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Evaluation of CO_2 enhanced oil recovery and CO_2 storage potential in oil reservoirs of petroliferous sedimentary basin, China

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Abstract. Carbon Capture, Utilization, and Storage (CCUS) technology has emerged as the bottom-line technology for achieving carbon neutrality goals in China. The development of Carbon Dioxide Enhanced Oil Recovery (CO_2-EOR) not only increases revenue for high-investment CCUS projects but also enables permanent CO_2 storage in the oil reservoir. However, the basin is used as the research object to evaluate the CO_2 storage potential of the oil reservoir. The evaluation results are inaccurate and unable to support the implementation of later CCUS projects. Here, more accurate oil reservoir data is employed as the evaluation object. It is the first time at the national level to screen oil reservoirs to distinguish between CO_2 miscible and immiscible, and evaluate the potential of CO_2-EOR and CO_2 storage in the reservoir. The research results show a total of 2570 suitable oil reservoirs in 4386 candidate oil reservoirs nationwide. About 1.26 billion tons of additional crude oil can be produced by CO_2-EOR technology. This includes approximately 580 million tons of additional oil from CO_2 miscible flooding and 680 million tons from CO_2 immiscible flooding. The study further refines the CO_2 geological utilization data and provides a theoretical basis for CCUS project site selection in China.

Keywords: CCUS, CO_2-EOR, CO_2 storage, Oil reservoir, CO_2 geological utilization.

1 Introduction

The impact of human activities on the climate system is definite, and global warming is probably having serious, widespread, and irreversible consequences [1]. To mitigate climate change, the "Paris Agreement" officially came into effect in November 2016, which means that the consensus on reducing greenhouse gas emissions and achieving global temperature rise by no more than 2 °C than before industrialization and working towards 1.5 °C is being gathered at the end of this century. At the general debate of the 75th Session of the United Nations General Assembly on September 22, 2020 China is willing to contribute more to the fight against climate change, as it aims to bring carbon emissions to a peak by 2030, and achieve carbon neutrality by 2060. Climate change can be mitigated through three aspects: (i) improving energy efficiency, (ii) developing renewable energy [2], and (iii) deploying CCUS technology [3]. CCUS technology is regarded as an important part of the technology portfolio to achieve carbon neutrality. It is not only the main technical means to maintain the flexibility of the power system [4, 5], but also a viable technical solution for industries that are difficult to reduce emissions, such as steel and cement. It is the bottom-line technology for achieving the goal of carbon neutrality in China [6].

Although CO_2 capture can be carried out in many places, for instance in power plants, steel plants, and cement plants, it is necessary to achieve permanent separation of CO_2 from the atmosphere in the end. Therefore, CO_2 storage is a key step in the CCUS industrial chain [7]. At present, CO_2 storage mainly includes mineral carbonization, ocean and geological storage [8]. The development of CO_2 geological storage is relatively mature and is considered an important way to reduce greenhouse gas emissions and mitigate climate change [9, 10], including three main types, namely, oil and gas reservoirs, deep saline aquifers

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[11], and unmineable coal seams [12, 13]. The oil reservoir is natural underground gas storage, because of its good airtight conditions, it can achieve long-term storage of CO_2. At the same time, CO_2-EOR technology has been proven to be one of the most effective technologies to increase oil production in oil fields [14–16]. The injection of CO_2 into the oil reservoir will achieve a significant increase in recovery efficiency, thereby achieving a win-win situation for CO_2 emission reduction and utilization [17].

However, not all oil reservoirs are suitable for implementing CO_2-EOR technology, and CO_2 flooding is divided into miscible and immiscible flooding [18, 19]. The current national level of CO_2 storage potential is mostly obtained by evaluating basins as the research object. There is a problem of inaccurate evaluation results, which cannot provide detailed data support for the follow-up of CCUS project implementation. Therefore, more detailed data on the geological utilization of CO_2 is urgently needed to solve the problems of CCUS project source-sink matching [20, 21], CO_2 pipeline network optimization [22, 23], and CCUS technology industry cluster development, especially data on the potential of CO_2-EOR and CO_2 storage that can increase the revenue of the projects, as a basis for optimizing the layout of the CCUS technology industry.

Therefore, the main purpose of this article is to screen the reservoirs suitable for CO_2-EOR and calculate the CO_2 storage potential of the reservoirs suitable for CO_2-EOR in China. Based on the oil reservoir data that has been explored in China, this study answers the following three questions: (1) Which factors are included in the selection of reservoir criteria suitable for CO_2-EOR; (2) Where are the major reservoirs suitable for CO_2 miscible and immiscible flooding; (3) How much oil production can be increased by CO_2-EOR technology, and how much CO_2 can be effectively stored?

Section 2 of this article reviews the literature related to the criteria for selecting reservoirs that can implement CO_2-EOR, as well as the research on the potential of CO_2-EOR and CO_2 storage in China's existing reservoirs. Section 3 summarizes the indicators for screening oil reservoirs, introduces the methods of reservoir CO_2 storage potential, and the compilation of reservoir data. Section 4 describes the evaluation results of this study. Finally, Section 5 concludes this paper.

2 Literature review

The selection of a suitable reservoir for CO_2-EOR is a very important work in the early stages of a CO_2-EOR project [24]. Whether the CO_2 flooding achieves successfully miscible displacement depends on the reservoir pressure and temperature, injected solvent and crude oil compositions [25]. Selecting suitable storage reservoirs can not only reduce the cost of CO_2 flooding and storage but also improve the safety of CO_2 storage and avoid the risk of CO_2 leakage [26]. Most studies summarize and generalize existing CO_2-EOR projects to obtain reservoir suitability screening criteria. Holtz, Nance summarized parameters such as depth, crude oil specific gravity, and porosity of existing project reservoirs, established a decision tree for gas-flooding oil production reservoirs and quickly evaluated suitable CO_2-EOR projects for wells in the Texas reservoir "[27]". In later studies, reservoir screening utilizing parameters such as crude oil gravity, reservoir temperature, and pressure, Minimum Miscibility Pressure (MMP), and residual oil saturation has become an effective method for rapid reservoir screening [28, 29]. With the deepening of research, the screening criteria of the reservoir are continuously refined, which are divided into two screening criteria: miscible and immiscible flooding [30]. Shaw and Bachu [28] summarized 14 screening criteria, which can be used to quickly screen the reservoirs suitable for miscible flooding, and use the screening criteria to screen the reservoirs in Alberta, Canada. The study also points out that the criteria that have the greatest impact on screening are oil gravity, reservoir thickness, and MMP. Oil gravity, reservoir thickness, and MMP are pointed out as the indicators that have the greatest impact on screening in the above study. Whether the reservoir pressure is greater than MMP is considered to be the most significant factor to distinguish CO_2 miscible and immiscible flooding [30, 31]. Zhang *et al.* [32] analysed the CO_2 storage capacity of 15,143 fields and showed that suitable CO_2-EOR potential of miscible flooding in oil fields amounted to 6895 million barrels, with a CO_2 storage potential of about 5.2 Gt in Alberta, Canada. Qin *et al.* [15] reviewed and summarized the CO_2-EOR project carried out in the United States from 2004 to 2014. The comparison and analysis of the application scale and reservoir adaptability of CO_2 miscible and immiscible flooding in the United States are carried out.

Rosiani *et al.* [33] developed a new simultaneous screening model using the interdependence of reservoir parameters. The proposed screening model is compared with 13 real projects to achieve rapid screening of miscible and immiscible flooding in reservoirs. Olukoga and Feng [34] exploited inputs of porosity, permeability, oil gravity and viscosity, reservoir pressure and temperature, MMP and depth parameters. Using a machine learning clustering approach, successfully executed miscible CO_2 flooding projects were classified into clusters of projects with similar fluid/reservoir characteristics. Lv *et al.* [35] added indicators reflecting economic benefits to the standards related to oil well production, forming a new method for selecting low-permeability reservoirs suitable for CO_2 flooding. The step screening method is proposed: technical screening, economic screening, fine feasibility evaluation, and recommendation of optimal gas flooding blocks. The above study proposes criteria and screening procedures for rapid reservoir screening utilizing existing projects around the world. These criteria provide screening criteria for the further study and evaluation of CO_2 miscible flooding and immiscible flooding oil reservoirs in China.

However, there have been few evaluations of CO_2 miscible flooding and immiscible flooding reservoirs at the national level owing to the difficulty of obtaining reservoir data and relevant parameters in China. The previous research mainly focused on the screening and evaluation of miscible flooding and immiscible flooding in a certain petroliferous basin or specific oil field. For the evaluation of reservoirs in the Ordos Basin, Zhao and Liao [36] evaluated the CO_2 storage capacity and EOR potential of the Changqing Oilfield in China by employing parameters such as reservoir pressure, reservoir temperature, and viscosity. The results show that 14 of the 26 wells in the Changqing field are suitable for CO_2 miscible flooding and 12 wells are suitable for CO_2 immiscible flooding. The oilfield has great potential for CO_2 storage and EOR in Changqing. He *et al.* [37] evaluated reservoirs within a 300 km radius of Yulin City. Of the 17 reservoirs evaluated, 9 are suitable for CO_2 immiscible flooding and 8 are suitable for CO_2 miscible flooding. The overall recovery rate is improved, with a recovery potential of 80 Mt and a CO_2 sequestration potential of 130 Mt. He *et al.* [38] adopted reservoir screening criteria to evaluate the feasibility of CO_2 flooding, CO_2-EOR, and CO_2 storage potential of 27 reservoirs in the Yanchang Oilfield. The results showed that in these 27 reservoirs, only 8 can implement CO_2-EOR, and only 1 reservoir is suitable for CO_2 miscible flooding. The CO_2 storage potential of the Yanchang Oilfield is very limited. Wang *et al.* [39] evaluated the CO_2 storage and EOR potential of the medium and low permeability reservoirs in the Gar Basin and concluded that in the 275 development blocks in the Junggar Basin, the CO_2 miscible flooding reservoirs can increase oil production by 125 Mt, and CO_2 non-permeability. Miscible flooding reservoirs can increase oil production by 59 Mt, the CO_2 storage capacity of miscible flooding reservoirs is about 300 Mt, and the CO_2 storage potential of immiscible reservoirs is 175 Mt. Yang *et al.* [31] used reservoir screening criteria to screen the oil reservoirs in the Bohai Bay Basin and obtained 613 reservoirs suitable for CO_2-EOR, of which 354 reservoirs are suitable for CO_2 miscible flooding and 259 reservoirs are suitable for immiscible flooding. With CO_2-EOR crude oil production, 140 Mt can be increased and 225 Mt of CO_2 can be stored. In addition, preliminary studies on enhanced recovery and CO_2 storage potential in offshore reservoirs have been carried out. Li *et al.* [40] proposed a multi-parameter rapid comprehensive evaluation method for the screening and evaluation of offshore CO_2 flooding potential and evaluated the oil reservoirs in the Pearl River Mouth Basin. Li *et al.* [41] used a multi-parameter dimensionless rapid screening model combined with reservoir composition simulation to evaluate the CO_2-EOR and CO_2 storage potential of the HZ2-1 Oilfield in the Pearl River Mouth Basin, and concluded that the HZ21-1 Oilfield can implement CO_2 miscible flooding, CO_2 storage potential is 8.1–10.8 Mt. Li *et al.* [42] assessed the potential of CO_2 sequestration in the major oil and gas reservoirs in the northern South China Sea, and showed that the four major geological basins had overall low, medium and high values of CO_2 storage potential of 1015.8, 1082.7 and 1151.5 Mt, respectively.

The aforementioned CO_2-EOR evaluation for oil reservoirs are limited to research in a certain basin or certain oil fields in China. There is a lack of national-level oil reservoir evaluation, and it is impossible to screen and evaluate Chinese oil reservoirs at the national level. Although there are existing studies on the storage potential of depleted reservoirs and CO_2-EOR at the national level, most national-level reservoir evaluation studies are limited to basin-level or do not distinguish between CO_2 miscible flooding and immiscible flooding [10, 43], and do not employ screening criteria as a national screening of available good data, providing no clear picture of the distribution of CO_2 miscible flooding and immiscible flooding reservoirs in China, as well as the corresponding CO_2-EOR and CO_2 storage potential. Therefore, this study summarized the screening criteria of miscible and immiscible flooding and used the national reservoir database to evaluate the CO_2-EOR potential and CO_2 storage potential of reservoirs using two screening criteria: CO_2 miscible flooding and immiscible flooding in China.

3 Data and methodology

In purpose of screening reservoirs suitable for CO_2 flooding and evaluating CO_2-EOR and CO_2 sequestration potential. In this study, an evaluation method for rapid reservoir screening was developed, which provided indicators for the evaluation of CO_2 miscible and immiscible flooding. For reservoirs suitable for CO_2 flooding, the additional crude oil production and CO_2 storage potential in the reservoir were evaluated by the CO_2-EOR and CO_2 potential assessment models.

3.1 Research framework

The research framework is shown in Figure 1. In the first step, reservoir screening criteria were established based on literature summary and practical engineering experience, and the 18 indicators were identified to distinguish between reservoirs meeting CO_2 miscible or immiscible flooding. In the second step, the 8 determining screening criteria were identified which quickly identify whether the reservoir fulfilled miscible or immiscible flooding. The third step is to carry out an evaluation of 4386 candidate reservoirs. The first step was to determine whether the reservoir was suitable for CO_2-EOR and the second step was to classify the reservoirs that were suitable for CO_2 miscible or immiscible flooding. The fourth step is to estimate CO_2-EOR and CO_2 storage potential in oil reservoirs. Finally, the assessment results were visualised and analysed by *ArcGIS*. The potential and distribution of CO_2 storage in sedimentary basins was obtained. This will provide detailed data for CCUS project deployment in China.

3.2 Data source

The oil reservoir database comes from *Sinopec Group* [44]. The database contains 4386 reservoirs. The database has detailed statistics on oil reservoirs. There is the location of each oil field, including the name, location, and location of the oil reservoir, as well as the basin and the affiliated oil company of each oil reservoir. In terms of recoverable reserves, there is a detailed time when the oil field is discovered, the proven recoverable reserves of the oil reservoir, and the amount of oil that has been exploited. The geographic characteristics of the reservoir are also described in detail, including the gravity of the reservoir, the depth

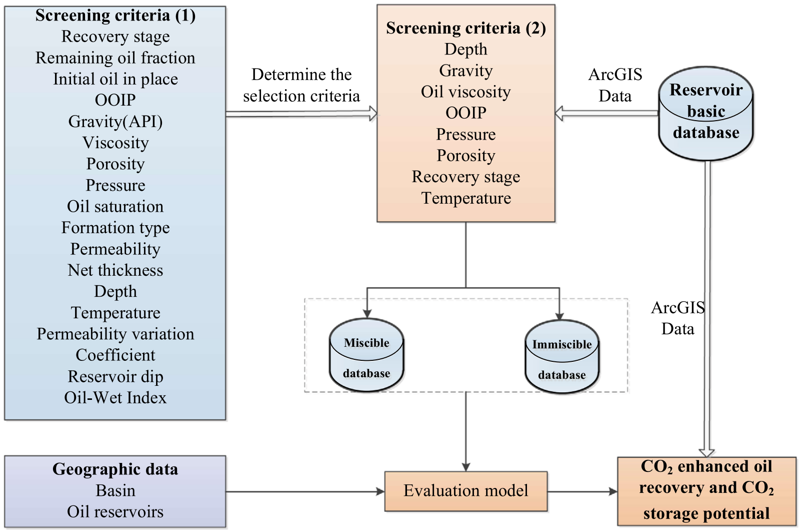

Figure 1. Evaluation framework for CO_2-EOR and CO_2 storage potential.

of the reservoir, the porosity, the good pressure, and the initial oil saturation of the crude oil. Because the database does not contain the temperature of the oil reservoirs, this study calculated the temperature of each oil reservoir according to the depth of the oil layer by the geothermal gradient. See the Appendix for the data of geothermal gradient in China.

3.3 Screening criteria for the CO_2-EOR

The definition of screening criteria is helpful to quickly and preliminarily screen candidate reservoirs [45]. This is also the first step to evaluate the storage potential of Chinese oil reservoirs CO_2-EOR and CO_2 in the reservoir [14]. This article summarizes the selection criteria for suitable CO_2 flooding, as shown in Table 1.

It has been pointed out that of all the reservoir screening criteria, reservoir depth, temperature, crude oil weight, crude oil viscosity, and original pressure are the most important screening criteria, while other screening criteria can be achieved by general reservoirs [46]. Further, CO_2 flooding can be divided into miscible or immiscible flooding according to the state of CO_2 and crude oil in the reservoir. In theory, if the pressure is high enough, CO_2 will be miscible with oil at the reservoir temperature. In this case, the minimum pressure becomes the MMP. If the reservoir pressure is equal to or greater than the MMP, CO_2 will drive oil efficiently under miscible conditions, otherwise, less efficient immiscible flooding will be implemented. According to relevant statistics, if CO_2 flooding can reach the miscible state, the final recovery rate of the oilfield can be as high as 60% to 70%; if the immiscible flooding is used, the final recovery rate of the oilfield can reach more than 50%. Although the efficiency of immiscible CO_2-EOR is lower than that of miscible CO_2-EOR, the relatively commonly used water flooding is still a better oil displacement method [31]. Taking into account the availability of important screening criteria and reservoir parameters, this paper uses the following factors as the evaluation criteria [31, 46], see Table 2 for details.

3.4 Minimum miscible pressure screening

When considering CO_2 flooding, the most concern is whether CO_2 will be miscible with the oil in the reservoir under the current reservoir conditions. Theoretically at MMP the maximum possible oil recovery (~70% in field scenario) can be achieved leading to huge economic benefit [48]. MMP is considered to be a key factor in evaluating whether a reservoir fulfills miscible flooding [49]. If the MMP is lower than the reservoir pressure, it is assumed to be a reservoir that is miscible with CO_2; otherwise, it is a reservoir that is immiscible with CO_2. Since the original formation pressure of all reservoirs cannot be determined, this study defines that the reservoir depth must be greater than 760 m, and the reservoir temperature must be lower than 121 °C, and the original formation pressure can reach MMP [14].

3.5 Calculation of oil viscosity

Crude oil viscosity is an important parameter for screening suitable CO_2-EOR reservoirs [50]. However, not all the crude oil viscosity of the reservoir is available in the reservoir data. Beggs and Robinson [51] proposed to use the depth and temperature of the reservoir and the gravity of the crude oil to estimate the viscosity of the middle crude oil in the reservoir. The detailed calculation process is shown in formula (1) and formula (2)

$$\mu_{\mathrm{od}} = 10^{\mathrm{X}} - 1, \tag{1}$$

where μ_{od} is the viscosity of residual oil, $\mathrm{X} = 10^{3.0324 - 0.02023\gamma_0}\mathrm{T}^{-1.163}$.

The relationship between crude oil viscosity and residual oil viscosity, see formula (2):

$$\mu = A\mu_{\mathrm{od}}^{B}, \tag{2}$$

where μ crude oil viscosity, $A = 10.715(R_s + 100)^{-0.515}$, $B = 5.44(R_s + 150)^{-0.338}$, R_s is the gas–oil ratio of the reservoir.

Table 1. Selection criteria for implementing CO_2 miscible flooding and immiscible flooding [27–31, 36, 38, 39, 41, 45–47].

Reservoir characteristics	Suitable for miscible	Suitable for immiscible
Recovery stage	Primary, secondary, or undeveloped	Primary, secondary, or undeveloped
Remaining oil fraction in the reservoir	≥20%	≥20%
Remaining oil fraction in the reservoir (MMSTB)	≥5	≥5
Initial oil in place (MMSTB)	≥12.5	≥12.5
Gravity (API)	≥22 and ≤45	≥11 and ≤35
Viscosity (mPa·s)	≥0.4 and ≤6	≥0.6 and ≤592
Porosity (%)	≥3 and ≤37	≥17 and ≤32
Pressure (psi)	≥MMP	<MMP
Oil saturation (%)	≥26.5	≥30
Formation type	Sandstone or Carbonate	Sandstone
Permeability (md)	≥1.5 and ≤4500	≥30 and ≤1000
Net thickness	Wide Range	NC
Depth (ft)	≥1600 and ≤13.365	≥1150 and ≤8.500
Temperature (°F)	≥82 and ≤260	≥82 and ≤198
Permeability variation coefficient	≤0.6	≥0.5 and ≤0.55
Oil reservoir dip (°)	>10	NC
Oil Wetness Index	≥0.4 and ≤1	NC

Table 2. Selection criteria for CO_2 in oil reservoirs.

Reservoir characteristics	Suitable for miscible	Suitable for immiscible
Recovery stage	Primary, secondary, or undeveloped	Primary, secondary, or undeveloped
OOIP (MMSTB)	≥12.5	≥12.5
Depth (ft)	≥1600 and ≤13.365	≥1150 and ≤8.500
Oil gravity (°API)	≥22 and ≤45	≥11 and ≤35
Temperature (°F)	≥82 and ≤260	≥82 and ≤198
Oil viscosity (mPa s)	≥0.4 and ≤6	≥0.6 and ≤592
Pressure (psi)	≥MMP	<MMP
Porosity (%)	≥3 and ≤37	≥17 and ≤32
Initial oil saturation (%)	≥26.5	≥30

Note: m = 3.28 ft; kPa = 0.145 psi; C = (°F − 32) × 5/9; mPa s = cP; Crude oil density (kg/m^3) = 1000 × 141.5/(131.5 + °API), 1 STB = 0.159 m^3; MMSTB = Million Standard Barrels. MMP is Minimum Miscible Pressure.

3.6 Calculation of CO_2-EOR and CO_2 storage potential

According to the calculation formula of Dahowski *et al.* [14, 52, 53], the theoretical storage potential of CO_2 enhanced oil exploitation is evaluated.

The existing data only obtains the Ultimately Recoverable Resources (URR) but does not know the Original Oil In Place (OOIP). The OOIP can be calculated by the formula (3):

$$\mathrm{OOIP} = \frac{\mathrm{URR} \times 100}{\mathrm{API} + 5}. \quad (3)$$

In the formula, OOIP is the Original Oil In Place, URR is the Ultimately Recoverable Resource, and *API* is *American Petroleum Institute* gravity:

$$\mathrm{OOIP_c} = \mathrm{OOIP} \times C. \quad (4)$$

OOIPc is the amount of crude oil that can be contacted with CO_2, and C is the contact ratio between CO_2 and crude oil, in this article 75%

$$\mathrm{EOR} = \mathrm{EXTRA} \times \mathrm{OOIP_c}, \quad (5)$$

$$M_{\mathrm{CO_2}} = \mathrm{EOR} \times (P_{\mathrm{LCO_2}} \times R_{\mathrm{LCO_2}} + P_{\mathrm{HCO_2}} \times R_{\mathrm{HCO_2}}), \quad (6)$$

$$\begin{cases} \text{EXTRA} = 5.3 & \text{API} < 31 \\ \text{EXTRA} = 1.3 \times (\text{API} - 31) + 5.3 & 31 \le \text{API} \le 41 \\ \text{EXTRA} = 18.3 & \text{API} > 41. \end{cases} \tag{7}$$

Here, EOR is the amount of crude oil that can be enhanced, and its unit is the same as OOIP, which is the amount of CO_2 that can be stored, called the reservoir's CO_2 storage potential, and the unit is ton; A and B are the lowest and highest probability of displacement coefficient. The corresponding probability values of different depths and crude oil severity are shown in Table 3; A is 2.113 t/m^3, B is 3.522 t/m^3; EXTRA is the ratio of CO_2 enhanced oil recovery, that is, the displacement coefficient and the unit is %.

Table 3. The lowest and highest probability values of displacement coefficient [54, 55].

Depth	API	P_{LCO_2}(%)	P_{HCO_2} (%)
<2000 m	High (>35)	100	0
<2000 m	Low (≤35)	66	33
≥2000 m	High (>35)	33	66
≥2000 m	Low (≤35)	0	100

4 Results

4.1 Suitable distribution of CO_2-EOR reservoir

The distribution of reservoirs suitable for CO_2 miscible flooding and immiscible flooding in China, is shown in Figure 2. The onshore oil reservoirs suitable for CO_2-EOR are mainly concentrated in Bohai Bay Basin, Songliao Basin, Tarim Basin, and Ordos Basin. The offshore oil reservoirs are mainly concentrated in Pearl River Mouth Basin, South Yellow Sea Basin, and Beibu Gulf Basin. There are 4386 candidate reservoirs, of which a total of 2570 reservoirs fulfill the screening criteria. 1556 reservoirs are suitable for CO_2 miscible flooding, and 1014 reservoirs are suitable for CO_2 immiscible flooding. About 56% of the 2579 oil reservoirs suitable for miscible flooding are concentrated in Bohai Bay Basin, and about 11% are distributed in Songliao Basin. The oil reservoirs in Ordos Basin and Junggar Basin account for more than 5% of the total oil reservoirs that can be implemented CO_2-EOR. The number of reservoirs suitable for oil displacement in Erlian Basin, Jianghan Basin, Qaidam Basin, Turpan-Hami Basin, and Tarim Basin account for 1% to 2% of the suitable miscible oil reservoirs, and the other basins are less than 1%.

4.2 CO_2-EOR storage potential

As shown in Figure 3, about 9.2 billion tons of crude oil have been increased by CO_2-EOR, of which 4.2 billion tons of crude oil can be increased by CO_2 miscible flooding, and 5 billion tons of crude oil can be increased by CO_2 immiscible flooding in China. The CO_2 storage potential in oil reservoirs is shown in Figure 4, the total CO_2 storage potential of the reservoir is about 339 million tons in China, of which the CO_2 storage potential of miscible flooding is about 166 million tons, and the CO_2 storage potential of immiscible flooding is about 173 million tons.

From Figures 3 and 4 it is easy to find that the differences in basin sequestration potential are outstanding. In order to better describe the results of the study, we will develop a basin-by-basin description of the CO_2 flooding and storage potential.

In Bohai Bay Basin, there could be 1,440 reservoirs where CO_2-EOR could be implemented, accounting for 56% of the total number of reservoirs. A total of 910 reservoirs can be implemented with CO_2 miscible flooding, which can increase oil production by approximately 15.55 Mt and can achieve CO_2 geological storage of approximately 6.38 Mt. There are 530 reservoirs where immiscible flooding could be implemented, which could increase production by 1769 Mt of crude oil. At the same time, 613 Mt of CO_2 will be storage in the reservoir. These reservoirs are mainly concentrated in northeastern coastal areas of Bohai Bay Basin. The reservoirs where CO_2 flooding is implemented mainly cover the Huabei, Shengli and Dagang oil fields, accounting for approximately 32% of the total CO_2 storage potential in Bohai Bay Basin.

There are 380 reservoirs in Songliao Basin, of which approximately 73% are suitable for CO_2 flooding. Of these, 202 reservoirs are suitable for miscible flooding. It is estimated that 2625 Mt of crude oil could be added and 907 Mt of CO_2 could be stored. Only 75 reservoirs are suitable for CO_2 miscible flooding. The volume of crude oil that could be added is approximately 350 Mt and the corresponding CO_2 storage potential is approximately 123 Mt of CO_2. The main factor that miscible flooding reservoirs are less than immiscible flooding is the shallower average buried depth of Songliao Basin. In Songliao Basin, Daqing Oilfield and Jilin Oilfield (Daqingzijing Oilfield and Da'an Oilfield) are the main oilfields implementing CO_2 flooding, accounting for about 80% of the total CO_2 storage potential of Songliao Basin.

In Ordos Basin, Junggar Basin, Tarim Basin, and Qaidam Basin, the amount of oil enhanced by miscible flooding and immiscible flooding is less than 100 Mt (see Fig. 3). Most of the reservoirs in these basins need to implement CO_2 miscible flooding. Because miscible flooding is more efficient than immiscible flooding. Therefore, these basins are still key areas for the implementation of CO_2-EOR. The most suitable field for implementing CO_2 miscible flooding is Changqing Oilfield, which can increase oil by about 78 Mt, accounting for about 72% of the oil recovery in Ordos Basin, with a CO_2 sequestration potential of about 2.28 Mt. The Karamay Field is the best field in Junggar Basin for the implementation of CO_2 miscible flooding. By applying CO_2-EOR, the oil increase is about 22 Mt and the CO_2 sequestration potential is about 50 Mt. The Taher Field is the best candidate for CO_2 miscible flooding in Tarim Basin, with an oil addition of about 9.5 Mt and a CO_2 sequestration potential of about 29 Mt. The Gaskule Oilfield is the most suitable field for CO_2 miscible flooding in Qaidam Basin. By applying CO_2-EOR, the oil increase is about 10 million m^3 and the CO_2 sequestration potential

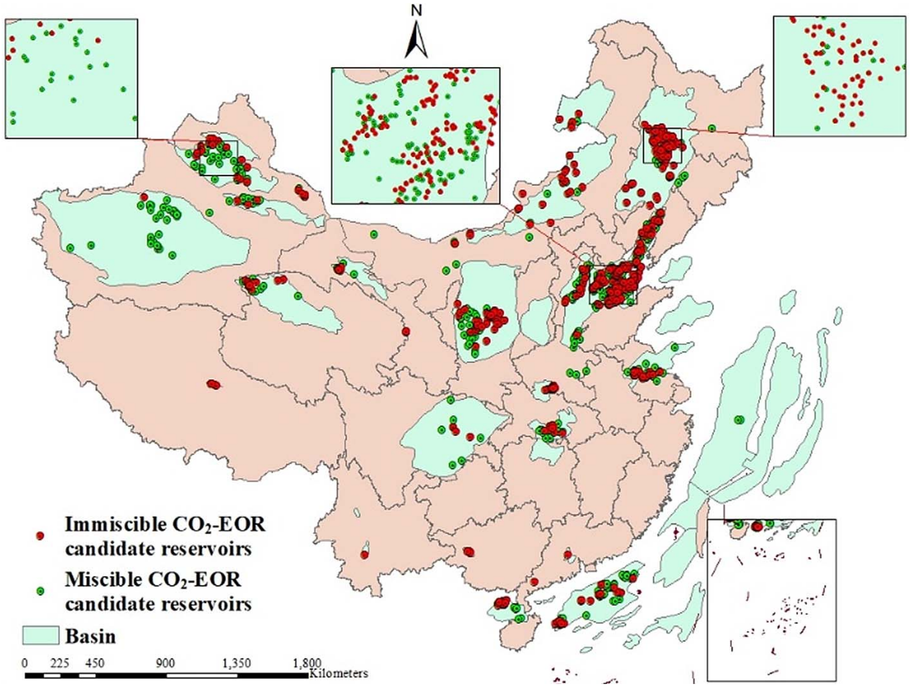

Figure 2. Reservoir distribution suitable for CO_2-EOR in China.

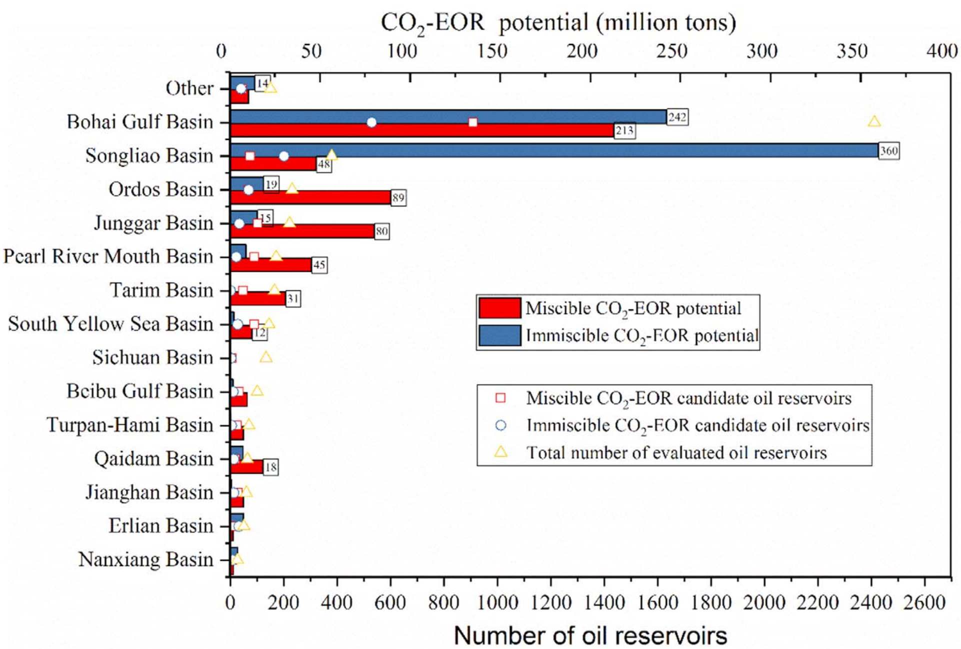

Figure 3. The total number of evaluated oil reservoirs and CO_2-EOR potential in a petroliferous sedimentary basin in China.

is about 30 million m^3. Shanshan Oilfield is the largest CO_2-EOR Oilfield in Turpan-Hami Basin. The field could increase approximately 2.9 Mt of oil and storage of about 8.6 Mt of CO_2.

In addition, the ratio of CO_2 miscible flooding suitable for offshore oil reservoirs is also relatively ideal in China. As shown in Figures 2 and 3, in Pearl River Mouth Basin, South Yellow Sea Basin, and Beibu Gulf Basin, CO_2 miscible flooding can be used to increase oil by approximately 45 Mt, 12 Mt, and 9.7 Mt, the corresponding CO_2 storage potential is 155 Mt, 36 Mt, and 27 Mt, respectively. More than 80% of the reservoirs can be enhanced by CO_2 miscible flooding. For the Pearl River Mouth Basin, The Huizhou Oilfield is the most suitable to implement

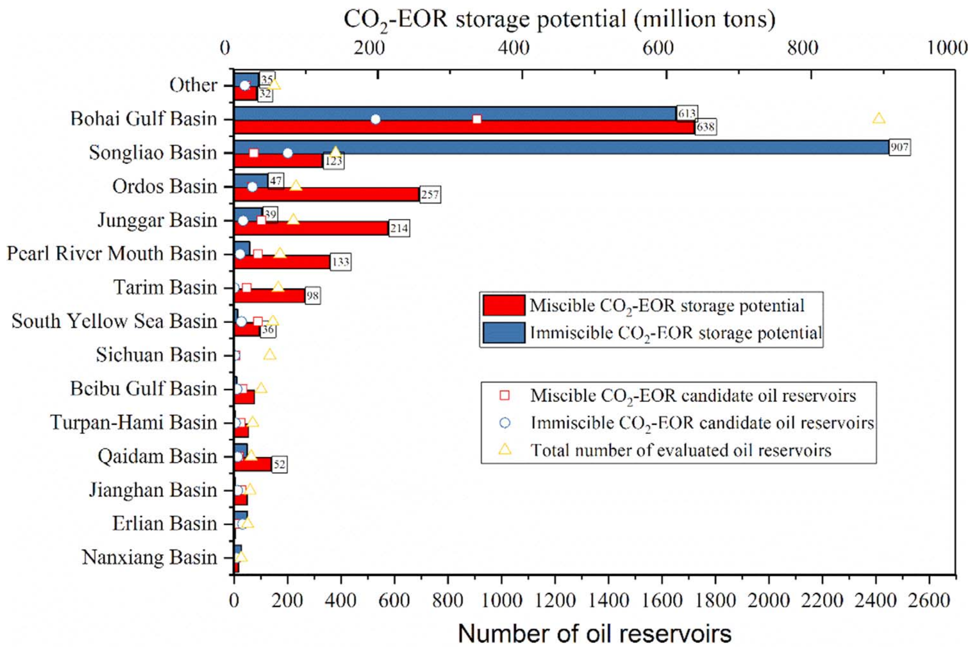

Figure 4. The total number of evaluated oil reservoirs and CO_2 storage potential in a petroliferous sedimentary basin in China.

CO_2-EOR, with the potential to increase 11.5 Mt crude oil and 35 Mt CO_2, respectively; The Sandian Oilfield is the best reservoir for CO_2 miscible in South Yellow Sea Basin. With an oil enhancement and CO_2 sequestration potential of approximately 1.5 Mt of crude oil and 4.7 Mt of CO_2, respectively, the Weizhou Oilfield is the most suitable reservoir for CO_2 miscible flooding in Beibu Gulf Basin, with an oil enhancement of around 5.7 Mt and CO_2 storage potential of about 17 Mt.

5 Discussion

5.1 Comparison of existing results with the results of this research

It is not difficult to find from Table 4 that the previous research based on the data source can be divided into three categories. The first category is for research institutions in China. This type of data source is an evaluation of the CO_2 storage potential based on the data of petroliferous basins in the literature [56]. Compared with this study, the specific geological data of oil wells are unknown, and only basin-level reservoir reserves can be obtained, to obtain CO_2 storage potential. The second type is the evaluation by the US Department of Energy and Chinese research institutions. The data source is the same as the first type of research, but the evaluation method has been improved. The third category is the evaluation of sustainable energy services and innovation companies. The data sources are different compared to the first two types of reservoirs. It comes from the US Geological Survey's assessment of global reservoir reserves in 2000 [57]. The data is more macroscopic. The data is not as detailed as the first two types of reservoirs. The reservoir data in this study comes from *IHS Markit* [44], this database is based on national actual reservoir exploration data. The database performs detailed statistics on the published oil reservoirs. It not only includes the crude oil reserves and geographic location of each oil well, but also includes detailed geological information, such as the depth of the reservoir, the gravity of crude oil, and the porosity of the oil. Therefore, this study obtained the CO_2 storage potential, carried out a screening based on the suitability of the reservoir for CO_2 flooding, and only retained the reservoirs suitable for CO_2 storage. In addition, according to the type of CO_2 flooding, it is divided into miscible flooding and immiscible flooding. These two points can provide more detailed data support for the deployment of CCUS in China, and they are also not available in the above-mentioned three types of research institutes.

5.2 Limitations of this study

The current reservoir screening criteria mainly use geological factors as the site selection criteria [60], and the purpose is to quickly and effectively screen out reservoirs suitable for CO_2 miscible flooding and immiscible flooding. However, there are no clear selection criteria for the economic, safety, social, and environmental aspects of the oil reservoir in the implementation of CO_2-EOR. The scale effect of CO_2-EOR should be considered. The large-scale or cluster implementation of CO_2-EOR can enable efficient use of infrastructure and reduce operating costs from an economic point of view [61], which is more conducive to project implementation. The safety screening criteria are mainly to prevent the damage of geological disasters to the reservoir and cause CO_2 leakage problems [62, 63]. The use of safety screening criteria should avoid areas with a high probability of occurrence of geological disasters such as earthquakes, landslides, and fire activities [64].

Table 4. Comparison of existing research results with the results of this research.

Research institute	Data sources	CO_2 storage potential
Institute of Rock and Soil Mechanics, Chinese Academy of Sciences	[56]	4.6 Gt CO_2
Tsinghua University	[56, 58]	3.6 Gt CO_2
U.S. Department of Energy	[56]	4.6 Gt CO_2
Ecofys	[59]	3.9 Gt CO_2
Oil Production Technology Institute, Dagang Oilfield	[44]	3.4 Gt CO_2

The social screening criteria need to consider the public's acceptance of the CO_2-EOR project. Whether the public accepts the CO_2-EOR project is a key factor that can significantly affect the implementation of the project. Environmental screening criteria mainly consider environmental issues during CO_2-EOR operation. The implementation of CO_2 flooding is accompanied by a large amount of water containing radioactive materials and toxic heavy metals. Without proper waste management and disposal standards, these substances can contaminate the source of drinking water. CO_2 storage screening criteria, adding economic, safety, social and environmental screening criteria is the trend of future CO_2 storage site selection in the future [14, 65].

In addition, with the continuous increase in the level of exploration technology and economic investment, the exploration volume of oil reservoirs has also increased year by year. In the past ten years, oil exploration and development and proven reserves have continued to increase at a high level in China. The CO_2 storage potential and CO_2-EOR displacement estimated in this study are only evaluated based on 2018 data. In the future, with the development of reservoir exploration technology, more reservoirs will be discovered, and the CO_2-EOR and CO_2 storage potential of reservoirs will also increase.

6 Conclusion

This study summarises the existing oil reservoir screening criteria and derives a standard methodology suitable for reservoir data screening. This paper utilises the reservoir screening criteria to screen reservoirs suitable for CO_2-EOR in China, and obtains the distribution of reservoirs with and without CO_2 miscible flooding, as with the corresponding potential for increased crude oil production and CO_2 storage. The main conclusions are as follows:

1. For rapid screening of reservoirs 17 indicators are grouped. These indicators are further classified to obtain a selection of the most critical factors in each category. Of these, crude oil viscosity and gasoline ratio are the key factors for fluid properties; reservoir temperature, pressure and depth are the most critical indicators for reservoirs; reservoir permeability and effective porosity are the central factors for reservoir characteristics. In addition, reservoir depth and MMP are the core elements to differentiate CO_2 miscible flooding from immiscible flooding.
2. The first screening of reservoirs for miscible and immiscible CO_2 flooding in China. The potential for CO_2-EOR and CO_2 storage have been evaluated and calculated. Out of 4386 candidate reservoirs, a total of 2570 reservoirs are suitable for CO_2-EOR. Of these, 1556 reservoirs are suitable for CO_2-miscible flooding and 1014 reservoirs are suitable for CO_2 immiscible flooding. In terms of CO_2-EOR potential, the volume of recoverable crude oil is approximately 1.26 billion tons, with an additional 580 million tons of crude oil recovered with CO_2 miscible drives and 680 million tons of crude oil recovered with CO_2 immiscible flooding. The total CO_2 storage potential of the reservoir is approximately 3.39 Mt, The CO_2 storage potential of the miscible flooding is about 1.66 Mt and the CO_2 storage potential of the immiscible flooding is around 1.73 Mt.
3. On the basis of the distribution characteristics and CO_2 storage potential of reservoirs in China. About 56% of the reservoirs are concentrated in Bohai Bay Basin and about 11% are distributed in 2,579 reservoirs suitable for CO_2-EOR in Songliao Basin. Reservoirs in Ordos and Junggar Basins account for about 5% of the CO_2-EOR that can be carried out. The number of oil reservoirs suitable for oil displacement in Erlian Basin, Jianghan Basin, Qaidam Basin, Turpan-Hami Basin, and Tarim Basin accounts for between 1 and 2% of the number of oil reservoirs suitable for CO_2-EOR, and all other basins are less than 1%. The Pearl River Mouth Basin, the South Yellow Sea Basin, and the Beibu Gulf Basin have 114 (4.4%), 119 (4.6%), and 44 (1.7%) oil reservoirs in offshore basins, respectively.

This study is more specific and detailed in the reservoir data. The reservoirs were screened and evaluated by CO_2 miscible and immiscible flooding and provided data support for the storage site selection of the CCUS project. However, the influence of geological conditions, social economy, natural environment, and other factors are in the actual engineering practice. The final CO_2 storage potential of source-sink matching level still needs further study, which requires the setting and evaluation of a more detailed comprehensive factor indicator system.

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Appendix

Table of average low temperature gradients in major basins and regions in China [66]

$$T_H = \alpha + G \times H$$

T_H is the low temperature at H; α is a constant, which can be found on the table; G is the ground temperature gradient (°C/100m); H is the depth (m).

The gradient data sources in the table are based on borehole temperature measurement data from various petroleum departments, except for the source indicated in the remarks. The low temperature of different depths can be calculated according to the formula.

Table A1. Table of average low temperature gradients in major basins and regions in China.

Basin and area	Geothermal gradient °C $(100\ \text{m})^{-1}$	Constant (α)	Coefficient (γ)
Songliao Basin	3.375	11.933	0.9232
Jizhong (Depression)	3.4	10.22	0.9432
Huanghua (Depression)	3.349	20.88	0.9774
	3.294	16.608	0.9709
Jiyang (Depression)	3.869	11.018	0.9978
	3.308	20.44	0.9823
Linqing (Depression)	3.21	13.632	0.9727
	2.69	22.21	0.9199
Baofeng-Shenqiu-Luyi Depression Area	2.82	16.19	0.9999
	2.35	24.51	0.9997
	2.41	22.57	0.9629
Southeastern (Unite, Tenggeer, Chuanjing Three Depressions)	2.87	18.16	0.9689
Central Sunit Uplift	2.166	16.3	0.99716
Northwest (Manit and Wulanchabu second depression area)	2.94	12.53	0.9766
Northern Jiangsu (basin)	2.64	18.573	0.9639
Nanyang (basin)	3.82	13.31	0.9673
Jianghan (basin)	2.84	25.06	0.978
Sanshui Basin	2.8-7.0	18.808	0.9261
Leizhou Peninsula	3.18-3.85	35.35	0.988
Hainan Island	2.56	29.46	0.9793
Beibu Gulf	3.47	30.622	0.9838
Yinggehai	3.35	27.656	0.9838
Ordos Basin	2.88	9.946	0.9646
Baise Basin	2.73	25.32	0.9801
Junggar Basin	2.016	14.692	0.9744
Tarim Basin	1.764	23.75	0.8689