

Article

Research and Application of Carbon Capture, Utilization, and Storage–Enhanced Oil Recovery Reservoir Screening Criteria and Method for Continental Reservoirs in China

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Abstract: CCUS-EOR is a crucial technology for reducing carbon emissions and enhancing reservoir recovery. It enables the achievement of dual objectives: improving economic efficiency and protecting the environment. To explore a set of CCUS-EOR reservoir screening criteria suitable for continental reservoirs in China, this study investigated and compared the CCUS-EOR reservoir screening criteria outside and in China, sorted out the main reservoir parameters that affect CO₂ flooding, and optimized the indices and scope of CCUS-EOR reservoir screening criteria in China. The weights of parameters with respect to their influences on CCUS-EOR were determined through principal component analysis. The results show that there are 14 key parameters affecting CO₂ flooding, which can be categorized into four levels. For the first level, the crude oil–CO₂ miscibility index holds the greatest weight of 0.479. It encompasses seven parameters: initial formation pressure, current formation pressure, temperature, depth, C₂–C₁₅ molar content, residual oil saturation, and minimum miscibility pressure. The second level consists of the crude oil mobility index, which has a weight of 0.249. This index includes four parameters: porosity, permeability, density, and viscosity. The third level pertains to the index of reservoir tectonic characteristics, with a weight of 0.141. It comprises two parameters: permeability variation coefficient and average effective thickness. Lastly, the fourth level focuses on the index of reservoir property change, with a weight of 0.131, which solely considers the pressure maintenance level. Based on the CCUS-EOR reservoir screening criteria and index weights established in this study, comprehensive scores for CCUS-EOR were calculated for six blocks in China. Among these, five blocks are deemed suitable for CCUS-EOR. Based on the comprehensive scoring results, a planning for field application of CCUS-EOR is proposed. The study provides a rational method to evaluate the CCUS-EOR reservoir screening and field application in continental reservoirs in China.

Keywords: CCUS-EOR; CO₂ flooding; continental reservoir; screening criteria; principal component analysis



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1. Introduction

To meet the production and lifestyle needs of the increasing global population, the demand for non-renewable energy sources is growing significantly [1], and greenhouse gas emissions are also rising with the industrial production [2]. The issues of global climate change and energy demand are becoming increasingly prominent, posing new challenges for environmental protection and energy utilization. CO₂ is the primary greenhouse gas in the atmosphere, and human activities such as fossil fuel-based power generation, heating, and transportation are the main sources of CO₂ emissions [3]. Since the industrial

revolution, the increase in CO₂ levels in the atmosphere has contributed to over 60% of environmental pollution [4], the sea-level rise has accelerated [5], and the environmental problems induced by climate change such as the melting of ice caps and polar glaciers are irreversible [6]. If the environmental impacts of human activities will not be controlled, these issues are expected to worsen rapidly in the coming decades [7]. Carbon capture and utilization (CCU) technologies, including Power-to-Gas (PtG) [8], Power-to-Liquid (PtL) [9], and CO₂-Enhanced Oil Recovery (CO₂-EOR) [10], in conjunction with carbon capture and storage (CCS) methods like physical absorption and chemical absorption [11], form a comprehensive carbon capture, utilization, and storage (CCUS) technology, which has been proven to be effective for mitigating climate change and achieving sustainable development [12]. It is a crucial tool for reducing carbon emissions in sectors such as coal-fired power generation, cement, and steel production [13]. CCUS-EOR (Enhanced Oil Recovery) [14], a key extension of CCUS, can inject the captured CO₂ into oil reservoirs to enhance oil recovery and reduce carbon emissions by storing the injected CO₂ in the reservoirs, thereby achieving the dual goals of increasing production efficiency and protecting the environment [15].

CO₂ flooding was initially proposed in laboratory research in 1930 and achieved industrial applications after 1950 [4]. Since 1970, projects utilizing CO₂ for displacing oil in (depleted) reservoirs have gradually increased. According to statistics of the International Energy Agency (IEA), as of 2017, there were over 160 CCUS-EOR projects globally. The United States, Canada, and China were among the early developers of such projects, and in recent years, countries like Brazil, Turkey, Norway, and Saudi Arabia have also employed to CCUS-EOR [16]. Research has indicated that the mechanisms of CO₂ in reservoirs include interfacial tension reduction by oil and gas mass transfer, as well as crude oil expansion and viscosity reduction through gas dissolution, thereby improving flooding efficiency [17,18]. Additionally, the injected CO₂ can be stored within depleted reservoirs through physical trapping and chemical reactions with rock formations, thereby reducing CO₂ levels in the atmosphere [19]. Therefore, CCUS-EOR has become the primary technology for improving oil recovery rate, following chemical flooding and thermal recovery methods. Identifying suitable depleted oil reservoirs for CCUS-EOR can help recover more reserves from reservoirs with more economic benefits. Most large-scale CCUS-EOR projects are concentrated in North America and Canada, where they have achieved high oil production rates [20]. In China, many oil reservoirs were initially developed using water flooding and chemical flooding methods, while since 2019, breakthroughs have been made in the research and engineering demonstration of CCUS-EOR [7], indicating that CCUS-EOR can be used in depleted oil reservoirs for further enhanced oil recovery. By screening key parameters such as reservoir characteristics and crude oil properties for developed reservoirs, the potential of CCUS-EOR is assessed to achieve the effective application of CO₂ flooding technology.

Since the occurrence of CCUS-EOR technology, numerous highly applicable reservoir screening criteria have emerged for various oil displacement projects. These criteria primarily focus on reservoir parameters and fluid properties that are closely related to the CO₂–crude oil miscibility, and they are mainly applicable to reservoirs in the United States and Canada [15,21]. However, with the evolution of CO₂ injection technology, these criteria have exhibited a deviation from the actual application scope and have become less representative [13]. In contrast to reservoirs in other countries/regions where CO₂ and crude oil are more miscible, most reservoirs in China face harsher conditions—particularly, the highly heterogeneous continental sedimentary reservoirs are estimated with inferior ultimate recovery to marine sedimentary reservoirs [22], and the reservoirs suitable for CCUS-EOR are deeper. Moreover, in China, the reservoirs are widespread with large spans and reflect distinct characteristics from region to region. Although laboratory studies and field tests have been performed on CO₂ flooding for some reservoirs in China, there is currently no comprehensive research summarizing CCUS-EOR reservoir screening criteria for all reservoirs across China. Therefore, it is necessary to further update and refine

the existing CCUS-EOR reservoir screening criteria to develop a set of criteria that align with the specific characteristics of reservoirs in China. Furthermore, the formulation of a complete set of CCUS-EOR screening criteria should ideally consider both technical and non-technical indices [23]. Technical indices include indicators of CO₂ capture capacity, CO₂-EOR capability, and CO₂ storage capacity. Non-technical indices encompass economic parameters, policy factors, safety risks, and more. This paper focuses on establishing parameters for screening reservoirs based on their CO₂-EOR capabilities without considering other technical and non-technical indices.

In this paper, the CCUS-EOR reservoir screening criteria are investigated through a review of the available literature, reports, and materials. The CO₂ flooding projects in the world are compared, and the parameters in the CCUS-EOR reservoir screening criteria are analyzed. Then, through principal component analysis, the influences of screening indices on CCUS-EOR for reservoirs in China are identified. Finally, the CCUS-EOR reservoir screening criteria suitable for reservoirs in China are proposed. The study results will provide theoretical guidance and optimization recommendations for the rapid and accurate screening of reservoirs for CCUS-EOR.

2. Investigation of CCUS-EOR Reservoir Screening Criteria

2.1. CCUS-EOR Reservoir Screening Criteria outside China

Reservoir screening is the first stage for CCUS-EOR project implementation, and the success of the CCUS-EOR project relies heavily on the reservoir screening results. A set of precise screening criteria can expedite the selection of reservoirs suitable for CO₂ flooding, thereby enhancing the overall economic efficiency of the CCUS-EOR project. The first commercial application of CCUS-EOR was achieved in the United States in 1972, followed by large-scale field applications. The CCUS-EOR technology in the United States is more mature and corresponds to more advanced reservoir screening criteria than that in other countries [21].

Initially, American scholars have screened reservoirs for CCUS-EOR by mainly depending on parameters such as reservoir depth, temperature, formation pressure, oil density and viscosity, and oil saturation. It was generally believed that reservoir depth, temperature, and pressure required the miscibility of CO₂ and crude oil, that oil viscosity and density represented the mobility of crude oil, and that oil saturation reflected the economics of the reservoir [24–28]. Carcoana discussed reservoir recovery methods in Romania and suggested that a reservoir with net thickness of less than 15 m allows for a good volumetric sweep efficiency for CO₂ [29]. Taber and Martin included crude oil components into screening parameters and indicated that CO₂ is more miscible with crude oil containing high levels of intermediate hydrocarbon components like C₅₊ [30–32]. Rivas argued against the exclusion of a reservoir solely based on a parameter not meeting the screening criteria and indicated that, among the reservoir parameters, oil viscosity, gas-oil ratio, and bubble point pressure are associated with oil gravity [33]; he used a normalization model and weighted ranking to determine the parameters of reservoirs in Eastern Venezuela suitable for CCUS-EOR. Diaz et al. evaluated 197 reservoirs in Louisiana by employing Rivas' screening technique and, through economic assessments, identified 39 reservoirs feasible for CCUS-EOR [34]. Shaw and Bachu emphasized the importance of crude oil components, density, and reservoir temperature in determining the minimum miscibility pressure (MMP) [35,36]. They recommended that reservoir temperature and pressure ideally should meet the conditions for CO₂ to become supercritical, and they also indicated that reservoir depth and oil viscosity can be disregarded as they are related to temperature and oil density.

Algharaib made a screening of 107 reservoirs for CCUS-EOR in the Middle East according to the criteria which took into account the influence of gas caps and pointed out the necessity for keeping the minimum miscibility pressure (MMP) below the reservoir fracture pressure [37]. Wo et al. suggested that even non-miscible CO₂ flooding could displace residual oil in water-flooded reservoirs [38]. They proposed two sets of screening

criteria for miscible and immiscible flooding in reservoirs in Wyoming, with the main differences being in oil gravity, reservoir depth, and oil viscosity—miscible flooding is considered feasible when the oil gravity is greater than 22° API, the reservoir depth exceeds 762 m, and the oil viscosity is less than 10 cP. Aladasani and Bai collected data from over 160 CCUS-EOR projects reported in various publications worldwide during 1998–2010 and updated the screening criteria for CO₂ miscible and immiscible flooding [39,40]. Gao et al. identified five key screening parameters, including reservoir depth, temperature, pressure, oil gravity, and oil components [41]. During a reservoir screening for CCUS-EOR in Abu Dhabi, United Arab Emirates, Hajeri et al. believed that reservoirs with a high vertical permeability or a high ratio of vertical permeability to radial permeability have low potential [42]. The U.S. National Energy Technology Laboratory (NETL) recommended that carbonate or sandstone reservoirs are more suitable for CO₂ flooding than other reservoirs and defined depth, temperature, pressure, permeability, oil gravity, viscosity, and residual oil saturation as screening parameters [43]. Koottungal collected the CO₂ flooding projects conducted in the United States from 1972 to 2014 and counted the parameter ranges of porosity, depth, oil gravity, viscosity, temperature, and oil saturation, with an emphasis on CO₂ miscible flooding [44].

Verma classified the screening parameters for CCUS-EOR projects in the United States depending on the lithology of reservoir rocks (limestone and sandstone dominantly in reservoirs with miscible flooding) [45]. Yin analyzed 134 CO₂ flooding projects in the United States and established corresponding screening criteria for carbonate and sandstone reservoirs [46]. Bachu developed CCUS-EOR reservoir screening criteria applicable to Alberta, Canada, which incorporated economic indicators such as initial oil reserves and remaining oil content and included the key parameters significantly affecting screening results such as oil gravity, MMP, and reservoir size [21]. Through statistical analyses on parameters used in global CO₂-EOR projects, Zhang et al. formulated the screening criteria for CO₂ miscible and immiscible flooding separately [47,48]; CO₂ miscible flooding imposes higher requirements on net reservoir thickness, oil viscosity, oil gravity, and MMP, whereas CO₂ immiscible flooding requires higher oil saturation to ensure effective oil displacement. Hares established new screening criteria applicable to oilfields in Alberta based on existing CCUS-EOR research, which increased the importance of oil gravity, MMP, and oil viscosity in the screening process [49].

The above findings reveal that the current CCUS-EOR reservoir screening criteria are primarily based on the characteristic parameters corresponding to CO₂ miscible flooding projects in the United States and Canada. Reservoirs selected for CCUS-EOR are usually composed of carbonate and sandstone, with favorable porosity and permeability, and contain light to medium oils with a low viscosity. Additionally, these reservoirs have sufficient depth and temperature to enable the pressures to exceed the MMP, allowing for the CO₂–crude oil miscibility. Reservoirs targeted for CO₂ immiscible flooding should have a high porosity, high permeability, and good homogeneity due to their relatively heavy and more viscous oil contents. It is worth noting that the ultimate recovery improvement achieved through immiscible flooding is generally lower than that through miscible flooding [50]. Tables (Tables 1 and 2) lists the reservoir screening parameters and scope defined by scholars/institutions for CCUS-EOR projects outside China since 1972. Generally, the screening parameters for CCUS-EOR projects that have been carried out are categorized as: (1) characteristic parameters of reservoir, including reservoir depth, pressure, temperature, porosity, permeability, net thickness, oil saturation, and reservoir dip angle; and (2) characteristic parameters of crude oil, including oil gravity, oil viscosity, and oil composition. Oil gravity and oil density are interchangeable using formulas. Oil composition is less considered but mainly represented by oil gravity. Reservoir dip angle is sparsely reported. In this study, the reservoir depth, temperature, pressure, porosity, permeability, net thickness, oil saturation, oil density, oil composition, and oil viscosity are used as screening indices.

Table 1. CCUS-EOR reservoir screening criteria outside China.

Scholar/Institution	Area	Year	Depth (m)	Temperature (°C)	Pressure (MPa)	Porosity (%)	Permeability (mD)
Geffen [24]	United States	1973			>7.6		
Lewin & Assoc [25]	United States	1976	>914		>10.4		
NPC [26]	United States	1976	>701	<121			
McRee [27]	United States	1977	>610				>5
Iyoho [28]	United States	1978	>762				>10
Carcoana [29]	Romania	1982	<3000	<90	>8	>18	>0.1
Taber & Martin [30]	United States	1983	>610		8.3–32		
Klins [51]	United States	1984	>914		>103		
Rivas [33]	Venezuela	1994		54–93	$0.1 \leq P/M \leq 1.3$	9–33	18–2500
Diaz et al. [34]	United States	1996		27–136	$0.1 \leq P/M \leq 1.47$	17.6–34	17–3485
Taber et al. [32]	World	1997	762–1219		>MMP		>5
Bachu [35]	Canada	2004		32–121	$0.95 \leq P/M$		
Alberta Research Council [52]	Canada	2009	>450	28–121	>MMP and $<P_f$	≥ 3	≥ 5
Algharaib [37]	Middle East	2009	>600	>30	>MMP		
Wo et al. [38]	United States	2009	>762			>7	>10
NETL [43]	United States	2010	610–2987	<121	>8.3–10.3		>1–5
Aladasani [39]	World	2010	457–4074	28–121		3–37	1.5–4500
Gao & Pan [41]	World	2010	>762			>12	>10
Koottungal [44]	United States	2014	487–3600	28–127		30	1–4500
Yin [46]	United States	2015	350–3642	28–127		4–23.7	>2
Bachu [21]	World	2016	500–4100	28–127	$\geq$ MMP	3–37	
Zhang et al. [47]	World	2018	426–2590	28–112		11.5–33	1.4–2750
Zhang et al. [48]	World	2019	>350	<127	$\geq$ MMP	3–37	>0.1
Hares [49]	Canada	2020	500–1400	27–127	$\geq$ MMP		

Table 2. CCUS-EOR reservoir screening criteria outside China.

Scholar/Institution	Area	Year	Oil Density (g/cm ³)	Oil Viscosity (cP, mPa·s)	Oil Saturation (%)	Net Thickness (m)	Oil Composition	Reservoir Dip Angle (°)
Geffen [24]	United States	1973			>7.6			
Lewin & Assoc [25]	United States	1976	<0.88	<3	>25			
NPC [26]	United States	1976	<0.88	<12	>25			
McRee [27]	United States	1977	<0.89	<10				
Iyoho [28]	United States	1978	<0.85	<5	>25			
Carcoana [29]	Romania	1982	0.8–0.88	<10	>25			
Taber & Martin [30]	United States	1983	<0.82	<2	>30	<15		
Klins [51]	United States	1984	<0.9	<15	>30		C ₅ –C ₂₀	
Rivas [33]	Venezuela	1994	<0.88	<12	>25			
Diaz et al. [34]	United States	1996	0.70–0.93		30–92	1.5–55		5–20
Taber et al. [32]	World	1997	0.79–0.91		8–80	1.5–53		0.03–64
Bachu [35]	Canada	2004	0.8–0.89	0.3–6	15–70		C ₅ –C ₁₂	
Alberta Research Council [52]	Canada	2009	0.79–0.89		>25			
Algharaib [37]	Middle East	2009	0.8–0.89	≤ 6	≥ 30			
Wo et al. [38]	United States	2009	<0.91	<10	>25			
NETL [43]	United States	2010	<0.92	<10				
Aladasani [39]	World	2010	<0.89	≤ 12	>25–30			
Gao & Pan [41]	World	2010	0.8–0.89	<35	15–89			
Koottungal [44]	United States	2014	<0.89	<10				
Yin [46]	United States	2015	0.8–0.89	0.4–6	5–50			
Bachu [21]	World	2016	<0.89	<6	>20	4.5–81		
Zhang et al. [47]	World	2018	0.8–0.92	0.4–6	≥ 20			
Zhang et al. [48]	World	2019	0.83–0.98	0.2–936	30–86	1.6–91		
Hares [49]	Canada	2020	0.79–0.90	<4	>15	4.5–250		

Table 3 shows the statistical analysis of CCUS-EOR reservoir screening criteria outside China. It can be seen that the parameter of temperature ranges in 28–127 °C, while the critical temperature of CO₂ is 31 °C. In this study, the range of temperature is adjusted to 31–127 °C to ensure that the matched reservoirs have certain conditions for CO₂–crude oil miscibility.

Table 3. Statistical analysis of CCUS-EOR reservoir screening criteria outside China.

Screening Parameter	Range
Depth (m)	350–4100
Temperature (°C)	31–127
Pressure (MPa)	$0.9 \text{ MMP} \leq P < P_f$
Porosity (%)	3–37
Permeability (mD)	0.1–4500
Oil density (g/cm ³)	0.79–0.92
Oil viscosity (cP, mPa·s)	0.4–12
Oil saturation (%)	≥20
Net thickness (m)	1.5–250
Oil composition	C ₅ –C ₂₀

Note: P is the initial formation pressure; P_f is the reservoir fracture pressure.

2.2. CCUS-EOR Reservoir Screening Criteria in China

Since 2000, China has accelerated its research and application of CCUS-EOR technology. China National Petroleum Corporation (CNPC) established the first national CCUS-EOR demonstration project in Jilin Oilfield and conducted relevant field tests and large-scale applications in oilfields such as Daqing, Changqing, and Xinjiang. Currently, CCUS-EOR is at a crucial stage of transition from field test to industrialization [10,50]. Compared to the favorable reservoir properties found in North America and other countries, the reservoirs in China are predominantly continental, with strong heterogeneity and low permeability. Furthermore, the reservoirs in China are widely distributed and diverse for varying types and sizes across basins [53]. Additionally, the scarcity of original CO₂ sources and the immaturity of high-concentration CO₂ capture technologies have created a shortage of CO₂ supply, further limiting the number of reservoirs suitable for CCUS-EOR [7,54]. As a result, existing CCUS-EOR reservoir screening criteria are limited in application to reservoirs in China. It is necessary to refine the screen parameters depending on the specific characteristics of reservoirs in China.

Scholars have often determined the required evaluation parameters and their ranges through literature reviews and mechanistic analyses [55,56]. Zheng et al. assigned the screening indices for gas-flooded reservoirs into three categories: oil viscosity, oil density, and oil saturation represent oil properties; permeability, porosity, wettability, and heterogeneity represent rock properties; reservoir depth, temperature, dip angle, and pressure represent reservoir characteristics. They quantified and partitioned these indices using a fuzzy preference model [57]. Xiang et al. applied the CCUS-EOR reservoir screening criteria commonly used in the United States and Canada to screen offshore reservoirs in China and suggested a good prospect for CO₂ miscible flooding and near-miscible flooding in reservoirs in the South China Sea [58]. Liang et al. evaluated 183 reservoirs in the Shengli Oilfield based on the existing screening criteria and defined 18 reservoirs suitable for CCUS-EOR [59]. They also identified a high oil gravity and high oil viscosity as the main factors limiting CO₂ flooding in these reservoirs. On the basis of previous studies, Liao et al. presented the CCUS-EOR reservoir screening criteria for the Changqing Oilfield, which consider heterogeneity and permeability coefficient in reservoir characteristics, and they stated that the reservoirs with a permeability variation coefficient of <0.75 are suitable for CCUS-EOR and the reservoirs with a permeability coefficient (K_h) >10^{−13}–10^{−14} can be selected for CO₂ flooding [60]. Wang et al. applied the U.S. CCUS-EOR reservoir screening criteria to the oilfields in the Ordos Basin, China, and the results showed that the reservoirs in Yanchang Formation are suitable for CO₂ miscible flooding due to high oil

gravity, oil viscosity, and oil composition, but their low porosity, low permeability, low reservoir pressure, and high heterogeneity are unfavorable for CO₂–crude oil miscibility [61]. Jiao et al. believed that injecting a certain volume of CO₂ for a certain duration can facilitate the CO₂–crude oil miscibility [62]. Wang et al., during CCUS-EOR reservoir screening for the Junggar Basin, proposed screening criteria for miscible and immiscible flooding depending on reservoir characteristics [63]. The main differences between the two criteria lie in oil density, oil viscosity, and reservoir depth. He et al. divided the screening indexes for gas-flooding reservoirs into three categories: reservoir oil properties, reservoir tectonic characteristics, and economic factors [64]. Meng et al. selected depth, pressure, temperature, porosity, permeability, oil viscosity, and oil density as screening indices and established the screening criteria for CO₂ miscible flooding and CO₂ immiscible flooding (applicable when the reservoir depth is small and the oil viscosity and density are high) [65]. Wang et al. developed an index screening system comprising 13 parameters based on the existing CCUS-EOR reservoir screening criteria [66]. They indicated that reservoir depth, thickness, initial oil saturation, and sedimentary rhythm have a significant impact on oil recovery, and the geological conditions and reservoir fluid properties carry relatively high weights according to a sensitivity analysis. They selected effective reservoir thickness, reservoir depth, average permeability, temperature, oil density, and oil viscosity as the final screening indices. Yang et al. established the CCUS-EOR reservoir screening criteria according to the characteristics of the reservoirs in the Bohai Bay Basin, and the screening results showed that a total of 613 reservoirs were suitable for CCUS-EOR, with a total potential of 68.3 billion tons, including 45.9 billion tons of potential for miscible flooding [67]. He et al. proposed the screening criteria for three types of CO₂ flooding (miscible, near-miscible, and immiscible) based on the ratio of reservoir pressure to MMP [68]. Wang identified reservoir depth, temperature, original pressure, oil gravity, and oil viscosity as important screening indices and also considered the impacts of porosity and initial oil saturation [69].

Tables 4–7 provide the CCUS-EOR reservoir screening criteria, proposed by Chinese scholars in recent years, for miscible, near-miscible, and immiscible flooding. In general, the CCUS-EOR reservoir screening criteria in China mainly include reservoir depth, temperature, pressure, porosity, permeability, oil saturation, heterogeneity, reservoir dip angle, oil density, oil viscosity, and oil composition. The ranges of various indices are similar for miscible and near-miscible flooding, but the main difference rests in the ratio of reservoir pressure to MMP. When the reservoir pressure falls within the range of 0.8–1 MMP, it is generally considered that the miscibility of CO₂ and crude oil can be improved by increasing the injection pressure and other methods. Table 8 provides a statistical analysis of the parameter ranges in CCUS-EOR reservoir screening criteria. Compared to the screening criteria in other countries, the screening criteria in China additionally consider reservoir heterogeneity and reservoir dip angle, reflecting the impact of reservoir physical properties on the efficiency of CO₂ flooding. Moreover, reservoirs in China have a greater range of depth and temperature for screening and are more diverse in types, making the CO₂–crude oil miscibility more difficult. Therefore, the development of screening criteria for CO₂ immiscible flooding in China has become more urgent.

Table 4. China’s CCUS-EOR reservoir screening criteria for miscible and near-miscible flooding.

Scholar/Institution	Year	Depth (m)	Temperature (°C)	Pressure (MPa)	Porosity (%)	Permeability (mD)
Xiong et al. [55]	2004				5–25	1–1000
Zeng et al. [56]	2005	1200–2500		$0.75 \leq P/MMP \leq 3$	>15	>50
Zheng et al. [57]	2005	800–3500	50–120	15–50	4–30	0.1–500
Shen et al. [70]	2009	800–3500	50–120	8–35		
Wang et al. [61]	2013	200–2500			5–17	0.1–7
Wang et al. [63]	2014	>600	32–120			>1
He et al. [64]	2015	900–3000	<90	$\geq$ MMP		<10
Meng et al. [65]	2016	800–3500	50–120	8–35	4–30	0.1–500
Yang et al. [67]	2017	488–4074	28–127	$\geq$ MMP	3–37	
He et al. [68]	2020	>1000	<120	$\geq$ MMP		>1
Wang et al. [69]	2023	488–4074	28–127	$\geq$ MMP	3–37	

Table 5. China’s CCUS-EOR reservoir screening criteria for miscible and near-miscible flooding.

Scholar/Institution	Year	Oil Density (g/cm ³)	Oil Viscosity (cP, mPa·s)	Oil Saturation (%)	Net Thickness (m)	Permeability Variation Coefficient	Oil Composition	Reservoir Dip Angle (°)
Xiong et al. [55]	2004				5–25	1–1000		
Zeng et al. [56]	2005		<20	30–80				
Zheng et al. [57]	2005	<0.88	<8	>30	3–20		C ₁ –C ₆	0–90
Shen et al. [70]	2009	<0.88	<4	>25		<0.65		>10
Wang et al. [61]	2013	0.795–0.9	<10	>25				
Wang et al. [63]	2014	0.73–0.86	1.3–9	40–56			C ₅ –C ₂₀	
He et al. [64]	2015	<0.92	<188	>20				
Meng et al. [65]	2016	<0.90	<10	>30		<0.75	C ₂ –C ₁₀	
Yang et al. [67]	2017	0.79–0.92	1.5–12					
He et al. [68]	2020		0.4–6	$\geq$ 26.5				
Wang et al. [69]	2023	<0.876	<10	>30		<0.75		

Table 6. China’s CCUS-EOR reservoir screening criteria for immiscible flooding.

Scholar/Institution	Year	Depth (m)	Temperature (°C)	Pressure (MPa)	Porosity (%)
Shen et al. [70]	2009	600–900			
Wang et al. [63]	2014	>550			
He et al. [64]	2015	>900			
Meng et al. [65]	2016	600–900			
Yang et al. [67]	2017	350–2590	28–92	<MMP	17–32
He et al. [68]	2020	>600	<120	<0.8 MMP	
Wang et al. [69]	2023	350–2591	28–92	<MMP	17–32

Table 7. China’s CCUS-EOR reservoir screening criteria for immiscible flooding.

Scholar/Institution	Year	Permeability (mD)	Oil Density (g/cm ³)	Oil Viscosity (cP, mPa·s)	Oil Saturation (%)	Permeability Variation Coefficient
Shen et al. [70]	2009	600–900				
Wang et al. [63]	2014		>0.9	100–1000	30–70	
He et al. [64]	2015		0.92–0.98	<600		
Meng et al. [65]	2016		<0.99	<600	>30	<0.75
Yang et al. [67]	2017		0.92–0.98	100–1000		
He et al. [68]	2020			0.6–592	$\geq$ 30	
Wang et al. [69]	2023	>1	<0.98	<600	>40	<0.55

Table 8. Statistical analysis of screening indices for CCUS-EOR in China.

Screening Index	Range	
	Miscible and Near-Miscible Flooding	Immiscible Flooding
Depth (m)	600–3500	>350
Temperature (°C)	28–127	<120
Pressure (MPa)	≥0.8 MMP	<0.8 MMP
Porosity (%)	3–37	17–32
Permeability (mD)	>0.1	
Oil density (g/cm ³)	<0.92	0.92–0.99
Oil viscosity (cP, mPa·s)	<20	<1000
Oil saturation (%)	>25	>30
Permeability variation coefficient	<0.75	<0.75
Oil composition	C ₂ –C ₁₅	
Reservoir dip angle (°)	>10	

3. Optimization of CCUS-EOR Reservoir Screening Criteria in China

In China, the increasing number of laboratory experiments and studies on CO₂-EOR with great attention and support from the government and petroleum companies for large-scale CCUS projects has deepened the understanding of CO₂ flooding mechanisms, enhanced the application of CO₂-EOR technology, and expanded the range of reservoirs suitable for CO₂ flooding. Under this background, it is necessary to update screening indices and their ranges in China's existing CCUS-EOR reservoir screening criteria, coupled with the results of CO₂ flooding laboratory experiments and pilot projects. Tables 9 and 10 shows the parameters of some CCUS-EOR reservoirs from pilot tests conducted in China. It has been found that, apart from relatively unique low-temperature, low-permeability, and low-pressure reservoirs, the reservoirs in China exhibit depths of 1000–3100 m, temperatures of 45–120 °C, formation pressures of 9–42 MPa, porosity of 6–28%, permeability of 0.1–1600 mD, oil density of 0.78–0.9 g/cm³, oil viscosity of 0.3–12 cP, oil saturation > 30%, and average effective thickness of 1.5–17.7 m. Moreover, most of the reservoirs have a strong heterogeneity, with the oil composition dominated by a C₇+ medium and heavy hydrocarbons, rarely containing light components. The limited records on formation dip angle suggests a range from 1° to 8°. The MMP ranges from 16 MPa to 55 MPa, while most reservoirs have formation pressures below the MMP, primarily favoring CO₂ immiscible flooding.

Table 9. Parameters of CCUS-EOR reservoirs in China.

Study Area	Depth (m)	Temperature (°C)	Pressure (MPa)	Porosity (%)	Permeability (mD)	Oil Density (g/cm ³)	Oil Viscosity (cP, mPa·s)
Daluhu Oilfield in Shengli Oil Area [71]	3147	116	31.56				
Fang 48 fault block [72]	1699	85.9	20.4	14.5	1.4	0.815	6.6
Taizhou formation in Caoshe Oilfield [73]	3065	110	35.9			<0.9	
Zhongnan fault block in Chujialou Oilfield [73]	2962.9		28.943	21.3	241		
Well Shu 101 in Daqing Oilfield [74]		108	22.05			0.78	2.8
Dagang Oilfield [75]	2700		27.21	19.04	300	0.88	6.59

Table 9. Cont.

Study Area	Depth (m)	Temperature (°C)	Pressure (MPa)	Porosity (%)	Permeability (mD)	Oil Density (g/cm ³)	Oil Viscosity (cP, mPa·s)
Well Shu 101 in Yushulin Oilfield [76]	2044	108	22.05	10.8	1.16		3.6
M Oilfield [77]	2880	119.2	30.2	9	6.5	0.865	5.2
Liubei block in Jidong Oilfield [78]	2625	102	29.5	17.05	273	0.794	0.329
Caoshe [79]	3020	107	35.9	13.2	24.8	0.88	7
Fumin [79]	2090	76	20.9	12	854	0.82	2.4
Sa II in Sanan Oilfield [79]	1072	49	11.6	25.3	1165	0.86	8.6
Sa I in Sanan Oilfield [79]	1140	45	12.3	27.6	1628	0.87	9.8
Jingbian [79]	1590	47	12.3	12.8	0.9	0.86	2.5
Huang 3 testing area in Changqing Oilfield [80]		84	15.78		0.3–1	0.73	1.81
Chang 3 reservoir in Weibei Oilfield [81]	550	29.2	2.06	11.2	0.76		6.64
Gao 89-1 block in Shengli Oilfield [82]	2900		42	9.18–14.7	0.29–4.92	0.86	11.83
Chang 4 + 5 reservoir in Wuqi Oilfield [83]		60	15	12.8	0.78	0.78	2.38
Chang 6 formation in Yanchang Oilfield [84]		46	8.9	7–12	0.94	0.79	3.4
M reservoir [85]	2025	75	21.3	16.3	15.7		3.64
A block in CQ Oilfield [86]	2200	75	18	9.8	0.07	0.825	8.73
Fu3 member in Zhangjiaduo Oilfield [87]		107	38	18.2	6.5		4.92
Yan 2 block in Benbutu Oilfield [88]	2550	95	186.27	12.2	9.8	0.64	0.68
Area A in Tahe Oilfield [89]	4600	110.5	128.5	21	733		2.89
North Xinghe block in Ansai Oilfield [90]	1250	48	29.9	10.39	0.61	0.766	2.26
Triassic Yanchang formation in Wuqi Oilfield [91]	2000	72.8	18.5	6.1	3.44	0.78	2.03

Table 10. Parameters of CCUS-EOR reservoirs in China.

Study Area	Oil Saturation (%)	Effective Thickness (m)	Permeability Variation Coefficient/Heterogeneity	Oil Composition	Reservoir Dip Angle (°)	P/MMP	Miscible/Immiscible Flooding
Daluhu Oilfield in Shengli Oil Area [71]				C ₇₊		1.21	Miscible
Fang 48 fault block [72]		6.6				0.37	Immiscible
Taizhou formation in Caoshe Oilfield [73]	30–50		Relatively heterogeneous			>1	Miscible
Zhongnan fault block in Chujialou Oilfield [73]	35		Highly heterogeneous			<1	Immiscible
Well Shu 101 in Daqing Oilfield [74]						<1	Immiscible
Dagang Oilfield [75]		10		C ₁₁₊		1.18	Miscible
Well Shu 101 in Yushulin Oilfield [76]		17.7		C ₈ –C ₂₅	2–4	0.68	Immiscible
M Oilfield [77]						1.12	Miscible
Liubei block in Jidong Oilfield [78]				C ₇₊		0.98	Near-miscible
Caoshe [79]	31	17				1.22	Miscible
Fumin [79]	36	6.1				0.96	Near-miscible
Sa II in Sanan Oilfield [79]	51.7	8.6				0.46	Immiscible

Table 10. Cont.

Study Area	Oil Saturation (%)	Effective Thickness (m)	Permeability Variation Coefficient/Heterogeneity	Oil Composition	Reservoir Dip Angle (°)	P/MMP	Miscible/Immiscible Flooding
Sa I in Sanan Oilfield [79]	45.8	9.2				0.48	Immiscible
Jingbian [79]	48	12				0.52	Immiscible
Huang 3 testing area in Changqing Oilfield [80]			Heterogeneous	C ₂ –C ₁₀		0.98	Near-miscible
Chang 3 reservoir in Weibei Oilfield [81]					1.1	0.13	Immiscible
Gao 89-1 block in Shengli Oilfield [82]		1.5	Highly heterogeneous		5–8	1.45	Miscible
Chang 4 + 5 reservoir in Wuqi Oilfield [83]	55	7.69				0.84	Immiscible
Chang 6 formation in Yanchang Oilfield [84]	42.2	14.1				0.62	Immiscible
M reservoir [85]				Light components		0.78	Immiscible
A block in CQ Oilfield [86]				Light components		0.75	Immiscible
Fu3 member in Zhangjiaduo Oilfield [87]						1.29	Miscible
Yan 2 block in Benbutu Oilfield [88]						0.76	Near-miscible
Area A in Tahe Oilfield [89]		15	0.74	C ₂ –C ₁₅	0.8	1.22	Miscible
North Xinghe block in Ansai Oilfield [90]			Highly heterogeneous	C ₂ –C ₁₅		0.46	Immiscible
Triassic Yanchang formation in Wuqi Oilfield [91]				C ₇₊		1.00	Miscible

By comparison, the average depths and temperatures of reservoirs in China are higher than those of marine reservoirs in other countries. Therefore, the lower limits of screening indices used in China should be adjusted upward accordingly. In China, reservoirs are predominantly tight with a wide range of low permeability and a strong heterogeneity. Moreover, the reservoirs contain crude oil with a higher content of heavy components than reservoirs in other countries, resulting in higher MMP values. So, CO₂ immiscible flooding is the primary mode of CCUS-EOR for such reservoirs. It is believed that China's screening criteria should focus more on the impact of reservoir heterogeneity. An investigation on reservoir heterogeneity relying on the parameters that can quantify the reservoir heterogeneity, such as permeability variation coefficient, can allow for a more rational screening result. The formation pressure referred to in the existing studies is the initial formation pressure, which, however, often changes after multiple rounds of exploitation. Therefore, the current pressure maintenance level can better reflect the relationship between reservoir pressure and MMP. Furthermore, as many reservoirs in China have been developed by water flooding, polymer flooding and other techniques, the selection of residual oil saturation, instead of oil saturation, as the screening index agrees more with the actual reservoir conditions.

To further clarify the screening indices for CCUS-EOR reservoirs in China, the current screening criteria are updated and improved with respect to indices and data. Specifically, the reservoir pressure index is categorized into initial formation pressure, current formation pressure, and pressure maintenance level. In view of oil composition, the molar content of C₂–C₁₅ is analyzed quantitatively. Additional investigation is performed on the characteristic parameters of similar reservoirs or oils. The influence of formation dip on CO₂-EOR has been rarely reported in previous studies and materials, and it cannot be examined sufficiently by using the limited sample size; therefore, it is excluded from the analysis below.

The various parameters impacting CO₂-EOR capabilities are interrelated. For instance, reservoir temperature tends to increase with the depth of the oil reservoir. Therefore, a correlation analysis is considered to explore the relationships between different parameters.

Furthermore, there are numerous indicators influencing the screening criteria, necessitating the categorization of similar indicators to identify the main factors impacting the criteria. Consequently, principal component analysis (PCA) is employed to classify and evaluate the different parameters of the oil reservoir.

3.1. Pearson Correlation Analysis

According to the data of parameters of reservoirs for CCUS-EOR in China, 13 data reflecting relatively complete reservoir information were selected for missing value processing. Based on the assumption of linear correlation, the linear relationships between parameters were analyzed by using the Pearson correlation coefficient. It is defined that two parameters are highly correlated when the absolute value of the Pearson correlation coefficient $|r|$ is >0.8 , moderately correlated when $|r|$ is 0.3 – 0.8 , and not correlated when $|r|$ is <0.3 .

Among the initially selected screening parameters, the data of reservoir temperature, depth, initial formation pressure, current formation pressure, porosity, permeability, and viscosity are integral. Regarding the missing data, the density is supplemented from its linear correlation with viscosity; the permeability variation coefficient is quantified through the description of reservoir heterogeneity; the molar content of C_2 – C_{15} is filled according to its scatterplot relationships with density, viscosity, and MMP. The Pearson correlation coefficient matrix for these processed parameters is shown in Figure 1.

It is found that there is a strong positive correlation ($|r| > 0.85$) between the reservoir depth and the initial formation pressure or current formation pressure, a moderate positive correlation ($|r| > 0.75$) between the reservoir depth and the temperature or permeability, and a moderate negative correlation ($|r| > 0.55$) between the reservoir depth and the residual oil saturation or molar content of C_2 – C_{15} . The reservoir temperature exhibits a strong positive correlation with the initial formation pressure and a strong negative correlation with the residual oil saturation. The current formation pressure and initial formation pressure show similar linear correlations with other parameters. The pressure maintenance level exhibits certain correlations with the current formation pressure, porosity, viscosity, molar content of C_2 – C_{15} , and MMP. The porosity has a strong positive correlation with the permeability and shows a moderate positive correlation with depth and pressure. The permeability shows a positive correlation with depth, pressure, and porosity. The density shows a positive correlation with viscosity and a negative correlation with residual oil saturation and permeability variation coefficient. The viscosity shows positive correlations with pressure maintenance level, density, effective thickness, and MMP. The effective thickness has a positive correlation with viscosity and permeability variation coefficient. The molar content of C_2 – C_{15} exhibits a negative correlation with depth, temperature, and pressure. MMP has a strong positive correlation with current formation pressure and porosity and a positive correlation with temperature and viscosity ($|r| > 0.35$). The Pearson correlation analysis results demonstrate certain correlations among the parameters, allowing for the application of PCA.

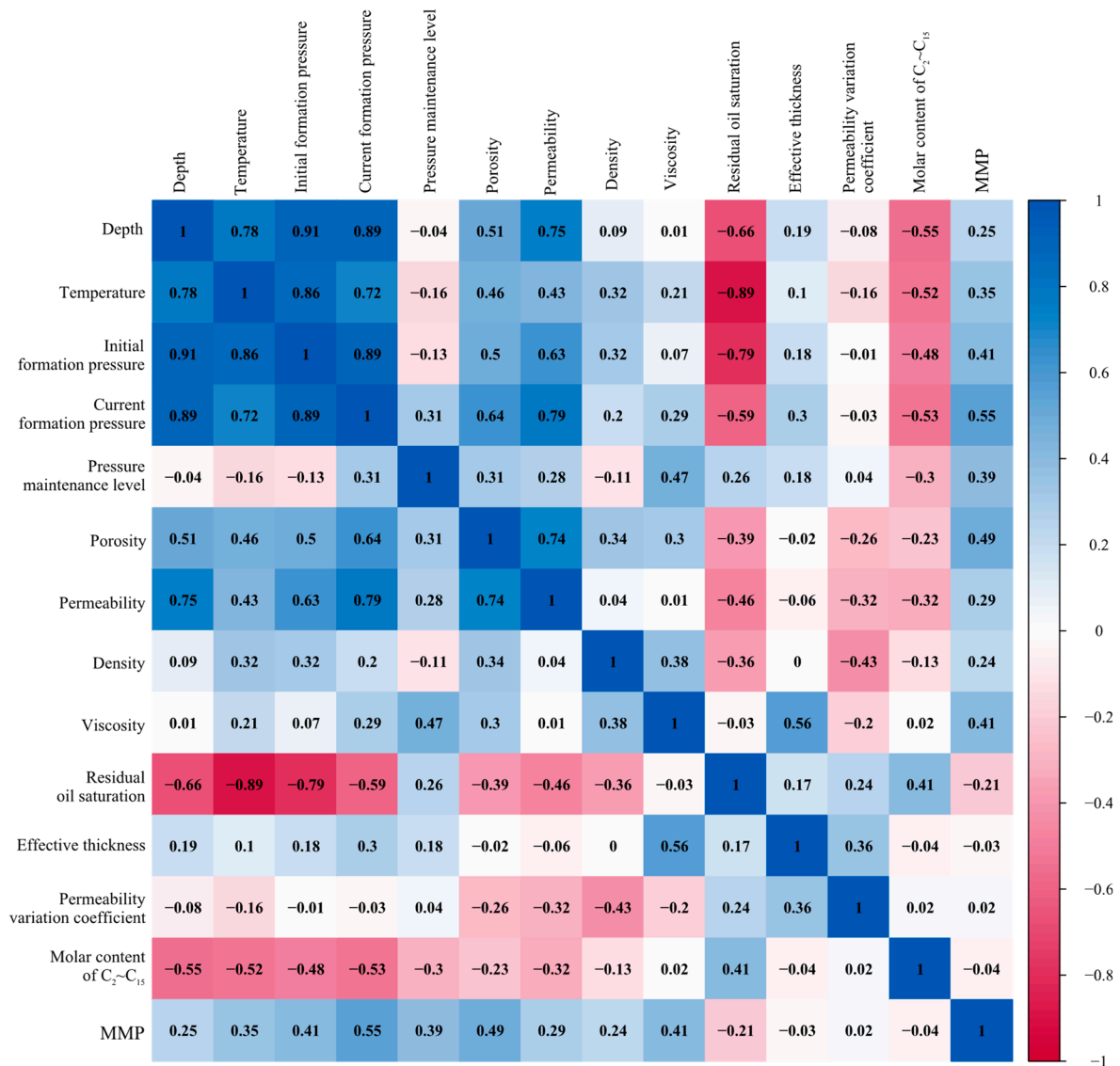


Figure 1. Pearson correlation coefficient matrix for reservoir parameters.

3.2. PCA of Screening Indices

The preliminary linear analysis reveals that most of the parameters are influenced by several other parameters. Therefore, it is necessary to further reduce the dimensionality of the parameters through principal component analysis (PCA) to simplify the data structure. PCA can transform the original variables into a set of mutually uncorrelated principal components through a linear transformation, thereby reducing the dimensionality of variables while retaining most of the information in the original data. It is suitable for dimensionality reduction and data simplification. Essentially, through an eigenvalue decomposition of the covariance matrix of the data, the principal components that explain the variability in the data are identified, and the weights of eigenvalues are determined. The analysis steps are as follows:

- (1) Collect the data of parameters that influence CO₂-EOR and assess the feasibility of PCA.
- (2) Normalize the data and calculate the covariance matrix to measure the correlation between the parameters.
- (3) Perform eigenvalue decomposition of the covariance matrix to obtain eigenvalues and corresponding eigenvectors.

- (4) Select the first few eigenvectors as the principal components and calculate their weights based on the magnitude of their eigenvalues.
- (5) Calculate the component scores by linearly combining the original variables with the selected principal components and their weights.
- (6) Determine the importance and weights of the parameters based on the component scores.

By using the parameters of CCUS-EOR reservoirs in Table 6 as raw data, the characteristic parameters of 25 reservoirs were selected for PCA after excluding the data from Weibei Oilfield with low temperature, low pressure, and low permeability to ensure the stability of the analysis. Before the analysis, missing value processing and supplementation were performed. Based on the Pearson correlation coefficient matrix and the mechanistic relationships between parameters, five indexes with relatively high levels of missing values, i.e., oil saturation, effective thickness, permeability variation coefficient, and molar content of C_2 – C_{15} , were supplemented using methods such as polynomial regression and logarithmic fitting.

According to the data verification results, the Bartlett's sphericity test yields a p -value of 0.000, which is less than 0.05, indicating a suitability for PCA. In the analysis results, the cumulative contribution rate of variance for the first four principal components exceeds 75%, suggesting that relatively little parameter information is lost overall. Therefore, it is considered that these principal components can effectively characterize the CCUS-EOR capability of the reservoirs. The PCA results for the first and second principal components are shown in Figure 2, and the corresponding parameter loadings for the first four principal components are given in Table 11. The analysis reveals that in the first principal component (PC1), the loading coefficients for initial formation pressure, current formation pressure, temperature, depth, residual oil saturation, molar content of C_2 – C_{15} , and MMP are relatively large. This suggests that PC1 can be considered as representing the potential for CO_2 miscible flooding in the reservoir. In the second principal component (PC2), the loading coefficients for porosity, permeability, viscosity, and density are relatively large, mainly characterizing the reservoir's fluid mobility. In the third principal component (PC3), the loading coefficients for effective thickness and permeability variation coefficient are relatively large, representing the influence of reservoir tectonic characteristics on CO_2 -EOR. In the fourth principal component (PC4), the loading coefficient for pressure maintenance level is the largest, primarily reflecting the impact of pressure changes on CO_2 flooding in the reservoir.

Table 11. Parametric component matrix of principal components.

Screening Parameter	PC1	PC2	PC3	PC4
Depth	0.906	−0.105	−0.018	0.015
Temperature	0.929	−0.186	−0.048	−0.149
Initial formation pressure	0.944	0.012	−0.030	−0.059
Current formation pressure	0.931	0.172	0.038	0.170
Pressure maintenance level	0.214	0.417	0.171	0.658
Porosity	0.078	0.860	−0.241	0.157
Permeability	−0.177	0.795	−0.283	0.116
Density	0.217	0.584	0.053	−0.561
Viscosity	0.071	0.716	0.417	−0.377
Residual oil saturation	−0.832	0.161	0.150	0.297
Effective thickness	0.277	0.111	0.857	−0.148
Permeability variation coefficient	−0.038	−0.193	0.644	0.400
Molar content of C_2 – C_{15}	−0.759	0.239	0.151	−0.164
MMP	0.559	0.326	−0.053	0.388

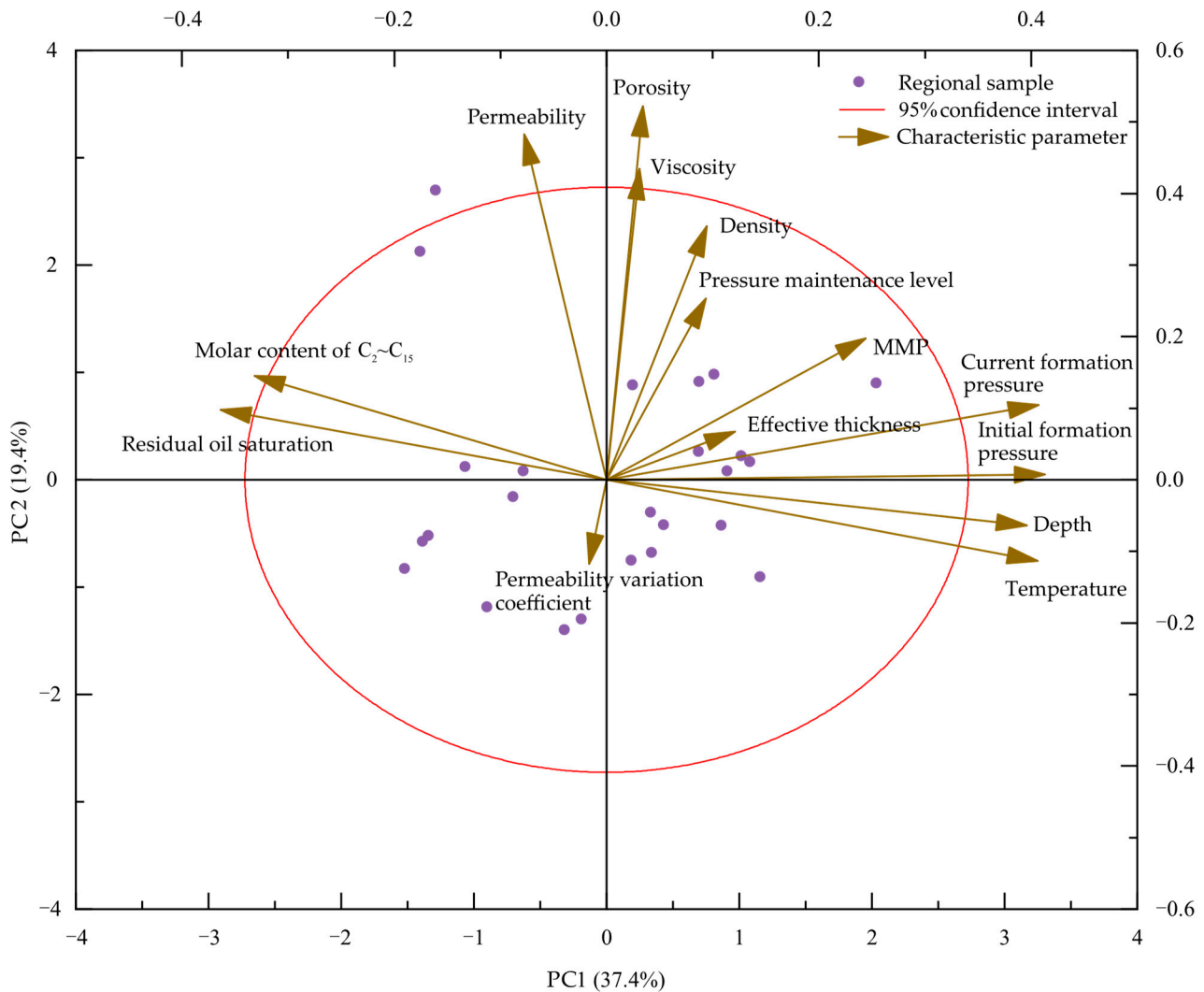


Figure 2. PCA results for PC1 and PC2.

Among the four principal components, PC1 contributes 37.41% to the variance, PC2 contributes 19.37%, PC3 contributes 11.04%, and PC4 contributes 10.22%. This indicates that among the factors influencing the screening of reservoirs for CCUS-EOR, the parameters representing the potential of CO₂–crude oil miscibility have the most significant impact on the reservoir scores, followed by parameters representing the oil mobility. Parameters characterizing reservoir tectonic characteristics and pressure changes have similar influences on the reservoir screening results. Using the coefficient matrix of the principal components, the linear combinations of parameters for different principal components can be obtained based on the weights of each parameter in different principal components. This allows for the calculation of scores for different principal components. By considering the proportion of variance contributed by each principal component, normalized weights for the four principal components can be calculated. The reservoir's comprehensive score can then be obtained by multiplying the corresponding weights with the principal component matrix. Table 12 provides the normalized weights for the first four principal components. The linear combination for calculating the reservoir's comprehensive score is shown in Equation (1):

$$\begin{cases}
 Y_1 = 0.396 * A_1 + 0.406 * A_2 + 0.412 * A_3 + 0.407 * A_4 + 0.094 * A_5 + 0.034 * A_6 \\
 \quad - 0.077 * A_7 + 0.095 * A_8 + 0.031 * A_9 - 0.364 * A_{10} + 0.121 * A_{11} - 0.017 * A_{12} \\
 \quad - 0.332 * A_{13} + 0.244 * A_{14} \\
 Y_2 = -0.064 * A_1 - 0.113 * A_2 + 0.007 * A_3 + 0.104 * A_4 + 0.253 * A_5 + 0.522 * A_6 \\
 \quad - 0.483 * A_7 + 0.355 * A_8 + 0.435 * A_9 - 0.098 * A_{10} + 0.067 * A_{11} - 0.117 * A_{12} \\
 \quad - 0.145 * A_{13} + 0.198 * A_{14} \\
 Y_3 = -0.014 * A_1 - 0.039 * A_2 - 0.024 * A_3 + 0.031 * A_4 + 0.138 * A_5 - 0.194 * A_6 \\
 \quad - 0.228 * A_7 + 0.043 * A_8 + 0.335 * A_9 + 0.121 * A_{10} + 0.689 * A_{11} + 0.518 * A_{12} \\
 \quad + 0.121 * A_{13} - 0.043 * A_{14} \\
 Y_4 = 0.013 * A_1 - 0.125 * A_2 - 0.049 * A_3 + 0.142 * A_4 + 0.550 * A_5 + 0.131 * A_6 \\
 \quad + 0.097 * A_7 - 0.469 * A_8 - 0.315 * A_9 + 0.248 * A_{10} - 0.124 * A_{11} + 0.334 * A_{12} \\
 \quad - 0.137 * A_{13} + 0.324 * A_{14} \\
 Z = 0.479 * Y_1 + 0.249 * Y_2 + 0.141 * Y_3 + 0.131 * Y_4 \\
 T = 60 + 10 * Z
 \end{cases} \quad (1)$$

where Y_1 to Y_4 represent the scores of PC1 to PC4, respectively; A_1 to A_{14} correspond to the normalized values of reservoir parameters from top to bottom as listed in Table 11; Z represents the comprehensive score for an individual reservoir based on its principal components; and T represents the reservoir's comprehensive score after being transformed into T-scores.

Table 12. Weights of the first four principal components.

	PC1	PC2	PC3	PC4
Variance contribution rate (%)	37.414	19.372	11.037	10.215
Normalized weight	0.479	0.249	0.141	0.131

The calculated comprehensive scores for the reservoirs are shown in Figure 3. It can be seen that in the testing areas and projects for CCUS-EOR, reservoirs with high comprehensive scores are mainly suitable for miscible flooding, while reservoirs with low comprehensive scores are more suitable for immiscible flooding. Reservoirs suitable for near-miscible flooding have comprehensive scores at an intermediate level. The comprehensive scores obtained through PCA can effectively reflect a reservoir's CCUS-EOR capability: the higher the comprehensive score, the stronger the oil mobility and the crude oil–CO₂ miscibility; and vice versa. Based on the actual conditions of reservoirs in China and the current range of comprehensive scores in the testing areas, it is considered that a reservoir with a comprehensive score of above 50 points is suitable for CCUS-EOR.

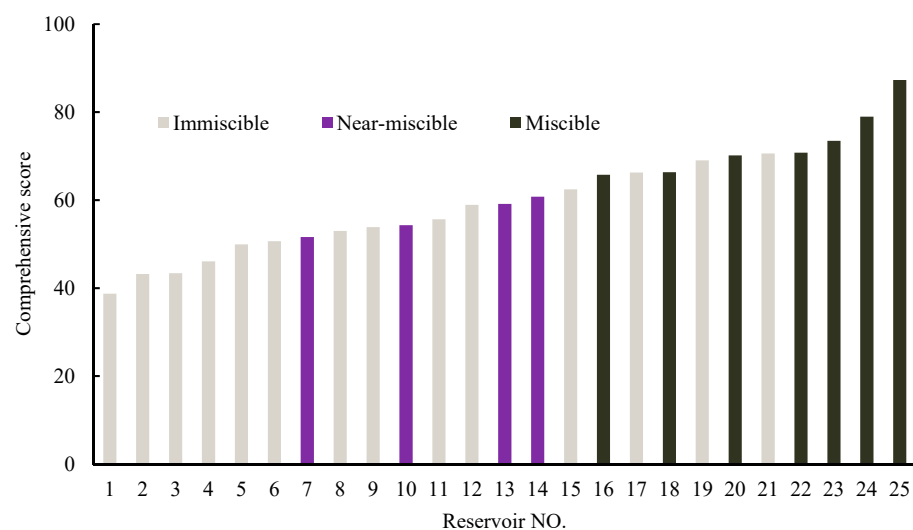


Figure 3. Comprehensive score and ranking of tested reservoirs.

3.3. Results of CCUS-EOR Reservoir Screening Parameter Range and Weight

Based on the results of the Pearson correlation analysis and PCA, it can be determined that the popular CCUS-EOR reservoir screening parameters in China can be mainly categorized into four groups. The first category of parameters represents the CO₂–crude oil miscibility, with a weight of 0.479. These parameters include temperature, depth, initial formation pressure, current formation pressure, residual oil saturation, molar content of C₂–C₁₅, and MMP. Specifically, temperature, depth, and pressure are highly positively correlated and can reflect the reservoir's ability to reach MMP; residual oil saturation shows a certain negative correlation with these four parameters; the molar content of C₂–C₁₅ and MMP can reflect the difficulty of miscibility between CO₂ and crude oil. The second category of parameters mainly represents the mobility of oil within the reservoirs, with a weight of 0.249. These parameters include porosity, permeability, density, and viscosity. A higher porosity and permeability indicate a better diffusion ability of crude oil and CO₂ within the pores. A higher density and viscosity imply stronger interactions at the interface between crude oil and medium. These four parameters also affect the mass transfer and diffusion of CO₂. The third category of parameters primarily represents reservoir tectonic characteristics, with a weight of 0.141. These parameters include effective thickness and permeability variation coefficient. The effective thickness can influence the CO₂ swept volume and sweep efficiency, while the permeability variation coefficient reflects reservoir heterogeneity and affects the CO₂ injection and displacement efficiency, as well as the extent of contact between CO₂ and crude oil. The fourth category of parameters mainly represents the impact of reservoir pressure changes, with a weight of 0.131. The pressure maintenance level can, to some extent, reflect changes in crude oil properties within the reservoir and have a certain influence on the potential of reservoir for CCUS-EOR.

Based on the ranges of selected reservoir parameters in the study areas and correlation analysis, some indices of the CCUS-EOR reservoir screening criteria in China are optimized, and some reservoir parameters with missing values are supplemented through a literature review and correlation fitting. Due to the limited data availability and low representativeness of reservoir dip angle, this parameter is removed from the screening parameters. Instead, two parameters, current formation pressure and pressure maintenance level, are added. Furthermore, the oil composition is changed to the molar content of C₂–C₁₅. The optimized CCUS-EOR reservoir screening criteria in China are shown in Table 13.

Table 13. CCUS-EOR reservoir screening criteria in China.

Weight	Screening Index	Range		
		Miscible Flooding	Near-Miscible Flooding	Immiscible Flooding
0.479	Depth (m)	2750–4600	2550–3050	1072–2963
	Temperature (°C)	107–120	84–102.5	45–126
	Initial formation pressure (MPa)	27–50	18–30.5	7–42
	Current formation pressure (MPa)	23–48	14–22	5–26
	Residual oil saturation (%)	31–40	37–43	27–55
	C ₂ –C ₁₅ molar content (mol%)	40–52	34–48	35–61
	MMP	23–40	16–30	14–55
0.249	Porosity (%)	9–21	8–17	6–27.6
	Permeability (mD)	1–735	0.5–273	0.05–1628
	Oil density (g/cm ³)	0.8–0.88	0.64–0.83	0.77–0.87
	Oil viscosity (cP, mPa·s)	2.9–15.1	0.3–1.8	1.98–9.8
0.141	Average effective thickness (m)	10–60	2–12	1.5–20
	Permeability variation coefficient	0.34–0.96	0.72–0.8	0.7–0.9
0.131	Pressure maintenance level (%)	77–97	64–86	56–110

3.4. Application Cases

Six reservoirs with relatively complete screening index data were selected for a comprehensive score assessment to validate the CCUS-EOR evaluation using the linear combination of comprehensive scores [92–97]. The ranking of the reservoir comprehensive scores is shown in Figure 4. It is found that the Y block in Dagang Oilfield has the highest comprehensive score, with a score of 78.9, while the A block in northern Shaanxi has the lowest comprehensive score, with a score of 45.3. Reservoirs feasible for miscible and near-miscible flooding have relatively high comprehensive scores, while reservoirs that require non-miscible flooding have relatively low comprehensive scores. For example, the Y block in Dagang Oilfield has a current formation pressure of 37.92 MPa, MMP of 35.12 MPa, oil density of 0.77 g/cm³, viscosity of 2.27 mPa·s, C₂–C₁₅ molar content of 43.03%, porosity of 11.75%, and permeability of 17.42 mD, indicating a good CO₂–crude oil miscibility. In contrast, the H block in Jilin Oilfield has a current formation pressure of 23 MPa and MMP of 23.2 MPa, making it suitable for near-miscible flooding; however, it has a relatively high permeability variation coefficient (1.11), resulting in a relatively low reservoir comprehensive score. The remaining reservoirs have current formation pressures below MMP, making the CO₂–crude oil miscibility impossible. Additionally, their permeability is less than 5 mD, which affects the oil mobility, resulting in relatively low comprehensive scores. Overall, only the A block in northern Shaanxi has a comprehensive score below 50, while the other five blocks are suitable for CCUS-EOR. In conclusion, the comprehensive scores of the reservoirs, calculated using the linear combination formula, can accurately reflect the comprehensive potential of the reservoirs for CCUS-EOR, which provide a basis for screening CCUS-EOR reservoirs.

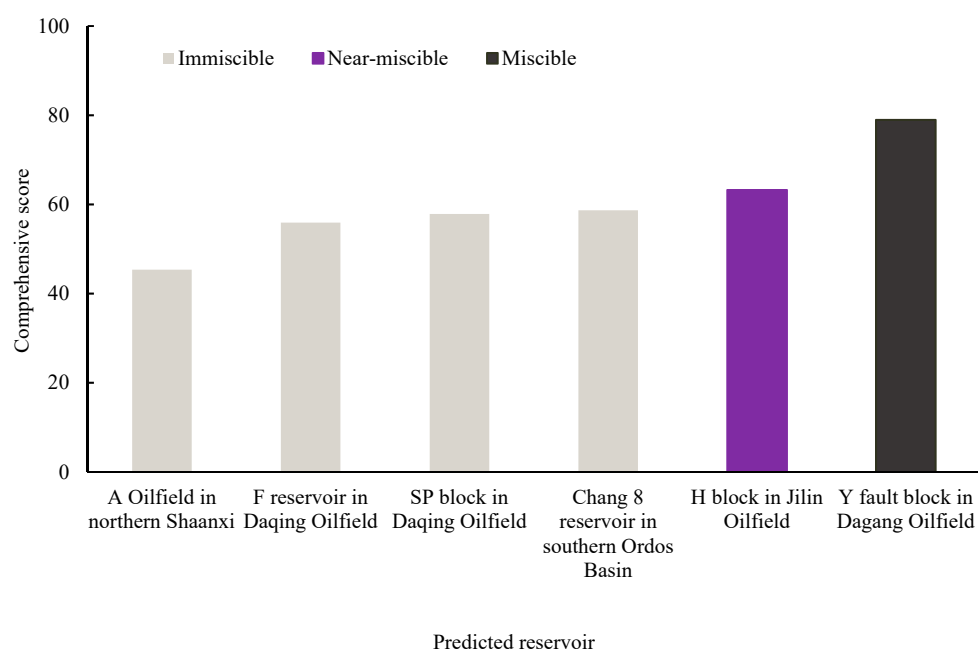


Figure 4. Comprehensive score and ranking of predicted reservoirs.

4. Conclusions and Prospect

Reservoirs outside China are relatively superior in physical properties and mostly contain light to medium oil; therefore, the applicable CCUS-EOR reservoir screening criteria are mainly constructed depending on the characteristic parameters of CO₂ miscible flooding reservoirs. These criteria typically include reservoir depth, temperature, pressure, porosity, permeability, net thickness, oil saturation, oil density, oil composition, and oil viscosity as indices. Specifically, reservoir depth and temperature are mainly used to assist in exploring the relationship between formation pressure and MMP, oil density and oil composition are key factors affecting MMP, and oil saturation reflects the economic potential of reservoirs for

CCUS-EOR. In China, the research and field applications of CCUS-EOR started relatively late, and mainly copied foreign screening criteria initially. However, reservoirs in China are primarily continental with strong heterogeneity, large depth, and high temperature, and they are also diverse in types and characteristics; so, a set of uniform screening criteria is infeasible for these reservoirs. In contrast, the CCUS-EOR reservoir screening criteria in China should incorporate heterogeneity and formation dip angle as indices, since the reservoirs are primarily suitable for CO₂ non-miscible flooding.

Based on the results of CO₂ flooding laboratory experiments and field applications in oilfields in China, the screening indices and their ranges were optimized. Most reservoirs in China exhibit differences between the current formation pressure and the initial formation pressure after years of exploitation. Therefore, when assessing the potential of reservoirs for CCUS-EOR, it is important to consider the influence of pressure maintenance level. Additionally, the oil saturation is replaced with residual oil saturation, and the molar content of C₂–C₁₅ in crude oil is also considered. The results of PCA indicate that China's CCUS-EOR reservoir screening indices can be categorized into four groups by their weights. The first category includes depth, temperature, initial formation pressure, current formation pressure, residual oil saturation, molar content of C₂–C₁₅, and MMP as indices of the CO₂–crude oil miscibility, with a weight of 0.419. The second category integrates porosity, permeability, density, and viscosity as indices of the oil mobility, with a weight of 0.249. The third category involves average net thickness and permeability variation coefficient as indices of reservoir tectonic characteristics, with a weight of 0.141. The fourth category considers pressure maintenance level as an index of reservoir property changes, with a weight of 0.131. By calculating the comprehensive scores of reservoirs based on normalized variables and weights, it is possible to quantify the potential of miscibility crude oil and CO₂ and make a preliminary ranking and assessment on the potential of reservoir for CCUS-EOR.

Compared to other countries and regions, oil reservoir characteristics in China are more complex, with a wider range of crude oil physical properties. It is not sufficient to simply categorize reservoirs into two types based on the miscibility capabilities between CO₂ and crude oil—those suitable for CO₂ miscible flooding or CO₂ immiscible flooding. It is also necessary to consider a third category of reservoirs that fall between these two types. Therefore, the ranges of screening indices are divided with respect to CO₂ miscible flooding, immiscible flooding, and near-miscible flooding. In general, miscible flooding has high requirements for depth, temperature, initial formation pressure, current formation pressure, permeability variation coefficient, and pressure maintenance level. A low MMP of the reservoir allows for miscible flooding. Immiscible flooding has low requirements for depth, temperature, and pressure but requires high residual oil saturation, molar content of C₂–C₁₅, and permeability. Near-miscible flooding requires parameters between miscible flooding and immiscible flooding. Based on the screening criteria established in this paper, a more efficient determination of the development approach for reservoirs undergoing CCUS-EOR can be made. This provides a more effective technical assessment for preliminarily determining the extraction potential of the reservoirs.

Indeed, when the parameters from CO₂ flooding projects in China are used for statistical analyses and PCA, the completeness and representativeness of the data are crucial to the results. For example, reservoir dip angle, a relatively important index, has to be excluded from the analyses because it has been rarely reported in the literature. Moreover, during analyses, the absence of certain reservoir parameters has led to deviations between the results and actual conditions. For instance, the permeability variation coefficients for some reservoirs are estimated based on qualitative descriptions of their heterogeneity. This approach may result in the final range of permeability variation coefficients being narrower than the actual range. Looking forward, it is necessary to complete and update the parameters in China's CCUS-EOR reservoir screening criteria by incorporating more diverse and representative indices, making the criteria more suitable for China's reservoir characteristics. Additionally, the incorporation of parameters such as CO₂ storage capacity,

safety risks, and economic metrics could be instrumental in further evaluating the comprehensive potential of reservoirs for CCUS-EOR. This expansion would significantly enhance the integrity of China's CCUS-EOR screening criteria.

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