Evaluation of coalbed methane resources in Xinjing Baoan block based on PCA, TOPSIS, & MLFM

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Abstract
Coalbed methane (CBM) resources are abundant in the Baoan blocks of the Xinjing coalfield, China; their exploration and development remain in infancy. Suitable development blocks can be selected by evaluating their development potential; that of the No. 8 and 15 CBM systems in the Baoan blocks was evaluated using three quantitative evaluation methods via existing geological data: multi-level fuzzy mathematics (MLFM), technique for order preference by similarity to ideal solution (TOPSIS), and principal component analysis (PCA). The results demonstrated that the CBM development potential in the central part of the Baoan blocks is low and unbecoming. The favorable areas of the No. 8 coal seam are distributed in the northeast and northwest, and that of No. 15 in the northwest and southwest. Differences exist in quantitative selection; with limited data, the evaluation of the TOPSIS method is considerably different from actuality, and is unbecoming for evaluating the development potential.

Keywords
Coalbed methane, potential evaluation, multi-level fuzzy mathematics, TOPSIS, principal component analysis

Introduction
China is rich in coalbed methane (CBM) resources, and the commercial development of CBM is primarily concentrated in the eastern margin of the Qinshui and Ordos basins. Previous studies on the relevant theories of CBM development selection evaluation systems have been conducted.

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Yangquan Coal mine, located in the east of Taiyuan city, is rich in CBM resources (Li et al., 2019b; Li et al., 2021a; Tao et al., 2022). Geological selection evaluation is a prerequisite for CBM development. Selecting only favorable blocks suitable for its development can be foundational (Bo et al., 2020; He et al., 2021; Okere et al., 2020).

Many evaluation methods for CBM geological selection have been established, such as the search for high-permeability area, formation energy, fuzzy matrix, analytic hierarchy process, catastrophe evaluation, grey clustering analysis, grey correlation, back-propagation neural network, and numerical simulation (Bo et al., 2020; Ghosh et al., 2016; Heo et al., 2010; Li et al., 2013; Lü et al., 2011). Based on the geological conditions of coal seams, these methods evaluate the advantages, disadvantages, and economy of CBM development from different aspects. However, CBM reservoirs are complex geological systems, and the factors affecting their development often restrict one another. Therefore, a large number of mathematical methods have been introduced to comprehensively consider the interaction and intervention of various factors. Among them, multi-level fuzzy mathematics is a method combining hierarchical analysis and fuzzy mathematics, and the geological index of mutual restriction is converted into a compatible geological index, eliminating the restriction between the influencing factors, which has a certain advantage for CBM selection evaluation. The technique for order preference by similarity to ideal solution (TOPSIS) method based on the coefficient of variation is another multi-objective decision analysis method, conducting a comprehensive evaluation based on the distance between the evaluation object and the most idealized decision target. TOPSIS has been widely used in evaluating oil and gas reservoir (Qu et al., 2021), resource and environment (Yan and Li, 2021), coal mining safety and other geological fields (Zhao et al., 2021a). However, there exists limited research on CBM selection using TOPSIS. In addition, factors of CBM development potential evaluation not only restrict and influence each other, but also possess repeated information among a large number of indicators, resulting in the complexity and uncertainty of CBM selection evaluation and decision-making system (Hower et al., 2021; Ye et al., 2022; Zhang et al., 2021a). Principal component analysis is a type of evaluation method that can deal with information jumbled in decision systems and evaluation systems. The main information in the data was extracted, and the target was evaluated by dimensionality reduction (Li et al., 2021b). Compared with single-factor analysis, these comprehensive evaluation methods have more advantages in CBM selection index analysis. Among them, fuzzy mathematics and PCA are the most widely used methods, in the evaluation of CBM development potential in many regions, including the southern Qinshui Basin in China (Zhang et al., 2016) and the Xishan coalfield in Shanxi Province, China (Wang et al., 2018). The Teviot-Brook region of Australia (Yang et al., 2020a, 2020b). (Zhang et al., 2019) used PCA method to evaluate the development potential of multiple synclines in western Guizhou, China, and the results were consistent with the actual production capacity. Wang et al. (2022) used the PCA method to analyze the characteristics of CBM drainage and production and considered that the gas content is the most important factor affecting CBM productivity. The TOPSIS method has also been widely used in geological resource-related research and favorable target optimization and has been successfully applied to coal resource safety and aquifer evaluation (Qiu et al., 2020; Yang et al., 2020b).

However, previous studies have mainly focused on using a single method to evaluate CBM development potential, and few comparative studies exist on different methods in the same area. Therefore, this study considers the Baoan blocks of Xinjing Mine its research object. Based on analyzing the geological elements in the research area, combined with the advantages and disadvantages of three evaluation index systems and methods, we conducted a comprehensive evaluation
of the development potential of the No. 8 and No. 15 coal seams, and determined the evaluation method most suitable for CBM development in the research area.

**Geological background**

Baoan blocks are located in the west of Yangquan mining of the Qinshui Basin, the west side of the Taihang Mountain north section, and the south foothill of the Liuzhao Mountain low and mid-mountain. The field is 7.9 km long from east to west, 7.5 km wide from north to south, and covers an area of 64.747 7 km² (Li et al., 2019a, 2019b; Zhao et al., 2021b) the surface topography in the mine field is complex and fluctuates substantially (Figure 1).

**Coal bearing strata**

The main coal-bearing strata in the study area are the Taiyuan Formation and the Shanxi Formation of the upper Carboniferous to lower Permian. Its average total thickness is 177.68 m, the average total thickness of the coal seam is 20.85 m, and the coal bearing coefficient is 11.73% (Zhang et al., 2016). The Taiyuan Formation contains nine layers of coal, among which the No. 15 coal seam is stable and recoverable, the No. 8 and No. 9 coal seams are stable, and most of them are recoverable. The average total thickness of the coal seam is 15.57 m and the coal bearing coefficient is 12.88%. The average total thickness of coal seam containing 6 layers in Shanxi Formation is 5.28 m, and the coal coefficient is 9.30% (Figure 2)(Cao et al., 2021; Li et al., 2019a, 2019b).

**Tectonic**

Overall, the Qinshui Basin is an NNE syncline structure adjacent to the Taihang Mountain uplift in the east and the Luliang Mountain uplift in the west Its axis is approximately along the Yushe-Qinxian–Qinshui line. The overall structure was relatively simple, and fault development was
The study area is located in the north of the Xining Coal Mine, which belongs to the Shenyang-Yangquan monocline zone at the northern end of the Qinshui Basin, Shanxi Province, and is a syncline formed by near-horizontal compression after the late Paleozoic coal-forming period in North China (Figure 1). (Hu et al., 2015; Wang et al., 2018).

**Selection evaluation index**

**Evaluation index of reservoir conditions**

**Coal thickness.** The thickness of the coal seam is an important parameter in evaluating the CBM reservoir that affects the resource amount and abundance of its development. The larger the
thickness of the coal seam, the higher the resource amount there is (Liu et al., 2009). The results demonstrate a positive correlation between gas production and the thickness of the coal seam in the Qinshui Basin (Zhang et al., 2016). According to the borehole data of several coal fields in the research area, the thickness of the No. 8 coal seam is 0.4–3.95 m, with an average of 2.15 m. The distribution characteristics of the No. 8 coal seam on the plane is relatively complex. Multiple high-value coal thickness areas were developed in the study area. In general, the coal seam in the middle of the study area was thin and its surrounding areas were thick (Figure 3(a)). The thickness of the No. 15 coal seam was larger than that of No. 8. It is the main mining coal seam in the study area, with a thickness of 2.05–9.81 m and an average of 6.5 m. From the perspective of plane region, coal seam No. 15 is mainly developed in the northwest, and the overall trend depicts a gradually thinning from northwest to southeast (Figure 3(b)).

**Buried depth.** The buried depth of the coal seam not only affects the reserves of CBM but is also an important evaluation index for developing CBM projects. The permeability of the coal seam decreases gradually, with increasing buried depth, which makes it difficult to discharge and depressurize CBM. However, with increasing burial depth, CBM sealing conditions improve and coal seam gas content and resource reserves increase (Li et al., 2015; Shen et al., 2016). Statistical data show that the buried depth of No. 8 in the research area is 431.94–744.75 m, with an average of 586.75 m. In terms of plane distribution, the buried depth of the No. 8 coal seam is the largest in the northeast and southwest and is greater than 700 m in some areas (Figure 4(a)). The buried depth of the No. 15 seam varies less than that of No.8, ranging from 523.6 m to 834.97 m, with an average of 674.86 m. The plane regional distribution trend of the buried depth was consistent with that of the No. 8 coal seam, with the largest buried depth in the northeast and southwest (Figure 4(b)).

**Gas content.** Gas content is one of the most important factors in evaluating CBM selection, which directly affects the gas production of CBM (Lv et al., 2012; Tao et al., 2014). The results show that the gas content of the No. 8 coal seam is 6.0–20.6 m³/t with an average of 12.7 m³/t; the gas content of the No. 15 coal seam is 3.8–19.3 m³/t with an average of 9.6 m³/t, such that it is lower than that of No. 8. In terms of regional distribution, the gas content of the No. 8 coal seam is high in the

![Figure 3. Contour map of coal seam thickness in the study area (a: No.8, b: No.15).](image-url)
northeast, high in the south, and low in the southwest and northwest, and the gas content of local and regional coal seams is characterized by aggregation. Combined with the tectonic development in the study area, the regional distribution of gas content is consistent with the tectonic track, and the complex structural development is the main reason for this difference. The regional distribution characteristics of the gas content in the No. 15 coal seam is different from that in No. 8. The gas content in the No. 15 coal seam was higher in the south than in the middle (Figure 5(b)).

**Permeability.** The permeability of the coal reservoir is the main factor restricting CBM production. The higher the permeability, the more easily methane could be desorbed and transported. Therefore, the main goal in the early potential evaluation process of CBM development, is to find a “high permeability area” as the dominant blocks of CBM development (Fu et al., 2016; Liu et al., 2020). Due to the lack of exploration in the research area, the permeability data of the No. 8 coal seam are missing. This study mainly analyzed the No. 15 coal seam, for which the permeability was $0.996 \times 10^{-2} \text{ mD}$, and the average was $1.02 \times 10^{-2} \text{ mD}$. In terms of

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**Figure 4.** Contour map of buried depth of coal seam in the study area (a: No.8, b: No.15).

**Figure 5.** Contour map of coal seam gas content in the study area (a: No.8, b: No.15).
regional distribution, the hypertonic areas were mainly distributed in the west and southwest of the study area (Figures 6 and 7).

**Resource abundance.** Resource abundance is one of the main economic indicators of CBM development. The higher the resource abundance, the greater the economic potential of CBM development (Liu et al., 2015; Zhao, 2021; Zhou et al., 2021). The borehole data in an study area show that the resource abundance of the No. 8 coal seam is $0.42–0.92 \times 10^8$ m$^3$/km$^2$, with an average of $0.60 \times 10^8$ m$^3$/km$^2$; and that of No. 15 is $0.58–1.53 \times 10^8$ m$^3$/km$^2$, with an average of $0.96 \times 10^8$ m$^3$/km. The resource abundance of the No. 15 coal seam was evidently better than that of No. 8. Combined with the plane distribution of resource abundance, we can see that the resource abundance of the No. 8 coal seam is lower in the middle and largest in the northeast The No. 15 coal seam shows similar distribution characteristics, and the resource abundance in the middle region is low. In contrast to No. 8, the resource abundance of the No. 15 coal seam in the southwest was the highest.

**Evaluating the index of conditions of preservation**

**Tectonic coal distribution in the study area.** A large amount of measured data and research results have revealed that the coal structure type has an important effect on permeability and CBM production.

![Figure 6. Contour map of permeability of No. 15 coal seam in the study area.](image)
According to the degree of damage, the coal structure can be divided into four types: primary structure coal, fragmentary coal, fragmentary coal and mylonite coal. Fragmentary and mylonite coal are also known as tectonic coal, which is not conducive to CBM development owing to its structure, disordered fracture direction, poor connectivity, and relatively low permeability (Wu et al., 2021; Zhang et al., 2021a, 2021b). Based on the analysis of well drilling results and logging data, we can see that both primary and structural coal developed in the Baoan blocks. The average tectonic coal thickness of the No. 8 coal seam was 0.59 m, accounting for 34%, and the average tectonic coal thickness of the No. 15 coal seam was 1.29 m, accounting for 20%. In terms of regional distribution, the tectonic coal of the No. 8 coal seam was relatively developed along the southeast direction near small faults. The tectonic coal of the No. 15 coal seam mainly developed along the NNE direction of fault DF4, which is subjected to weak tectonic stress. Most faults only developed in the coal seam, and the coal structure did not suffer severe damage (Cao et al., 2021; Zhang et al., 2021b, 2021c) (Figure 8).

**Roof and floor.** The lithology of the coal roof and floor affects the preservation of CBM and is a key factor affecting gas saturation. Because of their low permeability, mudstones are ideal roofs and floors for CBM sealing. According to the drilling data, the roof and floor of the No. 8 coal seam are mainly mudstone; the roof is 1.66–9.67 m with an average of 5.48 m. The thickness of the bottom plate was 0.3–9.35 m, with an average of 4.07 m. According to the contour map of the ratio of mudstone thickness to thickness of the roof of the No. 8 coal seam, we can see that the roof mudstone of No. 8 is thick in the southeast and northwest and thin in the middle (Figure 9(a)). The No. 15 coal seam roof is mainly limestone, 0.35–7.44 m thick, averaging 1.9 m. The bottom mudstone is 0.55–16.6 m thick with an average of 6.56 m. The thickness of the bottom plate was greater than that of the top plate. Combined with the contour map of the mudstone thickness ratio of the roof of the No.15 coal seam, we can see that the roof thickness of the No. 15 coal seam gradually thins from NE to SW (Figure 9(b)) (Ni et al., 2020; Tao et al., 2012).

**Fault fractal dimension.** Fault development is an important condition for CBM storage. Faults not only affect the preservation and migration of CBM but also need to consider faults and other structures during fracturing and exploitation (Wu et al., 2021). According to the structural outline map of
In the research area, the faults in the east of the No. 8 coal seam are more developed than those in the west, and there are 22 faults in total, including 11 normal and 10 reverse faults. The dip angle of the faults was large, ranging from 31.5° to 70°, with an average of 55° (Figure 10(a)). Small faults are more developed in No. 15, with 44 faults in the study area, mainly normal faults, with dip angles ranging from 38° to 75° and an average of 56° (Figure 10(b)).

To quantify the degree of fault development in the study area, the fault fractal dimension was used to evaluate the degree of structural failure of the coal seams. We can see from the fractal dimension contour map of the fault of the No.8 coal seam that the study area is moderately complex. Among them, due to a large number of faults, the northeast region is locally developed as a complex structural region, whereas the southwest region is the simplest structural region (Figure 10(a)). The northeastern area of the No. 15 coal seam is of medium structural complexity, whereas the structural development trend of the southwestern area is consistent with that of No. 8, which is a simple area. The structural complexity of the No.15 coal seam responded adequately to the fault trace of the fault in the Baoan blocks; the simple structural area is distributed between two
large fault traces (Figure 10(b)). The Figures show that the fractal dimension of the fault in the study area is consistent with the degree of development of the fault (Figure 10).

**Tectonic curvature.** The structure of the study area is a synanticline with wide and slow undulations. The NNE-NE strike of the fold, such as the S1 syncline, is consistent with the strike of the fault. The NE parts of the S1 syncline are characterized by multiple secondary small folds, showing alternate anticline development. The No. 15 coal seam is simpler than the No. 8 coal seam, and the secondary small syncline of the No. 15 coal is less than that of No. 8. (Li et al., 2013; Li et al., 2015; Zhang et al., 2016) (Figure 11).

Tectonic curvature is the result of the tectonic stress field. The curvature reflects the relative development degree of tensile fractures in curved strata, and a high curvature is located in areas with strong folding. Herein, the maximum curvature of the study area was calculated using the contour line of the coal floor to characterize the deformation degree of the fold. (Banerjee et al., 2021; Qi et al., 2022; Sun et al., 2021). Figure 11 shows that there is a good coincidence and
relationship between fold development and tectonic trace in the study area, and the maximum curvature can be used to characterize the degree of fold development.

**Potential evaluation and favorable area prediction of CBM**

After years of development, CBM selection methods and indicators have reached a consensus. The important indicators are gradually becoming clearer, such as resource conditions, reservoir conditions, preservation conditions, and so on. The selection method developed gradually from the initial qualitative evaluation to quantitative evaluation and then to qualitative and quantitative comprehensive considerations (Bo et al., 2020; Li et al., 2019a, 2019b; Wang et al., 2018). Herein, we selected three methods, namely multi-level fuzzy mathematics, the TOPSIS method based on the coefficient of variation, and principal component analysis, to evaluate the CBM development potential in Baoan blocks.

**Multi-level fuzzy mathematics**

The analytic hierarchy process is a decision-making method of system theory, which is decomposed into several levels, making index evaluation complex at different decision-making levels. Furthermore, considering the problem of insufficient data, the theory of analytic hierarchy process and fuzzy mathematics is introduced, and a multi-level fuzzy mathematics method is developed as an evaluation method for CBM constituency. The basic idea of this method is to decompose the problem to be solved into several components, group these components according to the dominant relationship, and establish a hierarchical structural model. According to a certain scale, a pairwise comparison of the importance of each element at the same level with respect to the previous level is made, and a pairwise comparison judgment matrix is constructed, by which the relative weight of the compared element to its criterion is calculated (Heo et al., 2010; Wang et al., 2018).

First, the decision objective was stratified and a discriminant matrix was established. Based on previous research methods, coal seam thickness, buried depth, gas content, permeability, and resource abundance were selected as the reservoir evaluation conditions of CBM. The structural coal content, roof mudstone thickness ratio, fault fractal dimension value, and structural curvature value were selected as the key factors of CBM preservation conditions, and a three-level evaluation model was established (Wang et al., 2018).

Second, the importance of each parameter was compared at the same level. We used the 1–9 scale method to rank the importance of the evaluation indicators and MATLAB to calculate the maximum feature root and feature vector of the judgment matrix, and the weight coefficients of the indicators at each level were obtained (Table 1).

To ensure the accuracy and reliability of the calculation results, it was necessary to conduct a random consistency test on the calculation results. The following formula was used to test the results.

$$C.I. = \frac{\lambda_{max} - n}{n - 1}$$  \hspace{1cm} (1)

$$C.R. = \frac{C.I.}{R.I.}$$  \hspace{1cm} (2)

where $n$ is the order of the matrix, $\lambda_{max}$ is the characteristic root, and R.I. is the random consistency index.
| No. | B1 | B2 | B3 | B4 | B5 | B6 | B7 | B8 | B9 | B10 | B11 | B12 | B13 | B14 | B15 | W_B | λ_max | C.R. | W_B | λ_max | C.R. |
|-----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|-----|------|-----|------|------|-----|
| A~B | A  | B1 | B2 | -  | -  | -  | -  | W_B | 2.00| 0.00| A~B | A  | B1 | B2 | -  | -  | -  | -  | W_B | 2.00| 0.00 |
| B1  | 1  | 4  | -  | -  | -  | -  | 0.8 | -  | -  | 0.8 | -  | -  | 0.8 | -  | -  | -  | 0.8 | -  | -  | -  | -  |
| B2  | 0.25| 0.1| -  | -  | -  | -  | 0.2 | -  | -  | 0.2 | -  | -  | 0.2 | -  | -  | -  | 0.2 | -  | -  | -  | -  |
| B1~C1| B1 | C1 | C2 | C3 | C4 | C5 | W_B | 5.21| 0.05| B1~C1| B1 | C1 | C2 | C3 | C4 | C5 | C6 | W_B | 6.25| 0.04 |
| C1  | 1  | 0.33| 0.33| 4  | 0.5| 0.13| -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |
| C2  | 3  | 1  | L  | 5  | 3  | 0.34| -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |
| C3  | 3  | 1  | L  | 4  | 3  | 0.33| -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |
| C4  | 0.25| 0.2| 0.25| 1  | 0.5| 0.06| -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |
| C5  | 2  | 0.33| 0.33| 2  | 0.14| -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |
| B2~C2| B2 | C2 | C3 | C4 | -  | -  | W_B | 3.02| 0.02| B2~C2| B2 | C2 | C3 | C4 | -  | -  | -  | -  | W_B | 3.05| 0.05 |
| C2  | 1  | 0.25| 0.33| -  | -  | 0.12| -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |
| C3  | 4  | 1  | L  | 2  | 0.56| -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |
| C4  | 3  | 0.5| L  | 1  | 0.32| -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  | -  |

Note: In the table, W_B is the eigenvector, λ_max is the maximum eigenroot, and C.R. is the random consistency ratio.
Table 2. Weight table of evaluation indices and evaluation parameters.

| The evaluation indices | weight | Evaluation parameters | weight | The evaluation indices | weight | Evaluation parameters | weight |
|------------------------|--------|-----------------------|--------|------------------------|--------|-----------------------|--------|
| Reservoir conditionsB₁ | 0.8    | Coal seam thicknessC₁₁ | 0.10   |Reservoir conditionsB₁ | 0.8    | Coal seam thicknessC₁₁ | 0.07   |
|                        |        | gas contentC₁₂        | 0.27   |                        |        | gas contentC₁₂        | 0.18   |
|                        |        | Resource abundanceC₁₃ | 0.26   |                        |        | Resource abundanceC₁₃ | 0.17   |
|                        |        | Tectonic coalC₁₄      | 0.05   |                        |        | Tectonic coalC₁₄      | 0.04   |
|                        |        | Buried depthC₁₅       | 0.11   |                        |        | Buried depthC₁₅       | 0.08   |
|                        |        | -                     |        |                        |        | -                     | 0.27   |
| Preservation conditionsB₂ | 0.2  | Ratio of roof mudstone thicknessC₂₁ | 0.02 |Preservation conditionsB₂ | 0.2  | Ratio of roof mudstone thicknessC₂₁ | 0.03 |
|                        |        | Fault fractal dimension valueC₂₂ | 0.11 |                        |        | Fault fractal dimension valueC₂₂ | 0.11 |
|                        |        | Structural curvature valueC₂₃ | 0.06 |                        |        | Structural curvature valueC₂₃ | 0.07 |
A consistency test was performed on each discriminant matrix, and was continuously iterated adjusting the matrix parameters until the C.R was < 10%.

Through the fuzzy evaluation model constructed above, combined with the weight of each evaluation index in Table 2, multi-level fuzzy comprehensive evaluation results of the study area can be obtained, and the advantage map of CBM development potential evaluation of Baoan blocks. As shown in Figure 12, the favorable areas of the No. 8 coal seam were mainly distributed in the northeast of the study area, where the potential for CBM development was low in the middle. The evaluation results of the No. 15 coal seam were considerably different from those of the No. 8 coal seam, and the area with the largest CBM development potential was located southeast of the study area. Similar to the evaluation results of the No. 8 coal seam, the development potential in the middle of the study area was the lowest.

**TOPSIS based on variation coefficient method**

Technique for order preference by similarity to an ideal solution (TOPSIS), also known as an ideal solution, is a common and effective method in multi-objective decision analysis. TOPSIS sorts the evaluation objects according to their proximity to the most ideal goal, calculates the distance between the evaluation objects and the optimal and worst schemes, and evaluates the relative advantages and disadvantages on this basis (Sun and Li, 2021; Yang et al., 2020a, 2020b).

Compared with the analytic hierarchy process, the TOPSIS method does not require the selection of the membership function and index weight; therefore, there is no subjective influence of the membership function and index weight. Herein, we chose the variation coefficient method to determine the weights of the evaluation indices, which is based on the general law of data samples, using the arithmetic mean and variance to determine the relative weight of each index. It can better reflect the relative weights of every index (Qiu et al., 2020; Sivaraja et al., 2020).

First, the original data were positively and normalized. For some indicators, the larger the data value, the greater the advantages of the evaluation object. However, for others, the opposite was true. Therefore, the more advantageous the evaluation object, the more appropriate the data needed to be forward-processed to increase the index. Equation 3 was used to forward the extremely small data, and to eliminate the impact of data dimension and the data needed to be standardized.

![Figure 12](image_url). Distribution map of CBM potential evaluation by multi-level fuzzy mathematics (a: No. 8, b: No. 15).
Equation 4 was used to standardize the data:

\[ x_i = x_{\text{max}} - x_i \] 

\[ t_i = \frac{x_i}{\sqrt{\sum_{i=1}^{n} x_i^2}} \]  

After processing the data, a standardized decision matrix \( T \) comprising \( n \) blocks and \( m \) evaluation indices was constructed.

\[
T = \begin{bmatrix}
    t_{11} & \cdots & t_{1n} \\
    \vdots & \ddots & \vdots \\
    t_{m1} & \cdots & t_{mn}
\end{bmatrix}
\]  

The weight of each evaluation index was calculated using the coefficient of variation method.

\[
t_j = \frac{1}{n} \sum_{i=1}^{n} t_{ij}
\]

\[
\overline{S}_j^2 = \frac{1}{n-1} \sum_{i=1}^{n} (t_{ij} - \overline{t}_j)^2
\]

Assuming \( v_i = |\overline{t}_i| / S_i \), then, normalized \( v_i \) was the weight of each indicator,

\[
\omega_i = \frac{v_i}{\sum v_i}
\]

According to the above method, the weights of the No. 8 and No. 15 coal seams in the study area were determined, as shown in Table 3.

The matrix of positive ideal solution \( Z^+ \) and negative ideal solution \( Z^- \) were established:

\[
T^+ = (\max t_{i1}, \max t_{i2}, \ldots, \max t_{im})
\]

\[
T^- = (\min t_{i1}, \min t_{i2}, \ldots, \min t_{im})
\]

The Euclidean distance between each target value and the ideal value is calculated, and the distance \( D_i^- \) from the evaluated blocks \( d_i \) to the positive ideal solution is:

\[
D_i^+ = \sqrt{\sum_{j=1}^{n} (t_{ij} - t_j^+)^2}
\]

The distance from alternative \( d_i \) to the negative ideal solution, \( D_i^- \) is:

\[
D_i^- = \sqrt{\sum_{j=1}^{n} (t_{ij} - t_j^-)^2}
\]

The comprehensive evaluation index of each program to be evaluated is calculated, and Equation 13 is used to calculate the proximity between each evaluation object and the optimal program \( f_i \).

\[
f_i = \frac{D_i^+}{D_i^- + D_i^+}
\]

The larger the \( f_i \) value, the farther scheme \( d_i \) was from the negative ideal solution and the closer it was to the positive ideal solution, and block \( d_i \) had more advantages. Based on the above calculation process, the potential evaluation advantages of CBM in the study area can be obtained, and
Table 3. Weight of each selected indices of No. 8 and No. 15 coal seam in the study area.

| Indices | Coal thickness | Buried depth | gas content | Resource abundance | structure coal | roof mudstone thickness ratio | permeability | fault fractal dimension | structural curvature |
|---------|----------------|--------------|-------------|-------------------|----------------|-----------------------------|--------------|------------------------|---------------------|
| No.8    | 0.06           | 0.05         | 0.09        | 0.11              | 0.21           | 0.03                        | -            | 0.22                   | 0.23                |
| No.15   | 0.07           | 0.05         | 0.09        | 0.12              | 0.15           | 0.07                        | 0.02         | 0.26                   | 0.17                |
Figure 13 shows the potential evaluation advantages of CBM development in the Baoan blocks. We can see from Figure 13 that the dominant areas of coal seam development in the No. 8 and No. 15 coal seams were mainly distributed in the middle of the research area, which was considerably different from the evaluation results of the multilevel fuzzy mathematics method.

Principal component analysis

Principal component analysis is a method of dimension reduction. The dimensionality reduction of a set of variables with a large correlation and mutual influence was transformed into a new set of variables with a weak correlation. During data processing, the total variance of the variable remained unchanged, and the variance of the new variable was controlled to ensure the new variable contained as much original information as possible. The greater the variance of the new variable, the less the original information is lost. The new variable with the greatest variance was defined as the first and second principal components (Hower et al., 2021; Ye et al., 2022).

Due to the large difference in the order of magnitude of each indicator, data should be standardized first in data processing, and the original data should be converted into dimensionless data to make it more adequately comparable. A standardized decision data matrix, Z, was constructed. Equation 4 was used for data standardization, and Equations 14 and 15 were used to calculate the correlation coefficient matrix, R.

\[
R = (r_k)_{n \times n} \tag{14}
\]

\[
r_k = \frac{1}{n-1} \sum_{i=1}^{n} Z_{ij}Z_{ik} \quad (k = 1, 2, \ldots, m) \tag{15}
\]

The eigenvalues and variances of the decision matrix were calculated (Table 4), and the principal components with eigenvalues greater than one were retained in order of magnitude. The principal component scores of CBM potential evaluation in the study area were calculated by combining the principal component score coefficients (Table 5).

Using principal component scores, the characteristic roots of the principal components were taken as the weights of each principal component to conduct a comprehensive evaluation of CBM development potential in the study area, as shown in Figure 14.
Table 4. Characteristic values and variance of evaluation indices.

| No.8 | Components | The eigenvalue | Percentage of variance% | The cumulative % | No.15 | Component | The eigenvalue | Percentage of variance% | The cumulative % |
|------|------------|----------------|--------------------------|------------------|-------|-----------|----------------|--------------------------|------------------|
| 1    | 2.37       | 29.66          | 29.66                    |                  | 1     | 2.64      | 29.36         | 29.36                    |                  |
| 2    | 1.75       | 21.87          | 51.53                    |                  | 2     | 1.64      | 18.24         | 47.60                    |                  |
| 3    | 1.19       | 14.91          | 66.44                    |                  | 3     | 1.31      | 14.57         | 62.17                    |                  |
| 4    | 0.97       | 12.13          | 78.56                    |                  | 4     | 1.10      | 12.20         | 74.37                    |                  |
| 5    | 0.72       | 9.01           | 87.57                    |                  | 5     | 0.70      | 7.75          | 82.12                    |                  |
| 6    | 0.67       | 8.42           | 95.99                    |                  | 6     | 0.61      | 6.73          | 88.85                    |                  |
| 7    | 0.32       | 3.97           | 99.96                    |                  | 7     | 0.59      | 6.59          | 95.44                    |                  |
| 8    | 0.00       | 0.04           | 100.00                   |                  | 8     | 0.40      | 4.47          | 99.92                    |                  |
| -    | -          | -              | -                        |                  | 9     | 0.01      | 0.08          | 100.00                   |                  |
Table 5. Principal component score coefficient table

| Indices                        | Components 1 | Components 2 | Components 3 | Components 1 | Components 2 | Components 3 | Components 4 |
|--------------------------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Resource abundance             | 0.52         | 0.40         | −0.12        | 0.59         | 0.07         | −0.07        | 0.07         |
| Tectonic coal                  | 0.46         | −0.36        | −0.07        | −0.41        | 0.30         | −0.14        | −0.12        |
| Coal thickness                 | 0.46         | −0.14        | 0.28         | 0.39         | −0.13        | −0.43        | 0.31         |
| Ratio of roof mudstone thickness| 0.31         | 0.09         | 0.35         | 0.03         | 0.11         | 0.55         | 0.54         |
| gas content                    | 0.29         | 0.57         | −0.33        | 0.52         | 0.19         | 0.19         | −0.16        |
| Fault fractal dimension        | −0.25        | 0.49         | −0.08        | −0.10        | −0.45        | −0.37        | 0.43         |
| Buried depth                   | 0.23         | −0.29        | −0.58        | −0.18        | 0.35         | 0.02         | 0.61         |
| Tectonic curvature             | 0.12         | 0.15         | 0.57         | 0.03         | −0.38        | 0.55         | 0.01         |
| permeability                   | -            | -            | -            | 0.11         | 0.61         | −0.11        | 0.04         |
As seen in Figure 14, the favorable areas for CBM development in the Baoan blocks were mainly concentrated in the surrounding areas of the study area, and the favorable areas for CBM development in the No. 8 and No. 15 coal seams showed similar distribution ranges. The difference was that the favorable areas for CBM development in the No. 8 coal seam were mainly distributed in the northeast and northwest of the study area. Combined with the above research results, we found that the favorable area of CBM development was consistent with the gas content distribution range, and the main controlling factor of CBM development was gas content. The most favorable area for CBM development in the No. 15 coal seam is distributed in the southwest, followed by the northwest. According to the contour map above, permeability was the main controlling factor for the CBM development potential in the No. 15 coal seam.

Comparison of selection methods

According to the above research results, the multilevel fuzzy mathematics method, TOPSIS, and principal component analysis method differed significantly in the evaluation results of CBM development potential in Baoan blocks, especially the evaluation results of TOPSIS. The results of the principal component analysis and fuzzy mathematics method are relatively similar, and it is believed that the development potential of CBM around the study area is the greatest. However, the evaluation results of TOPSIS indicate that the central part of the study area is the most favorable area for CBM development. Combined with previous research results (Hu et al., 2015), the evaluation results of multilevel fuzzy mathematics and principal component analysis were better, which accords with the actual development situation of the research area.

The evaluation results of the three evaluation methods adopted in this study are considerably different, especially those based on TOPSIS. The three methods were based on the geological characteristics of the study area. However, TOPSIS is more dependent on the overall law and the characteristics of the data samples. The more numerous the data, the more evident the law, and the more consistent the real situation. Qiu et al. (2020) predicted the groundwater in the Xinwen Coalfield based on over 90 data points. Li et al. (2020) evaluated the development potential of shale gas blocks in China based on 55 sary indicators using the TOPSIS. These studies used a large number of data samples to reflect the real situation, such that results were more reasonable and
in line with the actual development situation. In addition, compared with the coefficient of variation method adopted in this study to determine the weight of indicators, other studies chose to use grey relative analysis (GRA) or the entropy weight method to determine the weight of indicators. Unnecessary information can be removed during data preprocessing (Qiu et al., 2020; Sun and Li, 2021). Multilevel fuzzy mathematics and principal component analysis have been widely applied in the Qinshui Basin and Ordos Basin of China (Wang et al., 2018; Zhang et al., 2016). Compared with TOPSIS, these two methods are more suitable for the evaluation of favorable CBM development areas under complex geological conditions.

In addition, when using fuzzy mathematics to evaluate the potential of CBM development, the importance of each index at the same level is subjective, but the evaluation results are basically consistent with the evaluation results of principal component analysis, indicating that the multilevel fuzzy mathematics method is within an acceptable range, with the importance of each index set and the error of the result of subjective factors of this method being reasonable.

In the evaluation and analysis of the CBM potential in the study area, due to the different development levels of different coal seams in the study area, the permeability index of the CBM potential evaluation of the No. 8 coal seam was lower than that of No. 15. Comprehensive analysis of the above evaluation results shows that the No. 8 coal seam principal component analysis and multilevel fuzzy favorable area evaluation results are consistent with the No. 15 coal seam evaluation results, indicating that the loss of some parameters has little effect on the overall development potential evaluation results. However, more detailed data are required to select suitable locations for further CBM development.

Conclusions

In this study, the development potential of CBM in Baoan blocks was evaluated using multilevel fuzzy mathematics, TOPSIS based on coefficient of variation, and principal component analysis. The favorable area of CBM development in Baoan blocks was predicted by comprehensive analysis of the three evaluation results. The conclusions of this study are as follows:

1. The coal of No. 8 is relatively thin, with an average thickness of 2.15 m, and its development is unstable and the average burial depth was 586.75 m. The coal of No.15 was relatively thick, with an average thickness of 6.5 m. The burial depth was 674.86 m. The roof and floor of the No. 8 coal are mainly mudstone with a thickness of 0.3–9.6 m, and the sealing effect is adequate.
2. The fault dip angle in the study area is relatively large, with an average dip angle of 55°. There are few faults in No. 8 and a large number of small faults in No. 15. The tectonic development in the eastern part of the study area is complex, whereas that in the western part is relatively simple. The average thickness of No. 8 is 0.59 m, and the average thickness of No. 15 is 1.29 m. The gas content of the No. 8 coal seam is high in the northeast and south and low in the northwest and southwest The gas content of sample No. 15 was high in the south and low in the middle. The distribution of gas content in the study area was mainly controlled by the structure.
3. The northwestern and northeastern parts of the No. 8 coal seam are suitable for CBM development. The northwest and southwest parts of the No. 15 coal seam are favorable blocks for CBM. Considering the evaluation results comprehensively, we determined that the amount of data in the study area affects the evaluation results of the favorable area, especially the TOPSIS, which is not suitable for evaluating the CBM of the Xinjing Baoan blocks. In the evaluation process of CBM favorable area selection, the impact of missing geological evaluation indicators on the results can be ignored.
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