INTRODUCTION

At present, with the discovery of many low-porosity and low-permeability oil and gas reservoirs, improving enhanced oil recovery (EOR) technology is of great concern. Traditional oil recovery technology using water flooding is limited by the geological conditions of the reservoir, which leads to a low EOR. CO2 flooding technology, which can significantly improve EOR, has emerged. Flooding that uses CO2 can reduce the viscosity of crude oil, improve the fluidity ratio of crude oil to water, and greatly expand the volume of crude oil, which significantly improves EOR. CO2 flooding is less restricted by geological conditions and applies not only to conventional oil reservoirs but also to low-permeability and ultralow-permeability oil reservoirs. The remaining oil in abandoned waterdrive oil reservoirs can be extracted. The combination of carbon capture and carbon sequestration with oilfield oil recovery projects has partly mitigated the impact of the US withdrawal from the Paris agreement on reducing global carbon emissions. At present, CO2 flooding is one of the most widely used technologies used by countries to improve EOR. China is the world’s largest carbon emitter. Under the framework of the Paris Agreement, China has put forward four major objectives for effectively controlling the total amount of carbon emissions. Therefore, in order to achieve this goal,
injecting CO₂ underground is an important means. Since 2015, we have been injecting CO₂ underground in the target oil field. With the fluctuation of international oil prices and the compression of profit space, there is controversy about whether this activity can continue to operate, so this paper evaluates the economic benefits of this activity.

CO₂ flooding has become an effective way to achieve a win-win situation in economic development and environmental protection. The prospect of realizing resource utilization from greenhouse gases and improving EOR is promising. Many scholars have also studied CO₂ flooding, but mostly at the technical level, such as the mechanism, influencing factors, and effects. And the indicators are relatively simple and less systematic. Zhou et al¹ used slim-tube, component analysis, and microscopic simulation experiments to analyze the phenomena of reservoir blockage and a drop in the oil production rate and determined the reservoir blockage mechanisms in the process of CO₂ flooding. Cao et al² optimized four parameters (CO₂ pressure, simulation temperature, reaction time, and concentration of reactants) through an orthogonal experiment and determined the most appropriate conditions for four parameters. Abass et al³ used a fully compositional simulation model to predict the impact of CO₂ miscible flooding on reservoir oil recovery and net present value (NPV) and concluded that the best mode of operation is WAG (Water Alternating Gas), instead of straight CO₂ injection.

P city reservoir belongs to Sinopec, located in Puyang, Henan. P1-1 well group in the P city was developed in the 1980s. Degree of oil recovery is 50.04% at early 21st century and water cut reached 98.44%. It basically entered the stage of waterdrive abandonment. Since then, the rate of water cut is still accelerating, P city reservoir has entered a period of ultrahigh water-cut development. As a deep-bed, high-pressure, and ultralow-permeability reservoir, waterflooding is difficult to improve EOR. After the CO₂ flooding pilot experiment was carried out in the P city reservoir and positive effect has been achieved, it provides a new way for the high water-cut reservoir of P city to further improve the EOR.

In this paper, taking the P1-1 well group in the P city reservoir as an example, the development effect of CO₂ flooding is evaluated from three perspectives: technical, management, and economic benefits. This involves many evaluation factors, and they are complex, and most of the indicators are qualitative, with ambiguities and uncertainties. Therefore, this paper uses a combination of the analytic hierarchy process (AHP) method and the fuzzy comprehensive evaluation method to construct an evaluation system. The AHP method is used to weight the evaluation indicators, and we use the Gaussian, triangular, and trapezoidal membership function models to determine membership in the index; finally, the maximum membership degree method is used to judge the results.

Section 2 gives an introduction to fuzzy evaluation theory. Section 3 constructs a fuzzy comprehensive evaluation index system, including the analysis of factors and the calculation of indexes affecting development effect of CO₂ flooding. Section 4 is based on the AHP method to weight evaluation indicators. Section 5 explains the membership function to calculate the index membership. In Section 6, we calculate the final result and make judgments based on the previous calculation results.

2 FUZZY EVALUATION THEORY

Zadeh (1965)⁴ proposed using a “membership function” to describe the intermediate positions in a transition from one full state to another, which marked the birth of fuzzy mathematics. The fuzzy comprehensive evaluation method is a systematic analysis method that uses the principle of fuzzy mathematics to analyze and evaluate “fuzzy” things. It uses the AHP to determine a multilevel evaluation index system, most of which are suitable for multifactor and multilevel complex problems, and its evaluation effect is difficult to replace with other branches of mathematics and models. This type of analysis and evaluation method is mainly based on fuzzy reasoning, which combines a qualitative and quantitative analysis and accurate and imprecise analysis. The fuzzy comprehensive evaluation method selects a set of factors and determines the alternative evaluation set based on the characteristics of the objects evaluated, to show the subordinate relationship between the elements in the set of factors and the elements in the alternative set, and establishes a fuzzy evaluation matrix, which, combined with the weight of each factor, is used to calculate the comprehensive evaluation vector and comprehensive evaluation value. This method has recently been widely used in many fields and has good economic and social effects because of its unique advantages in dealing with various complex system problems that are difficult to describe accurately with mathematical methods.

The fuzzy evaluation method has been used for various purposes, including economic effect evaluation, performance evaluation, risk assessment, environmental quality assessment, and decision-making. The membership function varies based on the specific research goal. Wang et al⁵ used a symmetric triangular fuzzy set to describe fuzziness in stock investors’ thinking. Qu et al⁶ used a trapezoidal membership function and a ridge membership function to calculate the membership degree of the indicators and conducted a comparative analysis to comprehensively evaluate the DSM (Demand Side Management)’s effect. In addition, Sivaraman et al⁷ used trapezoidal membership functions in the study of multicriteria decision-making. Wu and Yang⁸ adopted the Gaussian function as the membership function in a credit evaluation of logistics enterprises, because the credit degree of enterprises
is relatively concentrated. Relatively few enterprises have extremely high or low credit quality, which is consistent with the characteristics of a normal distribution. Zhao et al. used parabolic distribution as the membership function for an evaluation index on the social cost of construction projects. In addition to these commonly used membership functions, some scholars have designed different methods for determining membership by combining the fuzzy evaluation method with other methods. For example, Wang applied the theory of set-pair analysis to propose a new model for evaluating the economic effect of industrial enterprises based on the degree of relationship membership. Wang and Yang constructed a performance evaluation model of the green agricultural product supply chain by combining the gray clustering method with a fuzzy comprehensive evaluation and using the albino weight function to determine the membership matrix.

The trigonometric (Figure 1) and trapezoidal (Figure 2) membership functions are relatively simple and require less data to calculate the model, so the calculation is easier. However, because of their simplicity, sometimes they cannot make full use of the information in the data, and to some extent they have difficulty in reflecting objective reality. When the Gaussian function (Figure 3) is selected as the membership model, the index distribution must be high, and the evaluation index can be less extreme and relatively concentrated, which is consistent with the characteristics of a normal distribution. Similarly, the parabolic distribution has the same requirements for the index distribution. When the value of the evaluation index is lower than the reference value, the index size is positively correlated with the evaluation result, and when the value of the evaluation index is higher than the reference value, the index size is negatively correlated with the evaluation result, so it is more reasonable to choose the parabolic distribution as the membership function.

Fuzzy comprehensive evaluation quantifies all indexes on the basis of a comprehensive consideration of all technical indexes, taking into account all types of characteristics and factors that are relevant, and distributes the weight coefficient based on the degree of influence of different indexes, to yield a quantitative comprehensive evaluation value. The steps in the fuzzy comprehensive evaluation method are as follows:

1. Establish the factor set \( U = \{u_1, u_2, \ldots, u_n\} \). Factors are all types of properties or performance levels of objects. In different situations, they are also called parameter indexes or quality indexes. They comprehensively reflect the qualities of objects, so they can be used to evaluate them.
2. Establish the evaluation set \( V = \{v_1, v_2, \ldots, v_n\} \), that is, the level set of evaluation objects. Evaluators design evaluation indicators based on specific principles, and then classify and summarize them. In general, they can be divided into 3-5 levels. We divide them into five levels: good, relatively good, medium, relatively bad, and bad.
3. Establish single-factor evaluation and fuzzy mapping from \( U \) to \( V \).
4. In the factor set of comprehensive evaluation, various factors make different contributions to the comprehensive performance of \( \text{CO}_2 \) flooding injected in abandoned water-drive reservoirs, so different weights should be assigned to each factor, and then, the effect should be evaluated based on the comprehensive evaluation model constructed. If the evaluation result is not 1, the result should be normalized.

These four steps consist of two key tasks: the construction of a single-factor evaluation matrix and the determination of a weight distribution set. Although no unified format exists, statistical tests or expert scoring methods are generally used.
3 | FUZZY COMPREHENSIVE EVALUATION INDEX SYSTEM

3.1 | Principles of evaluation index system design

The basis of our comprehensive evaluation and a basic guarantee of accurate and reasonable evaluation results are the implementation effect evaluation index of CO₂ flooding injected into abandoned waterdrive reservoirs. We construct this scientific, standard, systematic, and normative index system by combining a technical index with a management index and an economic index with a noneconomic index, so that we can comprehensively and objectively reflect the implementation of a miscible flooding test. Based on the characteristics of CO₂ flooding injected in abandoned waterdrive reservoirs and the characteristics of an evaluation index system, the construction of such a system should follow the following principles.

3.1.1 | Scientificity

Scientificity is the most basic principle. The evaluation technology used by Hu et al. involves 15 indicators in three aspects (technology, economy, safety, and environmental protection). They formulated the evaluation criteria of some critical indicators based on the data. Some scholars have constructed reservoir model with different influencing factors to study the effect of the CO₂ flooding through flooding experiments. Xiong et al. chose seven characteristic parameters of reservoir for evaluating suitability of CO₂ miscible flooding. They presented a new method of ranking reservoirs for CO₂ miscible flooding based on fuzzy analytical hierarchy process (FAHP). We construct a scientific index system based on existing research by Chinese and other scholars.

3.1.2 | Operability

The design of the index system should be as clear as possible. The indexes selected, whether qualitative or quantitative, should be operable, and the data should be easy to collect. In addition, the indexes selected should be simplified; that is, the design of the evaluation index system should not be too complicated. Under the condition that the objectivity and comprehensiveness of the evaluation results can be basically guaranteed, the index system should be simplified as much as possible, and indexes that have little impact on the evaluation results should be reduced or removed.

3.1.3 | Dynamic continuity

The field test for CO₂ flooding involves a process of dynamic development and continuous improvement. Therefore, the construction of the index system must reflect not only the current situation indexes but also the development trend and potential indexes of the CO₂ flooding test. The selection of indexes should consider a combination of static indexes and dynamic indexes. Static indexes should be used to reflect the current status and level of the CO₂ injection test, and dynamic indexes should be used to reflect its prospective development.

3.1.4 | Comparability

The purpose of constructing an evaluation index is to objectively assess the implementation effect of CO₂ flooding injected into abandoned waterdrive reservoirs, determine the gaps, and propose improvement measures. Therefore, the index system must be able to objectively compare the field test levels of CO₂ flooding in the target reservoir in P city, so as to guide the work of CO₂-EOR.

3.1.5 | Systematicness

The evaluation index system of the implementation effect of CO₂ flooding must be able to comprehensively reflect the current situation in EOR and evaluate the EOR of CO₂ flooding in all respects, because the EOR of CO₂ flooding involves not only material factors but also social benefit factors, such as reducing CO₂ emissions. It is necessary to comprehensively and systematically reflect the EOR effect of CO₂ flooding, so as to guide the construction of EOR in the future.

3.1.6 | Independence

When designing an evaluation index, we should try to avoid the obvious internal relationship among the indexes, weaken and eliminate implicit correlations, strive to create independence between them, and minimize their overlap.

3.2 | Analysis of factors affecting the development effect of CO₂ flooding

To fully and accurately evaluate the development effect of CO₂ flooding injected in abandoned waterdrive reservoirs, first we need to analyze the main factors affecting the development effect of CO₂ flooding, which we approach in terms
of three indexes: technical index, management index, and economic benefit index.

When the actual value of an indicator is between the standard values of two rating set elements, we cannot determine which evaluation set the actual value belongs to. So, we determine the membership degree of the two evaluation standard values, and the closer the actual value is to the standard value, the greater the degree of membership, and vice versa.

3.2.1 Analysis of technical factors in the development effect of CO2 flooding

1. Total CO2-oil exchange rate

The CO2-oil exchange rate refers to the increment of oil production with the injection per unit volume of CO2, which is the main index for evaluating the effect of CO2 flooding. The less CO2 that is needed for each additional ton of oil production, the more feasible is the CO2 injection to develop the oilfield.

Based on experience in the development of oilfields, the average value of total CO2 oil exchange rate is 2400 m³/ton (10.453 m³/ton under formation conditions), and the majority is in range of 6.53-10.89 m³/ton (under formation conditions). The evaluation standard for the total cumulative oil change rate is in Table 1.

2. Comprehensive injection and production ratio

The comprehensive injection and production (I-P) ratio is an important parameter for reflecting the formation depletion state in the injection stage. According to PetroChina’s “Oilfield Development Management Outline,” the annual I-P ratio of oilfield development must be maintained at about 1.0. The literature on CO2 flooding published outside China shows that it is appropriate to maintain an I-P ratio of between 0.75 and 1.25. See Table 2.

3. Total enhanced oil recovery

Based on the trend in the total EOR-pore volume (PV) curve, the oil recovery increase status evaluates whether oil production is developing according to predictions, so as to judge the effect of oil recovery. Displacement efficiency is an important parameter related to evaluation of the CO2 flooding effect and the basis for evaluating the effect of flooding. In CO2 flooding projections, an increase in displacement efficiency means the difference in displacement efficiency between CO2 flooding and water flooding. Statistics on mines outside China show that the increase in displacement efficiency is usually 3%-22%, with the majority 5%-15%. Based on this, the displacement efficiency evaluation criteria for CO2 flooding are in Table 3.

4. Accomplishment of production target

If oil recovery exceeds the level projected in the development plan, the effect is evaluated as good. If it achieves the projected level, the effect is evaluated as medium. If it does not reach the projected level, the effect is evaluated as bad. These three evaluations are quantified by the time it would take to go from the level actually achieved to the projected level. The evaluation standard is in Table 4.

5. Sweep efficiency of CO2 flooding

The sweep efficiency of CO2 flooding reserves—which consists of areal sweep efficiency and vertical sweep efficiency—is an important factor that affects evaluation of the development effect. Both should be considered when evaluating the effect of CO2 flooding.

Areal sweep efficiency is the ratio of the CO2 flooding areas to the total oil-bearing reserve areas that can be affected by injected gas under the current well pattern. The evaluation standard areal sweep efficiency of CO2 flooding is in Table 5.

Vertical sweep efficiency is the ratio of total liquid production thickness to the total thickness of oil wells. Combined with the water flooding reserve-producing degree standard, the evaluation standard for the vertical sweep efficiency of CO2 flooding is listed in Table 6.

6. Breakthrough time

The breakthrough time for CO2 flooding is a very important index for evaluating projections of CO2 flooding. To a certain extent, the breakthrough time reflects the physical properties of the formation, which is closely related to and can also reflect the development effect of flooding. Statistics on CO2 flooding in mines published outside China indicate that most projects, including those for secondary and tertiary

| Evaluation index | Good | Relatively good | Medium | Relatively bad | Bad |
|------------------|------|----------------|--------|---------------|-----|
| CO2-oil exchange rate (m³/ton) | <6.53 | 6.53-7.84 | 7.84-9.58 | 9.58-10.89 | >10.89 |
flooding oil extraction, have experienced early breakthrough of CO₂, which generally occurs between 0.05 PV and 0.2 PV and before 0.1 PV injection of CO₂. Based on this, the evaluation standard for the breakthrough time of CO₂ injection is listed in Table 7.

### Evaluation Criteria for Breakthrough Time of CO₂ Flooding

| Evaluation index | Good | Relatively good | Medium | Relatively bad | Bad |
|------------------|------|-----------------|--------|----------------|-----|
| Breakthrough time (PV) | >0.3 | 0.2-0.3 | 0.1-0.2 | 0.05-0.1 | <0.05 |

#### 7. Total carbon storage rate

In CO₂ flooding projects, the storage rate of CO₂ is the percentage of the storage volume in the total CO₂ injection volume that is also related to the treatment of CO₂ and environmental protection. In a balanced I-P ratio, a higher carbon sequestration rate means greater oil scavenging efficiency. Based on the statistics on the gas storage rate in other countries, 55% of the projects have a gas storage rate of 50%-75%. Based on this, the evaluation standard for the cumulative gas storage rate is listed in Table 8.

### Evaluation Criteria for Total EOR Increased Status of CO₂ Flooding of Total Enhanced Oil Recovery

| Evaluation index | Good | Relatively good | Medium | Relatively bad | Bad |
|------------------|------|-----------------|--------|----------------|-----|
| Total EOR (%) | >13 | 10-13 | 8-10 | 5-8 | <5 |

#### (2) Analysis on management factors of CO₂ flooding development effect.

1. Opening rate of injection and production wells

The comprehensive well opening rate of I-P wells refers to the utilization rate of I-P wells and the production time rate.
According to the industry standard “classification of oilfield development level,” the comprehensive production time rate of I-P wells in low-permeability sandstone reservoirs is required to be ≥70% for waterdrive I-P wells in first-level development, ≥60% and <70% in second-level development, and <60% in third-level development. Combined with the standard comprehensive production time rate of I-P wells, the evaluation standard for comprehensive production time rate of I-P wells can be analyzed as in Table 9.

2. Effective rate of old well measures

The effective rate of old well measures in low-permeability sandstone reservoirs is required to be ≥70% for waterdrives in first-level development, ≥60% and <70% effective rate in second-level development, and <60% for old well measures in third-level development. Combined with the efficiency standard for old well measures, the evaluation standard for the efficiency of CO₂ flooding old well measures can be analyzed as in Table 10.

3. Response time

Response time refers to the time from the beginning of CO₂ injection to the beginning of oil production. The response time of increased CO₂ oil production reflects the effect of CO₂ flooding to a certain extent, and it is an important index for evaluating CO₂ flooding. Early response does not mean the effect is better, but it may indicate the problem of poor oil scavenging efficiency. Experience in other countries shows that it is suitable for producing the desired result when CO₂ injection is 0.05-0.1 PV. Based on this, we can obtain the evaluation standard for breakthrough time as in Table 11.

4. Formation pressure maintenance level

The pressure maintenance level of formation is an important indicator for reflecting the natural energy and the degree of miscibility (immiscible, near-miscible, or miscible), which is important because the pressure directly affects the miscibility of injected CO₂. According to US statistics on 18 successful CO₂ miscible flooding mines, the range of formation pressure higher than the minimum miscible pressure (MMP) is 0.49-1.89, with an average of 1.08. According to statistics in China, the formation pressure is often below the MMP. Based on this, the evaluation criteria for the pressure maintenance level are obtained as in Table 12.

(3) Analysis on economic factors of CO₂ flooding development.

Oil and gas fields have an extremely complex development process, and each step has a huge impact on the overall project. These steps mainly consist of exploration, drilling, production, storage and transportation, and sales, each of which can lead to changes in the profit and loss of the entire project. So the economic boundaries might also change.

1. Projected rate of profit

The forecasted rate of profit is an important standard for measuring the success of the project. Based on actual conditions in a CO₂ flooding project in a target reservoir, the evaluation standard for profit from a CO₂ miscible flooding project is calculated as in Table 13.

2. International oil price

The international crude oil price affects the income of oilfields and reflects profitability. In China, the typical
breakeven price of crude oil is about $40-$50/barrel, shown in the evaluation standard for international oil prices in Table 14.

The price of crude oil is an important factor in determining the economic boundary, and with high oil prices, the effective development cycle for an oil well is longer. At this stage, oil prices fluctuate greatly, and competition among the major oil companies is fierce. Therefore, the economic boundary may change with oil price by different degrees at different stages.

3. Relative economic effect

The relative economic effect means the economic benefit achieved by one project compared with another. The superiority of CO2 flooding over water flooding can be seen by comparing the profit and investment of CO2 flooding and water flooding. When the relative economic effect is greater than 1, then the economic benefit of the project is positive, and the larger the value, the greater the economic benefit. There is currently no official evaluation standard for relative economic benefit index, and the relevant research is very limited. The oil increment multiple of CO2 flooding standard is applied, and based on actual conditions in a CO2 flooding project in a target reservoir, the evaluation standard for the relative economic effect of CO2 flooding is calculated as in Table 15.

### Table 11: Evaluation standard for response time of CO2 flooding

| Evaluation index | Good     | Relatively good | Medium   | Relatively bad | Bad    |
|------------------|----------|-----------------|----------|----------------|--------|
| Response time (PV) | 0.05-0.1 | 0.1-0.11        | 0.11-0.12| 0.12-0.125     | >0.125 |
|                  | 0.045-0.05 | 0.035-0.045    | 0.03-0.035|                | <0.03  |

### Table 12: Evaluation standard for formation pressure above MMP

| Evaluation index | Good  | Relatively good | Medium   | Relatively bad | Bad    |
|------------------|-------|-----------------|----------|----------------|--------|
| Pressure level (MPa) | >1.08 | 0.49-1.08      | 0-0.49   | −0.6 to 0      | <−0.6  |

### Table 13: Rate of profit evaluation standard for CO2 flooding

| Evaluation index | Good | Relatively good | Medium   | Relatively bad | Bad    |
|------------------|------|-----------------|----------|----------------|--------|
| Rate of profit (%) | >40  | 25-40           | 15-25    | 0-15           | <0     |

### Table 14: Rate of profit evaluation standard for CO2 flooding

| Evaluation index | Good | Relatively good | Medium   | Relatively bad | Bad    |
|------------------|------|-----------------|----------|----------------|--------|
| Oil prices ($/barrel) | >60  | 50-60           | 40-50    | 30-40          | <30    |

### Table 15: Evaluation standard for CO2 flooding

| Evaluation index | Good | Relatively good | Medium   | Relatively bad | Bad    |
|------------------|------|-----------------|----------|----------------|--------|
| Relative economic effect | >9    | 6-9             | 3-6      | 1-3            | <1     |

3.3 | Calculation of indexes affecting the development effect of CO2 flooding

3.3.1 | Total CO2-oil exchange rate

The cumulative total oil exchange rate of CO2 miscible flooding is the ratio of cumulative gas injection divided by the cumulative increase in oil production. Here, cumulative gas injection can be measured in terms of surface volume and the cumulative increase in oil production can be measured in terms of weight, calculated as follows:

\[
\text{CO}_2 \text{- oil exchange rate} = \frac{\text{Cumulative CO}_2 \text{ injection}}{\text{Total oil production increased}}
\]
For example, for the P1 well group, data on the CO₂-oil exchange rate are listed in Table 16. We can see that for the three years the CO₂-oil exchange rate is 10.8018, 10.5562, and 10.6244, respectively, which is not a good rate.

3.3.2 | Comprehensive injection and production ratio

For alternate injection of gas and water, the stage I-P ratio can be calculated based on the I-P ratio at the end of each injection cycle. For example, for the P1 well group, the calculation process is as follows:

\[
I - P \text{ ratio} = \frac{\text{Cumulative CO}_2 \text{ injection} + \text{Cumulative water injection}}{\text{Total oil production increased}}
\]

For the P1 well group, the data on the comprehensive I-P ratio are listed in Table 17, and the ratios are all below 0.75, which means the comprehensive injection and production situation is negative.

3.3.3 | Total enhanced oil recovery

The total EOR is calculated by the cumulative oil production and the original crude oil reserves of the gas injection block from the beginning of gas injection to the end of the entire CO₂ injection process. The calculation method is as follows:

\[
\text{Total EOR} = \frac{\text{Total oil recovery by CO}_2 \text{ flooding} - \text{Total oil recovery by water flooding}}{\text{Original crude oil reserves}}
\]

For the P1 well group, because the gas injection process is not over, total EOR is calculated based on the increase in oil production of the gas injection adjustment plan. The original crude oil reserves of the P1-1 well cluster are 102 600 t. At present, cumulative oil production after gas injection is 4020.82 t, and the oil recovery is 3.92%, which is lower than 5%, meaning the total EOR is not good.

3.3.4 | Achievement of the production target

The total oil production of CO₂ flooding over three stages is projected to be 8376.885 t, so total EOR is 8.18%. The achievement of production targets is listed in Table 18. Based on the data, oil production is not performing well.

3.3.5 | Sweep efficiency of CO₂ flooding

The areal sweep efficiency of CO₂ flooding reserves of well group P is 75%. Because of the sensitivity of the velocity ratio and the formation heterogeneity in the process of CO₂ flooding, the channeling flow in the displacement process is very obvious, and the sweep coefficient is low, which leads to a reduction in the sweep efficiency of CO₂ flooding reserves.
The ratio of the effective thickness of injection well to the total effective thickness of production well is 1. Thus, the total sweep efficiency of CO₂ flooding reserves of well group P is 75%, which is good.

3.3.6 Breakthrough time

The breakthrough time is expressed by injected HPV (hydrocarbon-containing pore volume), which can be calculated by cumulative gas injection and effective pore volume of the formation. The calculation method is as follows:

\[
\text{Breakthrough time (HPV)} = \frac{\text{Cumulative gas injection}}{\text{Effective pore volume of the formation}}
\]

For the P1 well group, the total gas injection volume at gas breakthrough is 4867 t, which is converted into an underground volume of 11,510.46 m³. The effective pore volume of the formation is 18.30 × 10⁴ m³, so the gas injection HPV at gas breakthrough is 0.0629, and the breakthrough time of the P1 well group is 0.0629 HPV, which is relatively poor.

3.3.7 Total carbon storage rate

The cumulative gas storage rate of CO₂ miscible flooding equals the amount of CO₂ stored underground divided by the total amount of injected CO₂. The specific calculation method is as follows:

\[
\text{Cumulative gas storage rate} = \frac{\text{Cumulative CO}_2\text{injection} - \text{Cumulative CO}_2\text{production}}{\text{Cumulative CO}_2\text{injection}}
\]

For example, in the P1 well group, the data on the carbon storage rate are listed in Table 19. As seen in the table, the cumulative CO₂ storage rate changes from good to bad.

3.3.8 Opening rate of injection and production wells

The equation for the comprehensive well opening rate is as follows:

\[
\text{Well opening rate} = \frac{\text{Number of opened wells} \times \sum \text{Actual calendar days}}{\text{Number of total wells} \times \text{Total calendar days}}
\]

The opening rate of each well is listed in Table 20.

3.3.9 Effective rate of old well measures

During implementation of the pilot project, the old wells have been measured for their deep profile control and corrosion, with good results. Only the P1-368 well has poor anticorrosion and has been shut down for a long time. Based on the comprehensive calculation, the effective rate of old well measures is 83%, which indicates that old wells are effective.

3.3.10 Response time

The response time is expressed by injection HPV, and the hydrocarbon injection HPV can be calculated with cumulative gas injection and the effective pore volume of the formation as follows:

\[
\text{Response time (HPV)} = \frac{\text{Cumulative gas injection}}{\text{Effective pore volume of the formation}}
\]

For the P1 well group, the total gas injection volume is 4867 t when it becomes effective, which is converted into underground volume of 11,510.46 m³, and effective pore volume of the formation is 18.30 × 10⁴, so the gas injection HPV is 0.0629, and the P1 well group HPV is 0.0629 when it becomes effective. This response time is good.

3.3.11 Formation pressure maintenance level

The formation pressure maintenance level can be obtained from the average formation pressure and the MMP of formation fluid in the present stage. It can be calculated as follows:

\[
\text{Formation pressure maintenance level} = \text{Average formation pressure} - \text{Minimum miscible pressure}
\]
At present, the pressure of the P1 well group is 21.48 MPa, and the MMP is 18.42 MPa, so the pressure maintenance level is 3.06 MPa, which is good.

3.3.12 | Projected rate of profit

The rate of profit is calculated as follows:

\[
\text{Rate of profit} = \frac{\text{Profit}}{\text{Total income}}
\]

The projected rate of profit is largely affected by the level of oil prices; the rate of profit with different oil prices is listed in Table 21.

3.3.13 | Relative economic effect

The relative economic effect index is calculated as follows:

\[
\text{Relative economic effect} = \frac{\text{CO}_2\text{flooding profit} - \text{water flooding profit}}{\text{CO}_2\text{flooding investment} - \text{water flooding investment}}
\]

The difference in profit compared with water flooding is due to the increase in oil production from CO2 flooding. CO2 flooding technology development and improvement have been completed for alternate injection of gas and water, and the difference in investment expenditure is mainly due to the increase in injected CO2 gas.

The data on the relative economic effect are listed in Table 22.

The dynamic index value of CO2 miscible flooding in the P1 well group is calculated based on the stage effect comprehensive evaluation index system. The sweep efficiency of the CO2 flooding well group is 75%. The inspiratory profile is better, and the degree of reserve production is 75%. The stage I-P ratio is 52.87%. In December 2010, the average formation pressure of the reservoir is still higher than the miscible pressure, with a value of 3.06 MPa. It is effective after the cumulative injection of 0.063 HCPV CO2. There has been a breakthrough for a long time, probably after the CO2 injection of 0.06 HCPV. Based on the current displacement efficiency, the total oil recovery predicted by the digital model is 8.3%. The development trend of EOR is lower than that predicted by the digital model, and the evaluated oil production is negative, mainly because the cumulative gas storage rate is 56.76%, the comprehensive production rate of the I-P wells is 74.5%, the effective rate of the old well measures is 83%, and the project rate of profit is 47.5%. When the international oil price below $50, the rate of profit is negative, and the relative economic effect is 9.39.

4 | FACTOR WEIGHT DETERMINATION USING THE AHP

The AHP was first proposed by T. L. Saaty, an American operational research scientist in the mid-1970s. Based on the characteristics of a research object, it can decompose a problem into different influencing factors, then aggregate, and combine the factors at different levels according to the interrelated influence and membership of the factors to form a multilevel analytical structure, which ultimately solves the problem. It comes down to the judgment of the merits of the lowest level indicators relative to the highest level evaluation objectives. The AHP method shows good

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**TABLE 19** Calculation of cumulative gas storage rate of the P1 well group in stages

| Stage | Stage CO2 injection (t) | Stage CO2 production (t) | Cumulative CO2 injection (t) | Cumulative CO2 production (t) | Cumulative CO2 storage rate |
|-------|-------------------------|--------------------------|-----------------------------|------------------------------|----------------------------|
| 1     | 10 096.00               | 1866.98                  | 10 096.00                   | 1866.98                      | 0.8151                     |
| 2     | 3168.00                 | 4920.20                  | 13 264.00                   | 6787.18                      | 0.4883                     |
| 3     | 2573.00                 | 2725.60                  | 15 837.00                   | 9512.78                      | 0.3993                     |

**TABLE 20** Comprehensive production time rate for the P1 well group

| Serial number of well | PI-1 | PI-2 | PI-3 | PI-4 | Total |
|-----------------------|------|------|------|------|-------|
| Actual production days | 777  | 902  | 880  | 880  | 3439  |
| Calendar days        | 923  | 923  | 923  | 923  | 3692  |

**TABLE 21** Sales revenue and rate of profit

| Price/barrel ($) | Price/ton (RMB 0,000) | Total income (RMB 0,000) | Rate of profit (%) |
|------------------|-----------------------|--------------------------|-------------------|
| 20               | 973                   | 391.4                    | -110.0            |
| 30               | 1460                  | 587.1                    | -40.0             |
| 40               | 1947                  | 782.8                    | -5.0              |
| 50               | 2434                  | 978.5                    | 16.0              |
| 60               | 2921                  | 1174                     | 30.1              |
| 70               | 3408                  | 1370                     | 39.9              |
| 80               | 3895                  | 1566                     | 47.5              |
comprehensiveness, scientificity, and systematicity in the decision-making process. Combining qualitative analysis and quantitative analysis, it provides a structure that people can use for making effective decisions about complex problems by simplifying the usual decision-making process. The AHP method meets our research needs well and comprehensively evaluates CO₂ flooding in three respects: technical, management, and economic benefits. Therefore, we use the AHP method to judge the index weight.

4.1 | Weight determination with the AHP

In this study, relevant experts were invited to fill in Table 23 according to the AHP method. On the basis of the scale in the table, the indicators at all levels are compared, graded by importance, and expressed in the form of a matrix. After full discussion, a judgment matrix for the evaluation index of the CO₂ flooding effect of an abandoned waterdrive reservoir is created.

### 4.1.1 | Determination of the first-level index weight

Through a pairwise comparison matrix, using the evaluation criteria in Table 23, the ratio of the importance of the technical index to the management index is 4, and the ratio of the importance of the management index to the technical index is 0.25. The ratio of the importance of the technical index to the economic benefit index is 2, and the ratio of the importance of the economic effect index to the technical index is 0.5. The relative importance of the first-level indexes is obtained through investigation by experts, as shown in Table 24.

The comparison judgment matrix of three first-level indexes is as follows:

\[
A = \begin{pmatrix}
1 & 4 & 2 \\
0.25 & 1 & 0.5 \\
0.5 & 2 & 1
\end{pmatrix}
\]

The eigenvalues and eigenvectors of the matrix can be calculated using the eigenvector method proposed by Saaty: \(AW = \lambda_{\text{max}} W\). The largest characteristic root is as follows:

\[
\lambda_{\text{max}} = 3, \quad W = (0.5714 0.1429 0.2857)^T
\]

### 4.1.2 | Consistency test of the judgment matrix of the first-level index

If a decision-maker compares the decision-making objects under the condition of logical consistency, the conclusion will have no inconsistencies. However, in reality, people’s thinking is inevitably affected by subjectivity and one-sidedness, so a paired comparison matrix constructed by people is usually inconsistent. So, when we use this method to analyze a problem, it is necessary to test the consistency of the judgment matrix. This can be accomplished by programming.

### 4.1.3 | Index system weight of each level

Referring to the calculation steps above, we use AHP to determine the weight of each index and conduct a consistency
test. Then, we can obtain the evaluation index system and weight as shown in Tables 25-27.

Weight vector:

\{0.2291, 0.1221, 0.6488\}

Maximum eigenvalue:

3.0006

The consistency of this matrix is acceptable:

\[ CI = 0.0790 \]
\[ CR = 0.0627 \]

4.1.4 | Constructing a set of weights

In this study, the final evaluation index system is obtained by decomposing the evaluation factors that affect the effect of CO\textsubscript{2} flooding injected into abandoned waterdrive reservoirs and combining them with the relevant literature. In addition, use the AHP method to weight the evaluation factors of CO\textsubscript{2} flooding injected into the P1 well group. The index system and weight are shown in Table 28.

Among the four factors of the first-level indicators, the largest proportion is made up of technical indicators, such as well pattern improvement status, injection status, and oil production increased efficiency, because they are the direct factors that affect the implementation effect. The economic benefit indicators are more important than the management indicators, because, although they are pilot tests, it is still important to obtain economic returns. The management index also accounts for a considerable weight, because the injection wells and production wells of the P1 well pattern are not ideal. They have problems such as corrosion, so the management index is also an important factor that affects the results of the effect evaluation.

5 | ESTABLISHMENT OF THE EVALUATION INDEX MEMBERSHIP FUNCTION

The membership degree function maps the evaluation factor index to a positive real number in the interval [0,1], which is its degree of membership in the evaluation set, thereby generating a fuzzy relation matrix. At present, the Gaussian membership function, the triangular membership function, and the trapezoidal membership function model are widely used in fuzzy comprehensive evaluation. To avoid deviations in the result due to the selection of the membership function model, we use three membership function models to calculate the final results. The following mainly discusses a detailed calculation of the Gaussian membership function.

We use the Gaussian membership function to calculate the index membership, and we use \(Z\)-type and \(S\)-type distribution functions at the left and right boundaries of the interval, calculated as follows:

\[ \mu_{ij} = \exp \left( - \frac{[x_{ij} - \xi]^2}{2\sigma^2} \right) \] (1)
where $\mu_{ij}$ is the membership degree of the secondary indicator $x_{ij}$. $E$ represents the mean value of the evaluation standard interval, and $\sigma$ is the width (i.e., standard deviation) of the Gaussian function, which is also called the standard deviation. When $x_{ij}$ is at the boundary of the interval, the degree of membership is the fuzziest, 0.5. Therefore, the parameter $\sigma$ in Equation (1) can be calculated as follows:

$$0.5 = \exp \left( -\frac{(x_{max} - E)^2}{2\sigma^2} \right)$$

$$\sigma = \frac{x_{max} - E}{2\sqrt{-\ln 0.5}}$$

We use \{I, II, III, IV, V\} to indicate the evaluation level \{good, relatively good, medium, relatively bad, bad\}. The degree of membership of the index is shown in Table 29.

By using the Gaussian membership function, we obtain the following first-level comprehensive fuzzy evaluation set:

$$R = \begin{bmatrix}
0.2227 & 0.1313 & 0.0320 & 0.1823 & 0.4316 \\
0.9979 & 0.0021 & 0 & 0 & 0 \\
0.9548 & 0.0453 & 0 & 0 & 0
\end{bmatrix}$$

The final result calculated with the Gaussian membership function model is as follows: (0.5426, 0.0883, 0.0183, 0.1042,
The result calculated with the triangular membership function and the trapezoidal membership function model is, respectively, 0.5018, 0.1310, 0.0164, 0.1480, 0.2028 and 0.5119, 0.1193, 0.0181, 0.1020, 0.2487. The result calculated with the three membership functions is similar.

6 | THE RESULT AND ANALYSIS OF THE FUZZY COMPREHENSIVE EVALUATION

6.1 Calculation of the fuzzy comprehensive evaluation

By using the AHP to determine the weight, the first-level fuzzy comprehensive evaluation can be carried out according to the single-factor fuzzy relation matrix and the operator of the underlying index.

According to the membership function, the fuzzy relation matrix can be obtained as follows:

\[ R = \begin{bmatrix}
    r_{11} & r_{12} & \cdots & r_{1n} \\
    r_{21} & r_{22} & \cdots & r_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    r_{m1} & r_{m2} & \cdots & r_{mn}
\end{bmatrix} \]

The fuzzy evaluation value of this level is as follows:

\[ B = \omega_i \circ R_i = (\omega_1 \omega_2 \cdots \omega_m) \circ \begin{bmatrix}
    r_{11} & r_{12} & \cdots & r_{1n} \\
    r_{21} & r_{22} & \cdots & r_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    r_{m1} & r_{m2} & \cdots & r_{mn}
\end{bmatrix} = (b_1, b_2, \ldots, b_n) \]

The fuzzy evaluation set of this level constitutes the fuzzy evaluation subset of the upper level. According to the same method, the first-level comprehensive fuzzy evaluation set can ultimately be obtained.

After the first-level comprehensive fuzzy evaluation is completed, the overall evaluation is carried out. The weight set of the first-level indicator is as follows: \( W = (\omega_1, \omega_2, \omega_3, \omega_4) \).

The fuzzy relation matrix of the second-level indicator is as follows: \( R = (B_1, B_2, B_3, B_4, B_5) \).

Then the total fuzzy comprehensive evaluation set is as follows:

\[ B = W \circ R = (\omega_1, \omega_2, \omega_3, \omega_4) \circ \begin{bmatrix}
    B_1 & B_2 & B_3 & B_4 & B_5
\end{bmatrix}^T = (b_1, b_2, b_3, b_4, b_5) \]

6.2 Processing the fuzzy comprehensive evaluation index

The result of the comprehensive evaluation of the fuzzy comprehensive evaluation model is the membership degree of each element in the evaluated set, which is a fuzzy vector,
rather than a point value, so it can provide more information than other methods. If we compare and rank many objects, we need to deal with a result vector of fuzzy comprehensive evaluation to advance our efforts. This paper mainly uses the method of maximum membership degree.

At present, the principle of maximum membership degree is a general principle. For example, the comprehensive evaluation set obtained is \( B = (0.4, 0.5, 0.7, 0.4, 0.3) \). Using the principle of maximum membership degree, the evaluation object is classified as the corresponding level of max = 0.7. Of course, in a fuzzy comprehensive evaluation, the principle of maximum membership degree is not universal. For example, if we obtain the evaluation result \( B = (0.2, 0.7, 0.69, 0.2, 0.1) \), we can deduce that the evaluation object is undoubtedly between the second level and the third level, but based on the principle of maximum membership degree, the evaluated object is classified as the second level, which is obviously inappropriate. Therefore, it is necessary to combine quantitative and qualitative analysis based on the actual situation and consider the confidence interval of the results to ensure the reliability of the evaluation.

### 6.3 Fuzzy comprehensive evaluation results

According to the earlier data, using the evaluation model of the effect of CO\(_2\) flooding of an abandoned waterdrive reservoir, the final comprehensive evaluation result with the three membership functions is as follows: \((0.5426, 0.0883, 0.0183, 0.1042, 0.2466)\), \((0.5018, 0.1310, 0.0164, 0.1480, 0.2028)\), and \((0.5119, 0.1193, 0.0181, 0.1020, 0.2487)\). Regardless of which membership function is used, the maximum membership can be accurately obtained: 0.5426, 0.5018, and 0.5119. Although the principle of maximum membership degree is very simple, based on the data in this paper, it can be concise and effective in determining the index level, without inappropriateness, so the principle of maximum membership degree is used. The final result of our comprehensive evaluation of the gas injection effect of the P1 well group of target oil reservoir in P city is good, but the score is not high for one of the following reasons.

First, the I-P ratio is too low. When well P1-67 starts to work, a large amount of liquid is extracted. However, because of the unstable gas source, the injection amount of CO\(_2\) is affected, which directly leads to imbalance in I-P and worsens the gas channeling, and ultimately affects the effectiveness of other wells.

Second, well P1-67 has a significant increase in the effect of oil production and successfully displaces the remaining oil, which cannot be produced by water flooding; the effect of the other wells is not clear, which affects the final effect of EOR.

Third, the early breakthrough of CO\(_2\), the serious gas channeling, and a large amount of CO\(_2\) that is not fully miscibly displaced in the formation results in a low utilization rate of injected gas, which can be confirmed by the cumulative gas storage rate.

Fourth, the result of the economic benefit index is relatively negative. On the one hand, the test is still in progress, and the total increase in oil production will improve further. On the other hand, the gas channeling of well P1-67 is serious, and the other two wells are not effective.

Comprehensively, there is a serious gas channeling phenomenon in well P1-67, which leads to insufficient miscible displacement of CO\(_2\). Controlling and preventing gas channeling needs to be solved effectively. Our research has further confirmed the importance of mitigating gas channeling for improving the effect of CO\(_2\) flooding. Many scholars have carried out the research on mitigating gas channeling. Zhao et al.\(^{17}\) and Hao et al.\(^{18}\) found that using high-strength gel, ethylenediamine and CO\(_2\) WAG flooding can significantly mitigate the gas channeling within major fracture and microfractures of the model they designed, and the incremental oil recovery could be more than 15% at least. P1-1 well group of P city can consider adopting these measures to mitigate gas channeling.

### 7 CONCLUSIONS

In this paper, a fuzzy comprehensive evaluation model is constructed to evaluate the development effect of CO\(_2\) flooding in P1-1 well group of P city reservoir in China from three aspects: technical, management, and economic benefit. Based on the AHP method, the index is weighted, and the membership degree of the index is calculated by using triangle, trapezoid, and Gaussian membership function, respectively. The three calculation results are very close, and the principle of maximum membership degree is adopted to judge the final result. The results show that the economic effect of CO\(_2\) flooding of P1-1 well group in P city reservoir is good, but the score is not high.

This article provides a new method for studying the economic effect of CO\(_2\) flooding. By constructing a fuzzy comprehensive evaluation system, the economic effect of CO\(_2\) flooding can be evaluated comprehensively and systematically, and the economic effect of CO\(_2\) flooding can be improved in a targeted manner. In the future research, researchers can choose different types of membership functions according to the different characteristics of the data, such as cloud model and clustering.

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REFERENCES
1. Zhou T, Liu X, Yang Z, Li X, Wang S. Experimental analysis on reservoir blockage mechanism for CO₂ flooding. Petrol Explor Dev. 2015;42(4):548-553.
2. Cao Y, Junbin C, Jianping X, Zongriao R, Xiang’an Y, Huaimin X. Microstructure and formula optimization of CO₂ flooding composite gel in supercritical carbon dioxide. Chem Technol Fuels Oils. 2019;55(1):35-46.
3. Abass AE, Gawish AA, Elakhal EM. Simulation study of different modes of miscible carbon dioxide flooding. Egypt J Petrol. 2018;27(4):1195-1207.
4. Zadeh LA. Fuzzy sets. Information & Control. 1965;8(3):338–353.
5. Wang H, Li Z, Yao J, et al. Sentimental propagation model of stock investors based on symmetric triangular fuzzy set. Acta Automatica Sin. 2020;46(05):1031-1043.
6. Qu X, Fu K, Long Q. Research on benefit evaluation of power demand side management based on improved fuzzy analytic hierarchy process. J Hubei Normal Univ (Nat Sci). 2019;39(04):1-9.
7. Sivaraman G, Vishnukumar P, Raj M. MCDM based on new membership and non-membership accuracy functions on trapezoidal-valued intuitionistic fuzzy numbers. Soft Comput. 2019;24(6):4283-4293.
8. Wu C, Yang K. Feasibility study on credit evaluation of logistics enterprises based on quantitative analysis. Logist Sci-Tech. 2019;42(11):25-28.
9. Zhao L, Yu L, Yuan S-S. Comprehensive evaluation study on the social cost in construction project. Eng Cost Manage. 2016;01:23-26.
10. Wang Y. Economic benefit evaluation model of industrial enterprises based on relational membership degree. Chin Foreign Entrepren. 2016;19:56-57.
11. Wang K, Yang Y. Grey clustering-fuzzy comprehensive model of supply chain performance evaluation of green agricultural products and its application. Math Pract Theory. 2020;50(02):111-119.
12. Hu Y, Hao M, Chen G, Sun R, Li S. Technologies and practice of CO₂ flooding and sequestration in China. Petrol Explor Dev. 2019;46(04):716-727.
13. Nian Y, Han B, Cheng W. Experimental study on combination hot water-CO₂-chemical flooding with effects on oil recovery and heat transfer. Appl Therm Eng. 2020;166:114683.
14. Wang Y, Shang Q, Zhou L, et al. Utilizing macroscopic areal permeability heterogeneity to enhance the effect of CO₂ flooding in tight sandstone reservoirs in the Ordos Basin. J Petrol Sci Eng. 2020;196(107633).
15. Xiong Y, Sun L, Sun L, et al. A new integrative evaluation way for candidate of carbon dioxide miscible flooding reservoir based on fuzzy analytical hierarchy process. Acta Petrol Sinica. 2002;06:60-62+3-2.
16. Wang G, Zheng X, Zhang Y, Lü W, Wang F, Yin L. A new screening method of low permeability reservoirs suitable for CO₂ flooding. Petrol Explor Dev. 2015;42(03):358-363.
17. Zhao F, Hao H, Hou J, Hou L, Song Z. CO₂ mobility control and sweep efficiency improvement using starch gel or ethylenediamine in ultra-low permeability oil layers with different types of heterogeneity. J Petrol Sci Eng. 2015;133:52-65.
18. Hao H, Hou J, Zhao F, Song Z, Hou L, Wang Z. Gas channeling control during CO₂ immiscible flooding in 3D radial flow model with complex fractures and heterogeneity. J Petrol Sci Eng. 2016;146:890-901.

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