 =472 =96.92 =78.38	Q1 (25th percentile) Q2 (50th percentile) Q3 (75th percentile)	=44 =80 =113

The PCA method reduced the data dimensions to 2 PCs, explaining the total data diversity of 79.2%, as shown in Figure 8a. PC1 explains 59.1% and PC2 explains 20.1%. Figure 8b shows the magnitude of the eigenvectors for each PC. The T_A^2 equation in Table 3 is simultaneous screening model A, a quadratic function of PC1 and PC2. The limit obtained was 11.13 at a confidence level of 99.5%, as shown in Figure 9. If the value of T_A^2 is less than 11.13, the miscible CO_2-EOR is the appropriate EOR method. The oil gravity and viscosity have a more significant effect on the value of T_A^2.



(**a**) (**b**)

Figure 8. (**a**) Scree plot and (**b**) eigenvectors of PCA for miscible CO_2-EOR simultaneous screening model A.

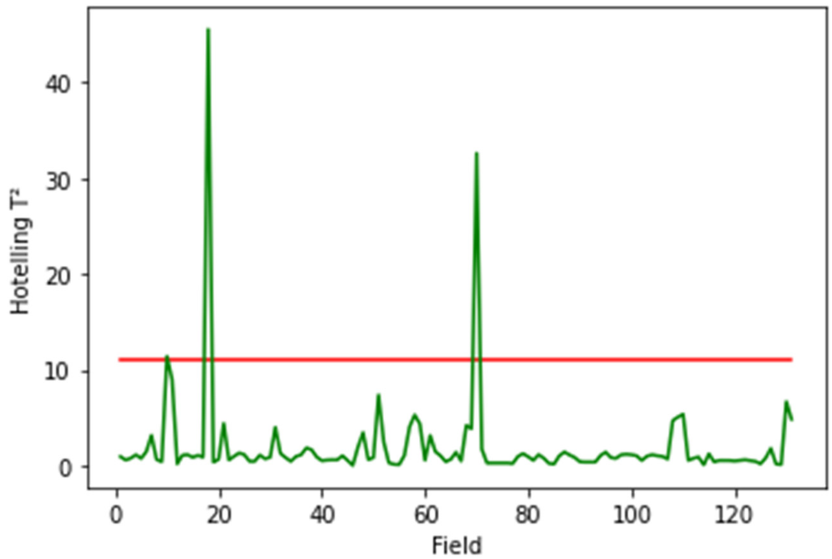
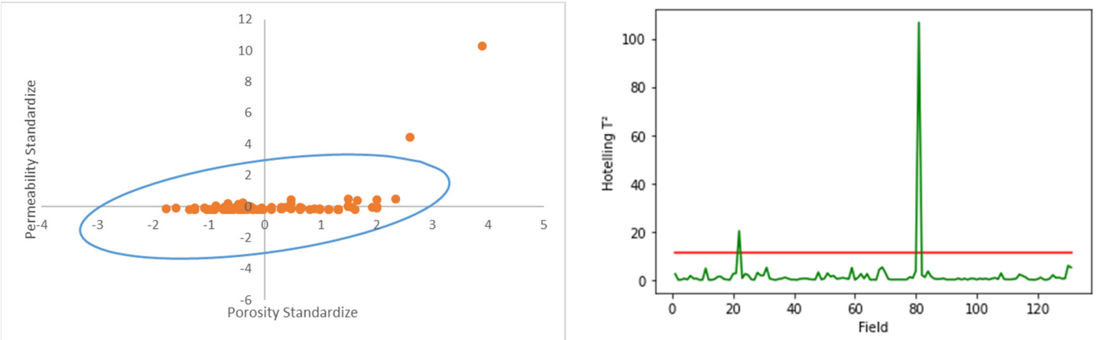


Figure 9. The Hotelling T^2 chart for miscible CO_2-EOR simultaneous screening model A.

Simultaneous screening model B includes two screening parameters, namely porosity and permeability. As commonly known in petroleum literatures, a dimension combining permeability and porosity parameters represents the measure of volumetric flow capacity. In the same sense, the screening model B may also have similar physical meaning.

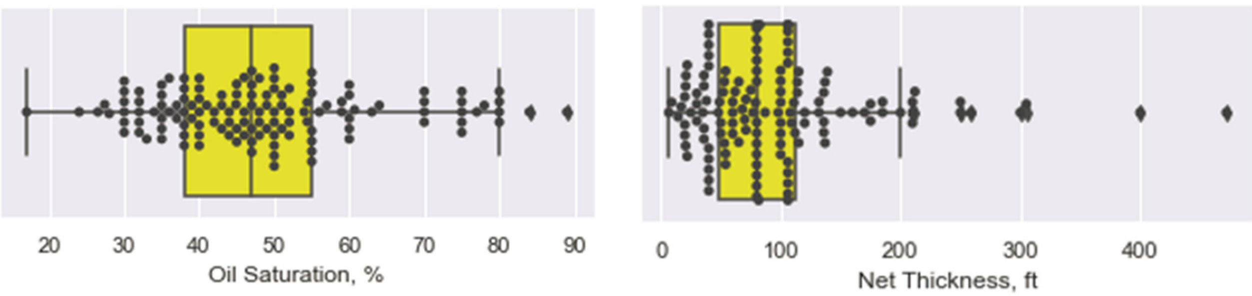
A simultaneous screening model was developed using the MQC method. Figure 10a,b indicate that the screening boundary is in ellipse form, and the Hotelling T^2 chart has an upper limit of 11.13 at a confidence level of 99.5%. The simultaneous screening model B is in the form of the T_B^2 equation, a function of porosity and permeability. If the value of T_B^2 is less than 11.13, it is suitable for the miscible CO_2-EOR.



(a) (b)

Figure 10. (**a**) Simultaneous boundary ellipse and (**b**) the Hotelling T^2 chart for miscible CO_2-EOR simultaneous screening model B.

Oil saturation and net thickness parameters employ an individual screening model. Figure 11a shows the integration of box and swarm plots for oil saturation and Figure 11b for net thickness. The individual screening criteria of oil saturation have a minimum data value of 17%, as of that of Olive Field [19], and a maximum of 89%, as of that of Salt Creek Field [20]. Meanwhile, the minimum data of net thickness is 9 ft, as of that of Chester Field [21], and the maximum data is 472 ft, as of that of Citronelle Field [22].



(a) (b)

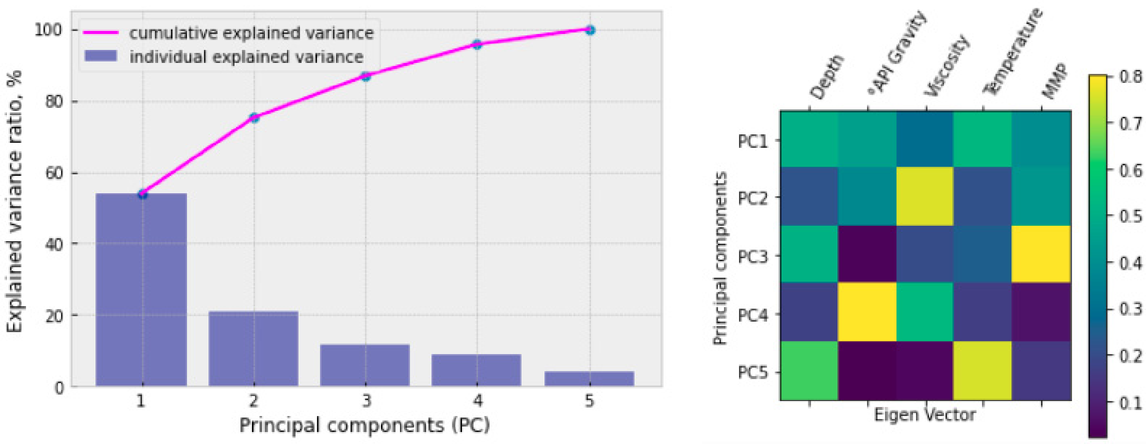
Figure 11. Miscible CO_2-EOR box plot and swarm plot: (**a**) oil saturation and (**b**) net thickness.

3.2. Immiscible CO_2-EOR Screening Model

Table 4 provides a complete simultaneous and individual combination screening model for immiscible CO_2-EOR. Therefore, all five parameters in the simultaneous screening model A are covered in 2 PC and by 75% data diversity, as shown in Figure 12a. Figure 12b gives the eigenvectors for each PC. As shown in Figure 13, the limit of simultaneous model A is 12.1 with a confidence level of 99.5%. In other words, any value of T_A^2 less than 12.1 means that the immiscible CO_2-EOR is amenable. Based on the correlation of T_A^2 expressed in Table 4, T_A^2 is more influenced by oil gravity and viscosity than the other three parameters. The simultaneous screening model B depends on the value of T_B^2, as shown in Figure 14, which means immiscible CO_2-EOR is suitable if T_B^2 is less than 12.1. In addition, the T_B^2 value is governed by porosity and permeability.

Table 4. Summary of the immiscible CO_2-EOR screening model.

	Screening Model			
Simultaneous A: • MMP, psi • Temperature, °F • Depth, ft • Oil Gravity, °API • Oil Viscosity, cp	$T_A^2 = \left(0.364176 \times PC1^2\right) + \left(0.92776 \times PC2^2\right)$ if $T_A^2 < 12.1$, then immiscible CO_2-EOR $PC1 = (0.000173 \times Depth) + (0.05312 \times API) - (0.00089 \times Visc) + (0.011223 \times Temp) + (0.00034 \times MMP) - 5.07638$ $PC2 = (0.00007563 \times Depth) - (0.04427 \times API) + (0.002297 \times Visc) + (0.004473 \times Temp) + (0.000365 \times MMP) - 1.11169$			
Simultaneous B: • Porosity, % • Permeability, md	$T_B^2 = \left(1.3478 \times X^2\right) - (1.3693 \times X \times Y) + \left(1.3478 \times Y^2\right)$ If $T_B^2 < 12.1$, then immiscible CO_2-EOR $X = \frac{\text{Por} - 22.4}{6.6}$ and $Y = \frac{\text{Perm} - 516}{607.5}$			
Individual for Oil saturation, %	Minimum Maximum Mean Standard Deviation	=22 =83.5 =52.13 =14.40	Q1 (25th percentile) Q2 (50th percentile) Q3 (75th percentile)	=45 =50 =60
Individual for Net Thickness, ft	Minimum Maximum Mean Standard Deviation	=5.2 =300 =78.17 =60.27	Q1 (25th percentile) Q2 (50th percentile) Q3 (75th percentile)	=38.8 =71 =98



(**a**) (**b**)

Figure 12. (**a**) Scree plot and (**b**) eigenvectors of PCA for immiscible CO_2-EOR simultaneous screening model A.

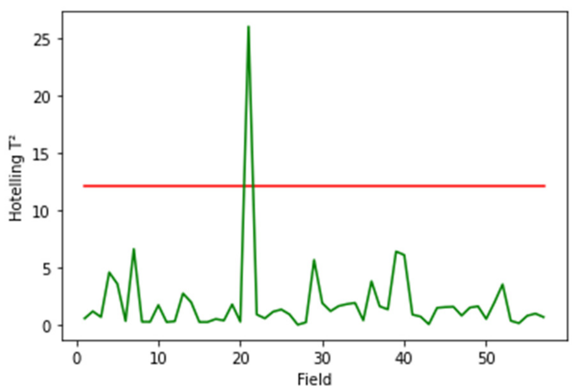
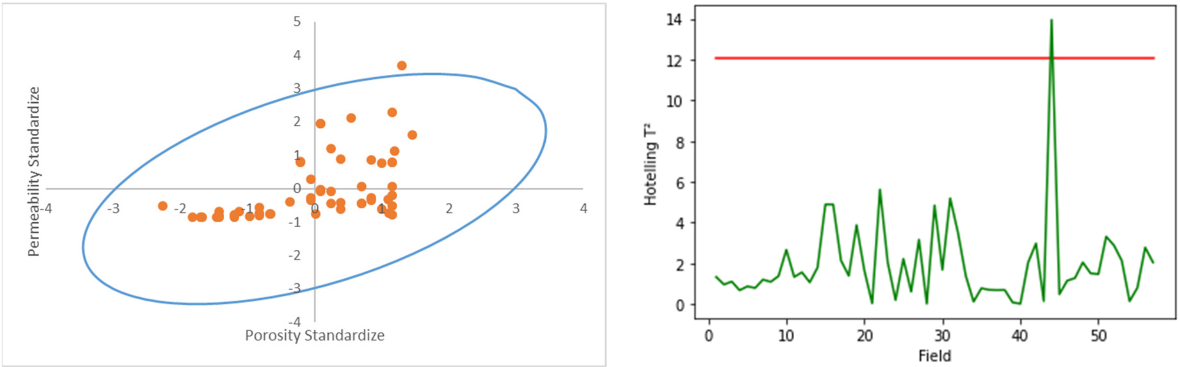


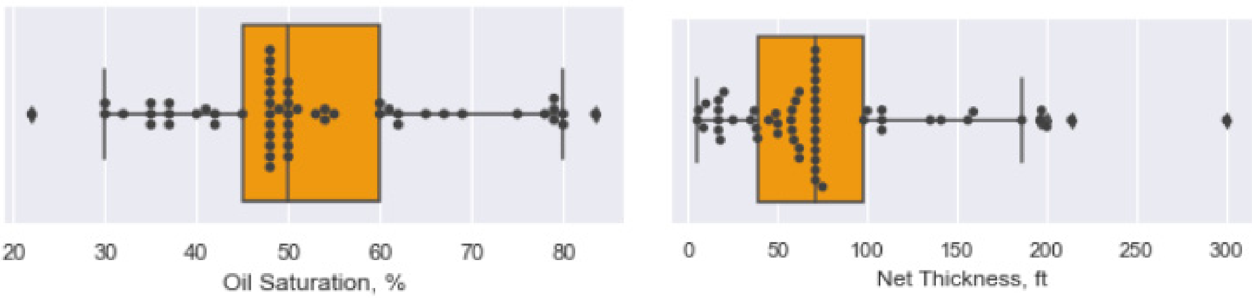
Figure 13. The Hotelling T^2 chart for simultaneous screening model A for immiscible CO_2-EOR.



(**a**) (**b**)

Figure 14. (**a**) Simultaneous boundary ellipse and (**b**) the Hotelling T^2 chart for immiscible CO_2-EOR simultaneous screening model B.

Figure 15 provides data distribution on the individual screening parameters of immiscible CO_2-EOR, namely oil saturation and net thickness. Individual screening criteria for oil saturation have a minimum data of 22%, as of that of Weeks Island Field [23], and a maximum data of 83.5%, as of that of Ponte Dirillo Field [24]. Net Thickness screening criteria have a minimum data of 5.2 ft, as of that of Yaoyingtai Field [12], and a maximum data of 300 ft, as of that of Huntington Beach Field [12].



(**a**) (**b**)

Figure 15. Immiscible CO_2-EOR box plot and swarm plot: (**a**) oil saturation and (**b**) net thickness.

3.3. Implementation

The simultaneous and individual combination screening model was implemented and the results were compared with the real conditions in the corresponding fields. The model for miscible CO_2-EOR was implemented only in Canadian fields. The reservoir properties and reference sources are shown in Table 5. The MMP values were obtained from the application of the Yellig–Metcalfe empirical correlation, whereas the other reservoir properties were collected from references and missing data were filled by mean imputation.

The combination screening models for miscible and immiscible CO_2-EOR were reviewed and compared with the screening model presented by Taber et al. [10], Al Adasani and Bai [11], and Zhang et al. [5]. Table 6 shows the implementation results of several screening methods in miscible CO_2-EOR fields. The proposed simultaneous and individual combination screening model recommended the injection of both miscible and immiscible CO_2 for the six fields. The screening results match the actual conditions and meet the real physical phenomena. The reservoir that is suitable for miscible CO_2 injection should also be appropriate for immiscible CO_2-EOR.

In the meantime, Zhang et al.'s model recommended that four fields were suitable for miscible CO_2 and were inappropriate for immiscible CO_2. This shows less precise results if they are compared with the expert domain rules. Similar results were obtained from using Al Adasani and Bai's model, where all the fields are unsuitable for immiscible CO_2-EOR but meet the requirements for miscible CO_2. Moreover, all fields are suitable for miscible and immiscible CO_2 in Taber et al.'s screening model. However, it is worth noting here that Taber et al.'s model utilizes the least screening parameters compared to the other models. Clearly, the results of the combination screening model match the actual conditions of the miscible CO_2 field and follows the rule of the expert domain.

The combination screening model for immiscible CO_2-EOR was implemented in seven fields located in Trinidad, US, Turkey, and Brazil. These fields have been proven as successful in implementing immiscible CO_2-EOR. The physical properties of the nine reservoir screening parameters are presented in Table 7. The screening parameter values were obtained from references and mean imputation was done for the missing data. In addition, the Yellig–Metcalfe correlation was used to determine the MMP. The results of implementing several screening models in the seven fields are shown in Table 8. The combination screening model recommended that the fields that are suitable for miscible CO_2 injection are also appropriate for immiscible CO_2 injection. However, a field that can be injected with immiscible CO_2 is not necessarily a field that can be injected with miscible CO_2. The results of implementing this combination screening method followed the rules of the expert domain. Differences are notable when these results are compared to those of Al Adasani and Bai [11], Zhang et al. [5], and Taber et al.'s [10] screening methods. Their results showed that the reservoirs in the Bayou Sale and West Hasting fields are suitable for miscible CO_2 injection but not for immiscible CO_2-EOR. As shown by the table, in reality, the fields have successfully implemented immiscible CO_2-EOR.

Table 5. Reservoir properties for implementation of miscible CO_2-EOR screening.

Country	Field	Porosity, %	Permeability, md	Depth, ft	Oil Gravity, °API	Oil Viscosity, cp	Temperature, °F	Oil Saturation, %	Net Thickness, ft	MMP, psi	References
Canada	Swan Hills	8.5	54	8300	41	0.4	225	45	50	2791	[20,25]
Canada	Judy Creek	12	50	8200	41.5	0.65	206	45	220	2558	[20,26]
Canada	Pembina	16	20	5300	41	1	128	38	41	1605	[20,27]
Canada	Jofre	13	500	4900	42	1.14	133	38	60	1671	[20]
Canada	Midale	16.3	7.5	4600	30	3	149	45	65	1872	[20,28]
Canada	Weyburn Unit	15	10	4655	28	3	140	45	65	1760	[20,29]

Table 6. Results of screening model implementation on miscible CO_2-EOR fields.

Country	Field	Actual EOR Method	Combination Screening		Zhang et al. [5]		Al Adasani and Bai [11]		Taber et al. [10]	
			Miscible	Immiscible	Miscible	Immiscible	Miscible	Immiscible	Miscible	Immiscible
Canada	Swan Hills	Miscible	√	√	√	X	√	X	√	√
Canada	Judy Creek	Miscible	√	√	√	X	√	X	√	√
Canada	Pembina	Miscible	√	√	√	X	√	X	√	√
Canada	Jofre	Miscible	√	√	√	X	√	X	√	√
Canada	Midale	Miscible	√	√	√	√	√	X	√	√
Canada	Weyburn Unit	Miscible	√	√	√	√	√	X	√	√

Table 7. Reservoir properties for implementation of immiscible CO_2-EOR screening.

Country	Field	Porosity, %	Permeability, md	Depth, ft	Oil Gravity, °API	Oil Viscosity, cp	Temperature, °F	Oil Saturation, %	Net Thickness, ft	MMP, psi	References
Trinidad	Area 2102	32	175	3000	19	16	120	56	144	1497	[20,30]
Trinidad	Area 2121	30	150	2600	17	32	120	60	58	1497	[20,30]
Trinidad	Area 2124	31	300	4200	25	6	130	44	196	1632	[20,30]
Turkey	Bati Raman	18	58	4265	13	592	129	78	197	1619	[20,31]
US	Bayou Sale	31	500	10,000	34	0.4	194	50.0	71	2413	[24]
Brazil	Buracica	22	525	1970	35	10.5	120	76	29	1497	[20,32]
US	West Hasting	30	1000	5700	31	1.2	165	30	75	2066	[20,33]

Table 8. Results of the screening model implementation on immiscible CO_2 fields.

Country	Field	Actual EOR Method	Combination Screening		Zhang et al. [5]		Al Adasani and Bai [11]		Taber et al. [10]	
			Miscible	Immiscible	Miscible	Immiscible	Miscible	Immiscible	Miscible	Immiscible
Trinidad	Area 2102	Immiscible	X	√	√	√	X	√	X	√
Trinidad	Area 2121	Immiscible	X	√	√	√	X	√	X	√
Trinidad	Area 2124	Immiscible	√	√	√	√	√	√	√	√
Turkey	Bati Raman	Immiscible	X	√	X	√	X	√	X	√
US	Bayou Sale	Immiscible	√	√	√	X	√	X	√	√
Brazil	Buracica	Immiscible	√	√	√	√	√	√	X	√
US	West Hasting	Immiscible	√	√	√	√	√	X	√	X

4. Conclusions

Understanding the interdependence among screening parameters has resulted in developing a new model capable of handling the correlating parameters, namely the simultaneous screening model. The integration of simultaneous and individual screening models resulted in a combination screening model. This model is used to screen CO_2-EOR methods and is a successful improvement on the previous models. The results obtained follow the expert domain rules. Assuming the field meets the miscible CO_2-EOR criteria, the immiscible CO_2-EOR is also implementable, but not vice versa.

The combination screening model was implemented using several CO_2-EOR field datasets and matched the real operations. This model also reduced screening time by determining several parameters simultaneously and not individually. Accordingly, applying the combination screening model in other fields should provide good, fast, realistic, and representative results. However, further research is still needed to develop a more reliable screening method that integrates economic aspects in order to fully assess CO_2-EOR projects.

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