

Article

Geological Evaluation of In-Situ Pyrolysis Development of Oil-Rich Coal in Tiaohu Mining Area, Santanghu Basin, Xinjiang, China

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Abstract

The applicability of the in-situ pyrolysis of oil-rich coal is highly dependent on regional geological conditions. In this study, six major geological factors and 19 key parameters influencing the in-situ pyrolysis of oil-rich coal were systematically identified. An analytic hierarchy process incorporating index classification and quantification was employed in combination with the geological features of the Tiaohu mining area to establish a feasibility evaluation index system suitable for in-situ development in the study region. Among these factors, coal quality parameters (e.g., coal type, moisture content, volatile matter, ash yield), coal seam occurrence characteristics (e.g., seam thickness, burial depth, interburden frequency), and hydrogeological conditions (e.g., relative water inflow) primarily govern pyrolysis process stability. Surrounding rock properties (e.g., roof/floor lithology) and structural features (e.g., fault proximity) directly impact pyrolysis furnace sealing integrity, while environmental geological factors (e.g., hazardous element content in coal) determine environmental risk control effectiveness. Based on actual geological data from the Tiaohu mining area, the comprehensive weight of each index was determined. After calculation, the southwestern, central, and southeastern subregions of the mining area were identified as favorable zones for pyrolysis development. A constraint condition analysis was then conducted, accompanied by a one-vote veto index system, in which the thresholds were defined for coal seam thickness (≥ 1.5 m), burial depth (≥ 500 m), thickness variation coefficient ($\leq 15\%$), fault proximity (≥ 200 m), tar yield ($\geq 7\%$), high-pressure permeability (≥ 10 mD), and high-pressure porosity ($\geq 15\%$). Following the exclusion of unqualified boreholes, three target zones for pyrolysis furnace deployment were ultimately selected.

Keywords: geological condition; analytic hierarchy process; favorable area optimization; pyrolysis furnace site selection



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1. Introduction

As a widely recognized special coal resource, the development of oil-rich coal is mainly divided into two categories: ground pyrolysis and underground in-situ pyrolysis. The underground in-situ pyrolysis of oil-rich coal transfers heat to the coal seam by heating methods such as electric heating, heat injection well, microwave or radio frequency, so that

the organic matter in the coal can be cracked in situ under the action of heat, and the solid state is transformed into oil and gas resources (liquid and gaseous), which is conducive to promoting the diversified development and utilization of coal [1,2].

The successful implementation of the in-situ pyrolysis of oil-rich coal is highly dependent on the fine understanding and scientific evaluation of the geological conditions of the target coal reservoir. The physical properties, chemical properties, geological structure, in-situ stress field and geothermal field of coal seam and surrounding rock constitute the core geological background of thermal-fluid-solid-chemical multi-field coupling, which directly determines the pyrolysis efficiency, oil and gas migration output efficiency, engineering feasibility and environmental impact [3–5]. Therefore, it is necessary to evaluate the geological conditions of the in-situ pyrolysis of oil-rich coal.

The most important thing in the geological evaluation of the in-situ pyrolysis development of oil-rich coal is the selection of evaluation indicators and evaluation methods. Although there are few geological evaluation studies on the development of oil-rich coal resources, from the perspective of resource attributes, oil-rich coal is a special kind of coal resource. Its comprehensive evaluation still belongs to the category of coal resource evaluation [1]. Therefore, comprehensive evaluation methods such as analytic hierarchy process (AHP), fuzzy mathematics and tabular classification are also applicable to the geological evaluation of the in-situ pyrolysis of oil-rich coal [6–11]. Li Huabing introduced the analytic hierarchy process for the first time in the evaluation of the development potential of oil-rich coal resources in the Shenfu mining area. He took the four factors of resource occurrence, coal seam occurrence, development technology and social and environmental benefits as the main indicators, and subdivided them into 10 evaluation parameters to establish an evaluation system for the development potential of oil-rich coal resources, but did not refine and quantify the evaluation indicators of development geological conditions [12]. In the geological evaluation of development, not only should the quality of coal and the occurrence state of the coal seam be considered, but also the sealing and hydrogeological conditions of the strata in in-situ mining [13,14]. The sealing of the stratum mainly considers the stability of surrounding rock conditions and tectonic activities. The coal seam of the roof and floor, with thick dense limestone, bauxite rock and mudstone, is far away from the fault, which is conducive to the improvement of in-situ pyrolysis sealing. Hydrogeological conditions are the key control factors of in-situ pyrolysis engineering. The water resistance of roof and floor and the occurrence characteristics of groundwater directly affect the operation stability of in-situ pyrolysis technology [15,16]. In addition, the environmental geological risks of in-situ pyrolysis engineering should also be considered, especially the release of harmful elements in coal during pyrolysis [17].

The Santanghu basin in Xinjiang, China has abundant coal resources. Jurassic strata represent the principal coal-bearing series, with a cumulative area approaching $3 \times 10 \text{ km}^2$. Oil-rich coal seams are primarily located in the upper Baodaowan formation (J_1b^2), the Sangonghe formation (J_1s), and the lower Xishanyao formation (J_2x^1). With a tar yield of approximately 13.67%, these coals are generally classified as high-oil types, providing a substantial basis for in-situ pyrolysis development [18]. Currently, coal mining and coalbed methane testing in this area are predominantly limited to shallow depths. The absence of a clear evaluation method and undefined favorable zones has hindered the development of medium- and deep-layer resources. Accordingly, this study focused on the Tiaohu mining area within the Santanghu basin, constructed a dedicated evaluation index system, selected a suitable evaluation methodology, and identified favorable areas for the in-situ pyrolysis of oil-rich coal, with the objective of promoting the diversified development and utilization of coal resources in the study area.

2. General Geology

The tectonic units of the Santanghu basin are distinctly divided (Figure 1a) and comprise three first-order tectonic belts: the northern thrust belt, central depression belt, and southwest thrust belt [19]. As the core area of the basin, the central sag zone exhibits thick sedimentary sequences, well-preserved strata, and abundant coal, oil, and gas resources, thus serving as a key zone for resource exploration. Six major mining areas are distributed within the central depression belt, where the topography typically exhibits elevated margins and a lower central region [19]. Tiaohu mining area is situated in the northwestern portion of the Tiaohu sag (Figure 1a). The structural pattern in the southwest of the area is relatively simple, whereas the northeast displays more complex structures. The western zone is dominated by an east-dipping monoclinic structure, whereas the eastern zone features a south-dipping monoclinic structure. The regional fault DF26 cuts across the northwest, forming the W2 syncline to the west of the fault and the M3 anticline to the south (Figure 1b).

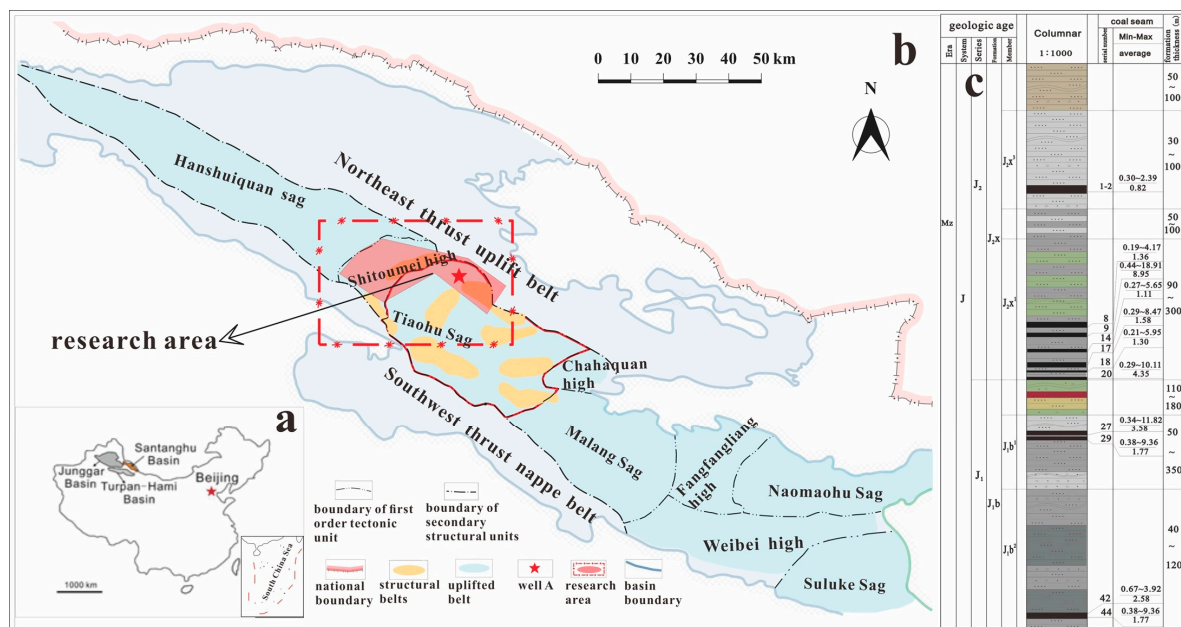


Figure 1. Geological survey map of the study area. (a) The Santanghu basin tectonic unit, (b) the study area geographical location, and (c) the study area strata.

In the Tiaohu mining area, the coal-bearing strata include the upper and lower sections of the Xishanyao formation from the Middle Jurassic and the upper and lower sections of the Baodaowan formation from the Lower Jurassic system (Figure 1c). Among these, the lower section of the Xishanyao formation is the principal coal-bearing unit, characterized by extensive development across the area and a stable stratigraphic horizon. This section contains a large number of coal seams with substantial thickness, rendering it the main coal seam occurrence zone in the study area. The coal seam thickness and stability vary significantly among the upper Xishanyao formation and the upper and lower Baodaowan formations. The upper Xishanyao formation exhibits an unstable horizon with low coal content [20,21]. A total of 41 coal seams were identified in the study area (Figure 1c). This study focuses on the No. 9 coal seam within the upper portion of the lower member of the Xishanyao formation. The seam is regionally developed across the study area, with local absence in the northwest. Investigation incorporated 56 boreholes, with locations detailed in Figure 2. Seam thickness ranges from 0.44 m to 18.86 m, averaging 8.95 m. The sequence structure of coal seams is mostly simple, and there are no dirt band or 1–2 thin interlayers.

There are 3–4 layers of dirt band in the local abnormal area. The composition of dirt band is mainly carbonaceous mudstone and fine-grained siltstone.

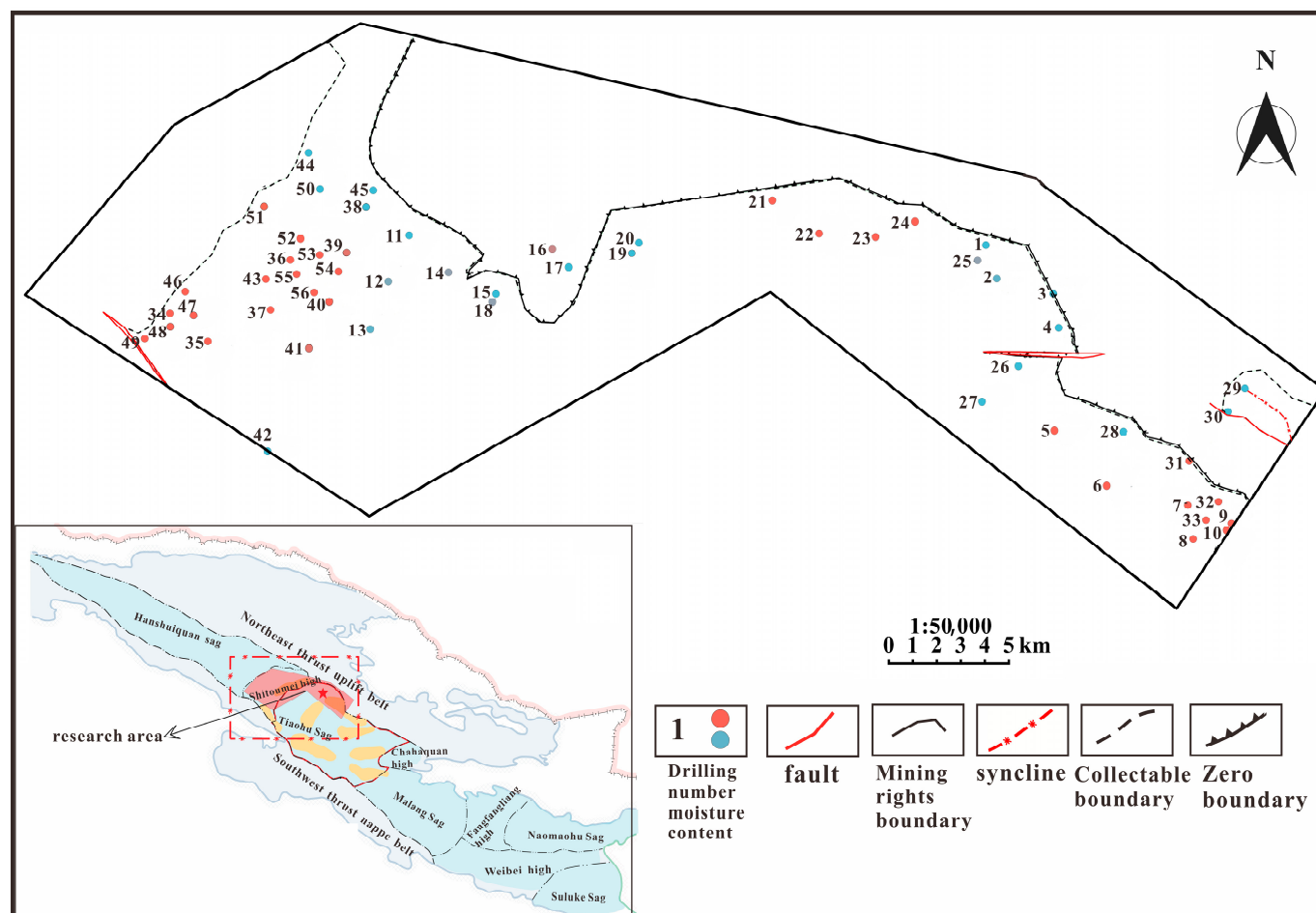


Figure 2. Drilling location in the Tiaohu mining area.

3. Evaluation Method

3.1. Construction of Evaluation Index System

Based on the core elements of the coal pyrolysis reaction process, including stability, furnace closure, and environmental risk control, a geological suitability evaluation index system for in-situ pyrolysis was established. By integrating previous research findings with geological exploration data from the study area, 6 categories and 19 subcategories of evaluation indicators were systematically extracted from geological conditions relevant to in-situ pyrolysis. Because there are few experiments related to the in-situ pyrolysis of oil-rich coal, the gasifier equipment for underground coal gasification after comprehensive analysis is, in principle, similar to the pyrolysis furnace in the in-situ pyrolysis experiment. In terms of coal quality conditions and coal seam occurrence conditions, the evaluation index of gasifier site selection for underground coal gasification is referred. The geological parameters to be evaluated were further classified into four grades: Class I (excellent), Class II (good), Class III (medium), and Class IV (poor). This classification system provides a quantitative basis for a comprehensive evaluation, with the specific results presented in Table 1 [12,13,22–25].

Table 1. Table of evaluation index system for in-situ pyrolysis geological selection site selection in the study area.

Serial Number	First Classification	Secondary Classification	Classification Evaluation Level							
			I (Excellent)		II (Good)		III (Medium)		IV (Poor)	
1	Coal rock and coal quality conditions U1	Types of coal U11	HM	CY	SM	QM	FM	PM	WY	JM
2		Moisture content (%) U12	0–15		15–35		35–55		>55	
3		Ash content (%) U13	0–10		10–20		20–50		>50	
4		Volatile producibility (%) U14	>37		37–20		10–20		<10	
5		Sulfur content (%) U15	0–1.00		1.01–3.00		3.01–4		>4	
6	Coal seam occurrence condition U2	Coal seam thickness (m) U21	5		5–15		2–5		>15; <2	
7		Dip angle of coal seam (°) U22	35		12–35		35–70		<12; >70	
8		Burial depth of coal seam (m) U23	500–1000		100–500		>1000		<100	
9		Gangue coefficient (%) U24	<20		20–30		30–60		>60	
10		Gangue layers U25	0		1		2		>2	
11		Variation coefficient of coal Thickness (%) U26	≥95		85–95		75–85		75	
12	Rock condition U3	Roof lithologic U31	SHY	NY	SZNY	FSY	XSY	ZSY	CSY	LY
13		Lithology of floor U32	SHY	NY	SZNY	FSY	XSY	ZSY	CSY	LY
14	Closure condition U4	Distance from fault (km) U41	<0.5		0.5–1		1–1.5		≥1.5	
15	Hydrographic condition U5	Relative water inflow (m ³ /t) U51	<3		3–10		10–15		>15	
16	Environmental condition U6	Fluorine (μg/g) U61	≤100		100–200		200–400		>400	
17		Arsenic (μg/g) U62	≤4		4–25		25–80		>80	
18		Chlorine (μg/g) U63	≤0.05		0.05–0.150		0.150–0.300		>0.300	
19		Phosphorus (μg/g) U64	≤0.010		0.010–0.050		0.050–0.100		>0.100	

Annotation: HM (brown coal); CY (lean coal); SM (gas coal); FM (fat coal); PM (meager coal); WY (anthracite); JM (coking coal); SHY (limestone); NY (mudstone); SZNY (sandy mudstone); FSY (siltstone); XSY (fine sandstone); ZSY (medium sandstone); CSY (coarse sandstone); LY (conglomerate).

3.2. Determination of Index Weight

Based on the AHP, the weight of each geological index is determined. The procedure for implementing AHP was as follows. (1) A hierarchical model was established based on an evaluation index system. (2) According to the principle of importance ranking, the scale of each indicator level was defined, and an evaluation matrix was constructed. (3) The matrix was then utilized to compute the weights of each index. (4) A consistency check was performed to validate the authenticity of the results [13,22,24]. The calculation process of the weight of each geological index is as follows below.

An AHP-based weight calculation was performed. According to the evaluation system for the preferred in-situ pyrolysis area, a comparison judgment matrix was constructed. If an element A in layer A was related to factors B₁, B₂, . . . , B_n in the next layer, a judgment matrix as shown in Table 2 can be established.

Table 2. Establish a judgment matrix table.

A _k	B ₁	B ₂	...	B _n
B ₁	b ₁₁	b ₁₂	...	b _{1n}
B ₂	b ₂₁	b ₂₂	...	b _{2n}
⋮	⋮	⋮	⋮	⋮
B _n	b _{n1}	b _{n2}	...	b _{nn}

In the judgment matrix, b_{ij} denotes the ratio of the influence of the factors B_i and B_j on A_k. The values were assigned using a nine-point scale method. The meanings are presented

in Table 3, where scale 1 indicates that B_i and B_j exert the equal influence on $A\Omega$, and scale 9 signifies that B_i has an absolutely stronger influence than B_j .

$$b_{ij} = \frac{b_{ik}}{b_{jk}} \quad (i, j, k = 1, 2, \dots, n) \quad (1)$$

Table 3. Scale b_{ij} meaning table.

b_{ij}	Implication
1	B_i factor and B_j factor are equally important.
3	B_i factor and B_j factor are slightly important.
5	B_i factor and B_j factor are obviously important.
7	B_i factor and B_j factor are strongly important.
9	B_i factor and B_j factor are extremely important.
2, 4, 6, 8	Between the above two adjacent elements

If all elements of the judgment matrix satisfy the conditions specified in Formula (1), the matrix can be considered completely consistent. Based on factors such as coal quality, seam occurrence, surrounding rock, structural features, hydrology, and environmental conditions, the judgment matrix was constructed, as shown in Table 4.

Table 4. Judgment matrix A-B table.

Index	U1	U2	U3	U4	U5	U6
U1	1	0.5	1	1	0.5	1
U2	2	1	2	2	1	2
U3	1	0.5	1	1	0.5	1
U4	1	0.5	1	1	0.5	1
U5	2	1	2	2	1	2
U6	1	0.5	1	1	0.5	1

In this study, weighted calculations were conducted for the judgment matrix, accompanied by a consistency check. Specifically, the maximum eigenvalue $\lambda_{\max}$ of the comparison matrix and corresponding eigenvector W were first calculated. Based on these results and utilizing two key indicators, consistency index and relative consistency ratio, a consistency test was performed to assess the rationality and reliability of the matrix. If the matrix passes the test, the normalized eigenvector W can be accepted as the weight vector. Otherwise, the matrix should be revised accordingly. One method of determining the weight coefficient involves multiplying the elements in each row of the matrix, as follows:

$$\bar{u}_1 = \prod_{j=1}^n b_{ij}$$

The product opens an n -th power, as follows:

$$u_i = \sqrt[n]{\bar{u}_1}$$

This is normalized, i.e., converted into a feature vector, as follows:

$$W = \frac{u_i}{\sum_{i=1}^n u_i}$$

In addition to numerical calculations, consistency checking is a critical component of the analytic process. Subjective cognition and judgment frequently influence the formation of a judgment matrix, resulting in significant uncertainty and a high probability of produc-

ing inaccurate evaluation outcomes. To ensure the scientific validity and accuracy of the overall analysis and minimize the matrix inconsistency caused by subjective error, strict consistency testing is essential. Therefore, the maximum eigenvalue of the decision matrix was adopted as a diagnostic measure.

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^n \frac{(BW)_i}{W_i}$$

The consistency index is calculated as follows:

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

The random consistency ratio is calculated as follows:

$$CR = \frac{CI}{RI} \quad (2)$$

RI represents the average random consistency index, which corresponds to order n of the judgment matrix. The relationship is presented in Table 5.

Table 5. Average random consistency index table.

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46

In general, when $CR = 0.1$, the model is considered to have inadequate consistency and should be revised accordingly.

Following the calculation, the weights assigned to coal quality, seam occurrence, surrounding rock, sealing, hydrological, and environmental conditions were 0.1252, 0.2496, 0.1252, 0.1252, 0.2496, and 0.1252, respectively. The detailed results for both first- and second-level index weights are presented in Table 6.

Table 6. In-situ pyrolysis geological index weight table.

Serial Number	Type	Weight	Detailed Evaluation	
				Weight
1	U1	0.1252	U11	0.3048
2			U12	0.1327
3			U13	0.2310
4			U14	0.2653
5			U15	0.0663
6	U2	0.2496	U21	0.2886
7			U22	0.1297
8			U23	0.1911
9			U24	0.1317
10			U25	0.1479
11			U26	0.1110
12	U3	0.1252	U31	0.6667
13			U32	0.3333
14	U4	0.1252	U41	1
15	U5	0.2496	U51	1

Table 6. Cont.

Serial Number	Type	Weight	Detailed Evaluation	
				Weight
16	U6	0.1252	U61	0.3333
17			U62	0.3333
18			U63	0.1667
19			U64	0.1667

3.3. Mathematical Evaluation Method of Geological Selection

The comprehensive index method, the fuzzy comprehensive evaluation method, the list classification method, and the grey clustering method represent the most classical mathematical approaches used in quantitative analysis [26]. The core advantage of the fuzzy comprehensive evaluation model is that it can effectively deal with such complex information that combines qualitative and quantitative factors and which has unclear boundaries. The model can systematically integrate multiple key evaluation indicators, transform the measured data into a fuzzy relationship by constructing a membership function, and use a reasonable weight system (such as the AHP method) for comprehensive quantitative evaluation. Finally, a comprehensive evaluation value representing the favorable degree is obtained, which intuitively reflects the advantages and disadvantages of the evaluation unit [27–29]. Therefore, we choose the fuzzy comprehensive evaluation model. The model was implemented based on fuzzy mathematics. The evaluation level was determined based on the weight of each criterion. Membership functions are typically categorized into two theoretical paradigms: linear and nonlinear. Membership determination relies on binary comparison sorting, reasoning methods, intuitionistic approaches, and fuzzy statistical analysis [30] (Table 7). In this study, the trapezoidal membership function was applied because of its effective balance between computational simplicity and result accuracy for calculating membership degrees.

Table 7. Common membership function table of the fuzzy mathematics comprehensive evaluation method.

Index Types	Excellent	Medium	Poor
cost-oriented	$A(x) = \begin{cases} 1 & x \leq u_1 \\ \frac{u_2-x}{u_2-u_1} & u_1 < x < u_2 \\ 0 & x \geq u_2 \end{cases}$	$A(x) = \begin{cases} 0 & x \leq u_1 \\ \frac{x-u_1}{u_2-u_1} & u_1 < x \leq u_2 \\ \frac{u_3-x}{u_3-u_2} & u_2 < x < u_3 \\ 0 & x \geq u_3 \end{cases}$	$A(x) = \begin{cases} 0 & x \leq u_2 \\ \frac{x-u_2}{u_3-u_2} & u_2 < x < u_3 \\ 1 & x \geq u_3 \end{cases}$
Types between cost-oriented and benefit-oriented	$A(x) = \begin{cases} 0 & x \leq u' \\ \frac{x-u'}{u_2-u'} & u' < x \leq u_2 \\ \frac{u'-x}{u'-u_2} & u_2 < x < u' \\ 0 & x \geq u_3 \end{cases}$	$A(x) = \begin{cases} 0 & x \leq u' \\ \frac{x-u'}{u_2-u'} & u' < x \leq u_2 \\ \frac{u'-x}{u'-u_2} & u_2 < x < u' \\ 0 & x \geq u_3 \end{cases}$	$A(x) = \begin{cases} 1 & x \leq u_1 \\ \frac{u'-x}{u'-u_1} & u_1 < x \leq u' \\ 0 & u' < x \leq u' \\ \frac{x-u'}{u_3-u'} & u' < x < u_3 \\ 1 & x \geq u_3 \end{cases}$
benefit-oriented	$A(x) = \begin{cases} 0 & x \leq u_2 \\ \frac{x-u_2}{u_3-u_2} & u_2 < x < u_3 \\ 1 & x \geq u_3 \end{cases}$	$A(x) = \begin{cases} 0 & x \leq u_1 \\ \frac{x-u_1}{u_2-u_1} & u_1 < x \leq u_2 \\ \frac{u_3-x}{u_3-u_2} & u_2 < x < u_3 \\ 0 & x \geq u_3 \end{cases}$	$A(x) = \begin{cases} 1 & x \leq u_1 \\ \frac{u_2-x}{u_2-u_1} & u_1 < x < u_2 \\ 0 & x \geq u_2 \end{cases}$

4. Evaluation of Favorable Area of Target Coal Seam in the Study Area

4.1. Quantification of Regional Geological Indicators

According to the quantitative requirements for the selected area, it is necessary to systematically compile geological index data for each borehole and quantify qualitative

indicators. The following presents the quantitative process of drilling data analysis for the No. 9 coal seam in the Tiaohu mining area in detail.

4.1.1. Coal Quality Conditions

The coal rock and coal quality indices of each borehole in the No. 9 coal seam of the Tiaohu mining area are presented in Schedule S1. By integrating these data with the borehole distribution across the study area, the regional characteristics of coal rock formations and coal-forming conditions were systematically analyzed.

(1) Coal type

The in-situ pyrolysis suitability of coal types increased in the following order: coking coal, anthracite, lean coal, fat coal, gas coal, lean coal, long-flame coal, and lignite. The No. 9 coal seam in the study area primarily comprised long-flame coal (41CY) and locally contained non-caking coal (31BN), with minimal variation in coal seam quality.

(2) Moisture content

The average water content in each development unit of the No. 9 coal seam ranged from 2.77% to 6.74%, with a mean value of 4.75%. According to the contour map of water content for the No. 9 coal seam (Figure 3), the moisture levels were generally higher in the northeastern and north-central regions of the study area and lower in the northwest. Overall, the water content exhibited a slight increasing trend from west to east, although the range of variation remained limited.

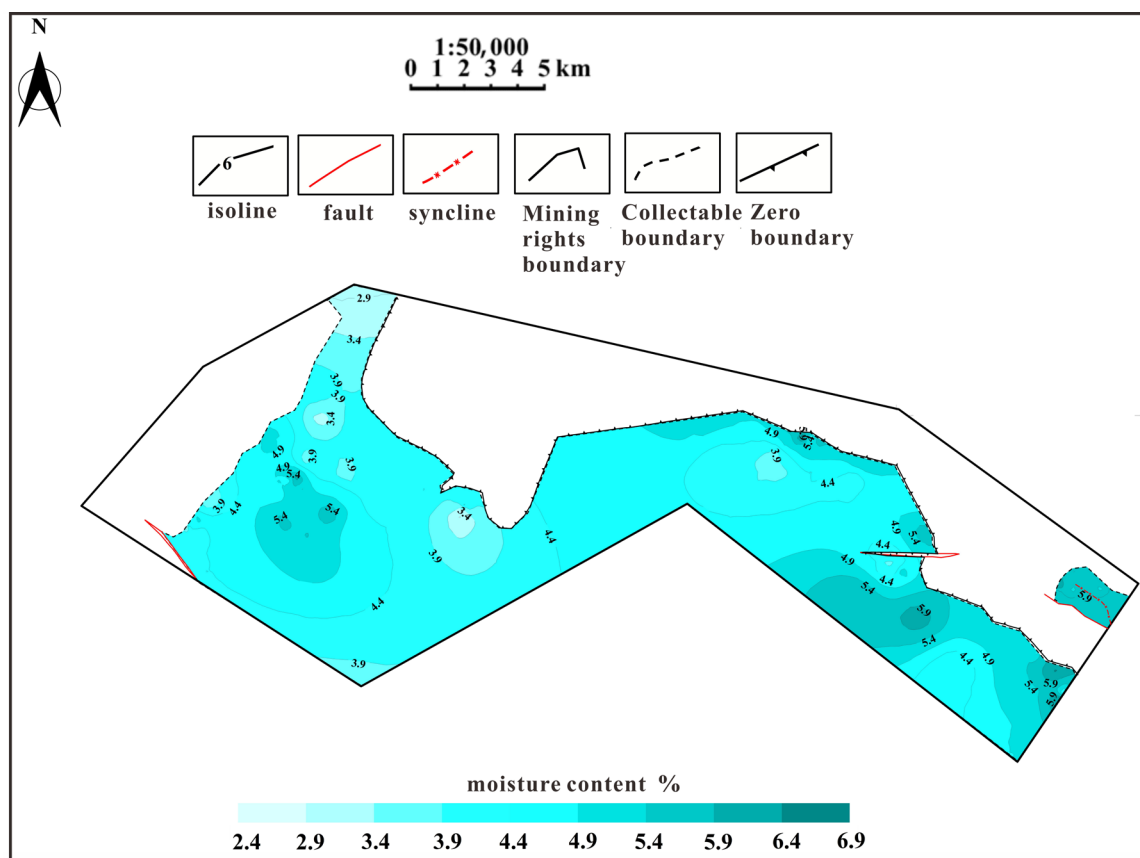


Figure 3. Contour map of water content of No. 9 coal seam in the study area.

(3) Ash yield

The average ash yield of the coal seam ranged from 1.79% to 37.27%, with a mean value of 11.62%. Based on the contour map of ash yield for the No. 9 coal seam (Figure 4),

the spatial distribution pattern was as follows. The ash yield was relatively high in the northwest, northeast, and southeast corners of the study area, whereas lower levels were observed in the southwest and northeast. Overall, the ash yield increased from north to south with relatively stable regional variations.

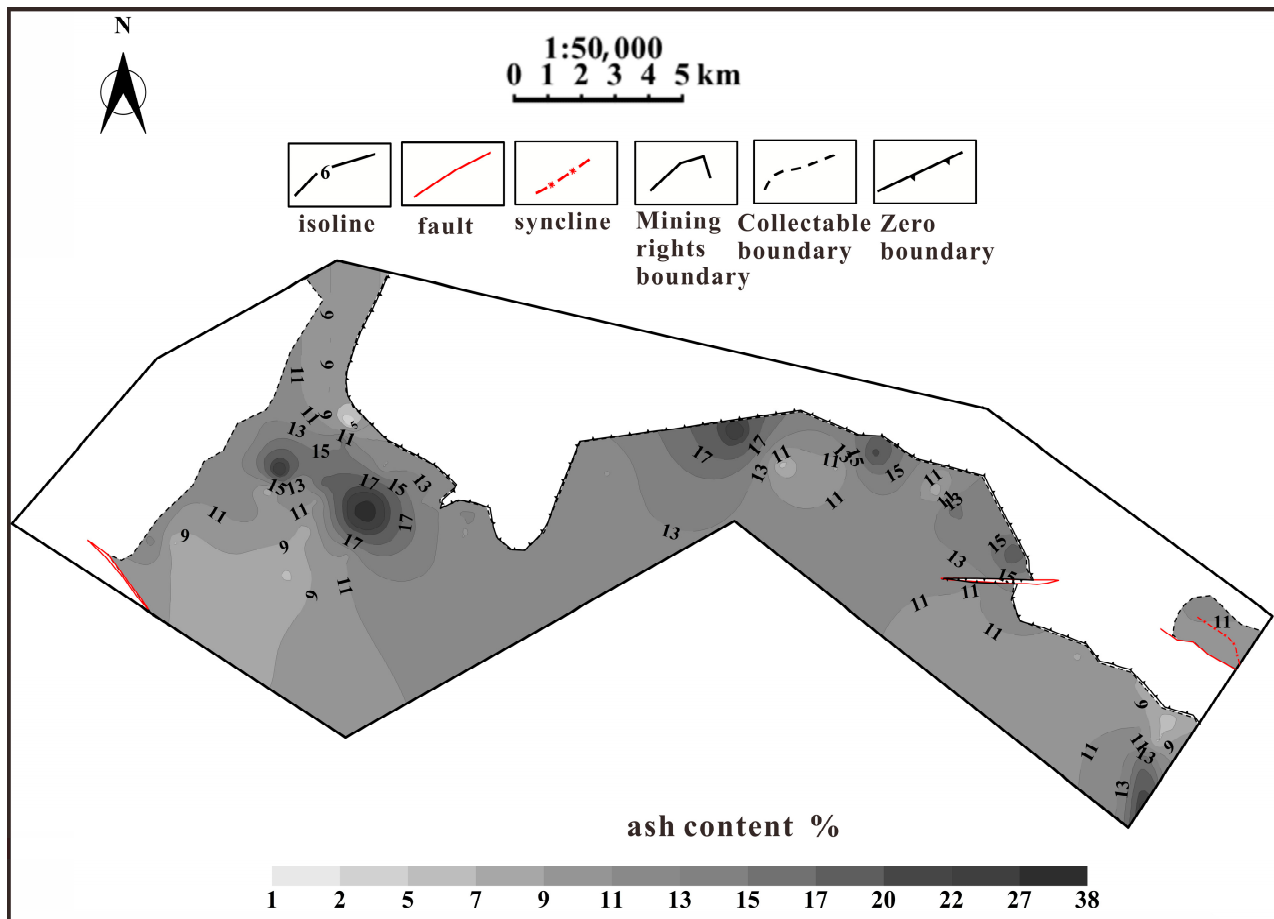


Figure 4. Raw coal ash contour map of the No. 9 coal seam in the study area.

(4) Volatile yield

The average volatile yield of the No. 9 coal seam in the study area ranged from 29.28% to 53.12%, with a mean value of 39.57%. As shown in the contour map of volatile yield (Figure 5), the spatial distribution was higher in the northern and southeastern parts of the study area and lower in the west. Overall, the volatile yield exhibited an increasing trend from east to west with a relatively wide variation range.

(5) Sulfur content

The average sulfur content of the No. 9 coal seam in the study area ranged from 0.1% to 1.1%, with a mean value of 0.27%. Overall, the variation was relatively small. According to the contour map of sulfur content (Figure 6), sulfur levels were higher in the central and western regions and lower in the southwest, central, and southeast. Overall, the sulfur content exhibited an increasing trend from east to west with a relatively large overall range.

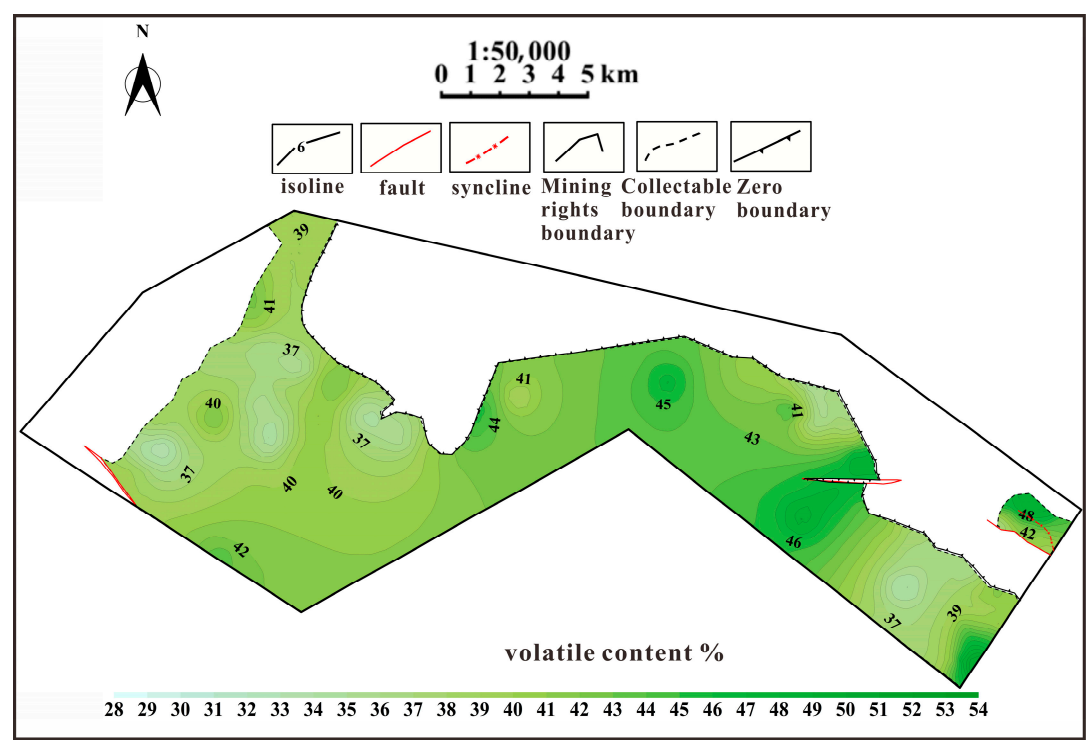


Figure 5. Volatile matter (Vdaf) contour map of the No. 9 coal seam in the study area.

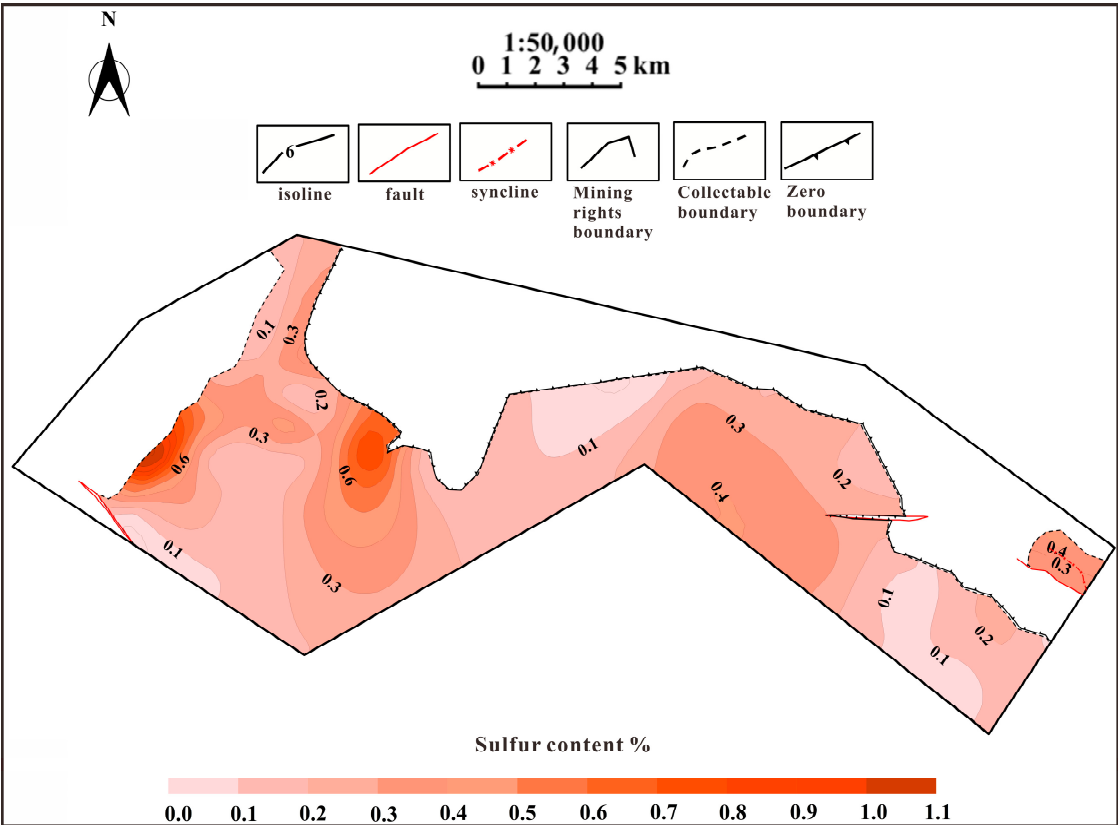


Figure 6. Isoline of total sulfur (St-d) of raw coal in the No. 9 coal seam in the study area.

4.1.2. Coal Seam Occurrence Conditions

The No. 9 coal seam in the study area contained a minor amount of gangue, with a simple to medium structure (0–4 gangue layers), and was classified as a relatively stable

medium-to-thick seam type. The seam thickness ranged from 0 to 18.46 m, with an average of 8.74 m. The mineable seam thickness ranged from 0.84 to 18.46 m, averaging 8.59 m. The No. 9 coal seam, as part of the Xishanyao formation, is a recoverable thick coal seam across the entire area and is characterized by thin-middle-thick lateral variation (Schedule S2).

4.1.3. Surrounding Rock Conditions

The roof strata of the No. 9 coal seam in the study area primarily consists of fine sandstone and siltstone, with localized occurrences of mudstone, medium sandstone, coarse sandstone, and carbonaceous mudstone. The floor is predominantly composed of siltstone and mudstone with interbedded layers of coarse sandstone, fine sandstone, medium sandstone, and carbonaceous mudstone. The gangue layer consists mainly of mudstone, carbonaceous mudstone, siltstone, and high-carbon mudstone. Interbedded siltstones and high-carbon mudstones were observed in some locations (Schedule S3).

4.1.4. Closed Condition

The distance from each borehole to the fault in the No. 9 coal seam ranged from 0.36 to 11.22 km, with an average of 4.74 km (Schedule S4).

4.1.5. Hydrogeological Conditions

As a core indicator in the comprehensive evaluation of hydrogeological conditions, water inflow prediction is essential to ensure mine safety. This section focuses on calculating the water inflow for the No. 9 coal seam within the study area. By systematically integrating the water inflow prediction models for each sub-mining area, a tailored prediction system was constructed to assess the water inflow under pyrolysis furnace conditions. Numerical simulation, large-well, and analogy methods have been commonly employed to estimate mine water inflow. The experimental results indicate that the numerical simulation and analog methods exhibited a higher spatial correlation, whereas the large-well method tended to produce systematic positive deviations [31]. Based on the geological context of the study area, and to enhance the prediction accuracy and support the pyrolysis furnace design, the analogy method was selected for water inflow estimation. The calculation formula is as follows:

$$Q = \frac{Q_1 S F}{S_1 F_1}$$

where Q (m^3/t) represents the pyrolysis furnace, Q_1 represents the measured water inflow of each sub-mining area in the Dajing mining area, S represents the maximum water level drop depth (m) at the location of the pyrolysis furnace, F denotes the area of the pyrolysis furnace (km^2), S_1 denotes the maximum water level drop depth (m) of each sub-mining area in Tiaohu, and F_1 refers to the area of each sub-mining area in the study area (km^2).

The relative water inflow of the main coal seam (the No. 9 coal seam) for each borehole in the study area ranged from 0 to $0.33 \text{ m}^3/\text{t}$, with the average value of $0.15 \text{ m}^3/\text{t}$, as detailed in Schedule S5.

4.1.6. Environmental Geological Conditions

The 25 trace elements in coal have been internationally recognized as environmentally significant. Based on their environmental impact, these elements can be classified into four categories. Class I elements (As, Cd, Cr, Hg, and Se) pose serious ecological hazards. Class IIA elements (B, Cl, F, Mn, Mo, Ni, and Pb), particularly B, Mn, and Mo, exhibit strong leaching and migration potentials. In addition to their mobility, Cl and F accelerate the corrosion of atmospheric acidification engineering materials. Class IIB elements (Be, Cu, P, Th, U, V, and Zn) are associated with combined pollution effects; among them, U and Th present radioactive risks, while Be has carcinogenic properties. Class III elements

(such as Ba, Co, Sb, Sn, and Tl) mainly include Ba and Tl, which adversely affect biological health. Therefore, prior to in-situ pyrolysis, it is essential to analyze the concentration characteristics of hazardous elements in coal.

The fluorine content (F_{ad}) of the raw coal in the No. 9 coal seam ranged from 13 to 94 $\mu\text{g/g}$, with an average of 44 $\mu\text{g/g}$. It was classified as ultra-low-to-high fluorine coal (SLF-HF) but predominantly ultra-low-to-low fluorine coal (SLF-LF). The arsenic content (As_d) ranged from 0 to 5 $\mu\text{g/g}$, averaging 0.69 $\mu\text{g/g}$, and was categorized as low arsenic coal (LAC). The phosphorus content ranged from 0.001% to 0.12%, with a mean of 0.0056%, and belonged to ultra-low phosphorus coal (P-1 to P-2). The chlorine content (Cl_d) ranged from 0.01% to 0.165%, with an average of 0.031%, classifying the coal as ultra-low-to-medium chlorine coal (CL-1–CL-3). Overall, the No. 9 coal seam was dominated by ultra-low-to-low chlorine coal (CL-1–CL-2) (Schedule S6).

Surrounding rock diffusion and seepage migration can be observed when the pyrolysis products are dissolved and transported by groundwater [32–34]. The migration of gaseous pollutants through fractures presents a threat to groundwater, forming two primary migration pathways for pollutants during combustion. Owing to the complexity of multi-field coupled transport mechanisms, this study aimed to establish a quantitative estimation model for the initial dissolution–diffusion–seepage process. The key influencing factors included the size of the pyrolysis furnace, coal seam thickness, surrounding rock permeability, and groundwater dynamics. In this study, the water inflow from the pyrolysis furnace was utilized to characterize hydraulic conditions, whereas other influencing factors were not considered. Parameters such as roof and floor lithology, coal seam thickness, and maximum water consumption have been analyzed in previous studies and are not further discussed in this paper.

4.2. Determination of Membership Degree and Weight of Geological Evaluation Index

Based on the differences in the mechanism of action of the main coal seam geological indicators and research objectives, the trapezoidal function distribution curve was categorized into three types: cost, intermediate, and benefit. Evaluation levels were divided into three categories: favorable area, more favorable area, and unfavorable area. Each index type corresponded to three membership functions (Table 7). The cost type and benefit type membership functions each included three hierarchical parameters, whereas the intermediate membership function included five parameter settings [3].

Based on the classification criteria listed in Table 1, the membership degrees of geological indicators were determined using the classification criteria for borehole water inflow, with the specific results shown in Table 8. After establishing the threshold parameter system, the membership function was applied to calculate the three-dimensional membership space of favorable, general, and unfavorable areas. The index judgment matrix $R = \{r_{ij}\}_{m \times 3}$ was then constructed. The subjective weight of each geological index was obtained using an AHP. This approach enables the systematic processing of multi-dimensional indicators and supports the scientific decision-making process.

The membership degrees of the six geological indicators in the study area were evaluated according to the drilling data, grading definitions, and relative weights of each geological index. The calculation types of membership degrees for the six indicators were specified in the evaluation process. For coal quality conditions, coal quality data from each borehole in the No. 9 coal seam were used. Based on the suitability of coal types for in-situ pyrolysis, lignite and long flame coal were assigned a score of 1; gas coal as 2; non-caking coal, weak caking coal, and fat coal as 3; lean coal as 4; anthracite as 5; and coking coal as 6. Using the cost type membership calculation method, the membership degrees for each borehole were assigned according to favorable, more favorable, and unfavorable coal

types for in-situ pyrolysis. Simultaneously, the membership degrees of coal seam moisture, ash, volatile matter, and sulfur were calculated using cost type, cost type, benefit type, and cost type functions, respectively, each indicating the favorability for in-situ pyrolysis. The intermediate membership function method was applied to assess the membership degrees of the No. 9 coal seam's thickness, dip angle, and buried depth, which were categorized as favorable, more favorable, and unfavorable. For the gangue content, gangue layer count, and variation coefficient, the cost type method was used to compute the degree of unsuitability for in-situ pyrolysis. The lithology of the surrounding rock was quantitatively assigned values to evaluate suitability. Specifically, coarse sandstone was scored as 1, medium sandstone as 2, fine sandstone as 3, siltstone as 4, carbonaceous mudstone as 5, and mudstone as 6. A lower value indicates better lithological suitability. The lithological values for each borehole roof were generally between 2 and 6, and the floor lithology ranged between 3 and 6 on average. Based on the surrounding rock conditions, benefit type functions were used to calculate the membership degrees of the roof and floor lithology of the No. 9 coal seam, categorized as favorable, more favorable, and unfavorable. Regarding the fault proximity, where a closer distance implied poorer pyrolysis sealing performance, the benefit type functions were also used to determine the membership degrees. Similarly, by combining the benefit membership functions with the relative water inflow data of the No. 9 coal seam, the membership degrees for in-situ pyrolysis suitability were calculated. Finally, the membership degrees of fluorine, arsenic, chlorine, and phosphorus content in the No. 9 coal seam were computed using the cost type functions and were also classified as favorable, more favorable, and unfavorable for in-situ pyrolysis.

Table 8. The classification definition value of each geological index and the summary of related weights.

Serial Number	Evaluating Indicator	Type	Defined Value of Grading					Weight
			u_1	u'	u_2	u''	u_3	
1	U11	Cost oriented	2		4		5	0.3048
2	U12	Cost oriented	15		35		55	0.1327
3	U13	Cost oriented	10		20		50	0.2310
4	U14	Benefit oriented	10		20		37	0.2653
5	U15	Cost oriented	1		3		4	0.0663
6	U21	Types between cost oriented and benefit oriented	2	5	15	20	25	0.2886
7	U22		12	25	35	45	70	0.1297
8	U23		100	500	600	1000	2000	0.1911
9	U24	Cost oriented	0.2		0.3		0.6	0.1317
10	U25	Cost oriented	1		3		4	0.1479
11	U26	Cost oriented	0.15		0.25		0.35	0.1110
12	U31	Benefit oriented	1		2		4	0.6667
13	U32	Benefit oriented	1		2		4	0.3333
14	U41	Benefit oriented	2		4		7	1
15	U51	Cost oriented	3		10		15	1
16	U61	Cost oriented	100		200		400	0.3333
17	U62	Cost oriented	4		25		48	0.3333
18	U63	Cost oriented	0.04		0.15		0.3	0.1667
19	U64	Cost oriented	0.01		0.05		0.1	0.1667

Based on the analysis of the six geological condition types, the evaluation process involved multiplying the weight matrix W by the index judgment matrix R using matrix operations to obtain the evaluation result matrix B . Matrix B consists of m rows and 3 columns, where m represents the number of blocks, and each block corresponds to three evaluation grade values: b_{i1} , b_{i2} , and b_{i3} . The evaluation results of each block were

analyzed. According to the principle of maximum membership degree, the grade with the highest value was selected as the final evaluation result for the block. The specific evaluation results are presented in Schedule S7.

4.3. Comprehensive Evaluation

Based on a comprehensive evaluation using multi-level fuzzy mathematics, the coal seam drilling units were divided into four levels according to their membership degree: favorable area (greater than 0.7), more favorable area (0.6 to 0.7), more unfavorable area (0.5 to 0.6), and unfavorable area (less than 0.5).

The total area of the study region was approximately 563.73 km², of which the evaluation area of the No. 9 coal seam was approximately 326.28 km².

The favorable zones for in-situ pyrolysis were primarily concentrated in blocks 1-1, 1-2, 1-3, and 1-4 of the mining area, corresponding to the red areas in Figure 7. In these blocks, the membership values exceeded 0.70. The geological conditions, including coal quality (U1), coal seam occurrence (U2), surrounding rock (U3), sealing (U4), hydrological (U5), and environmental factors (U6), were relatively favorable. The membership degrees for these areas ranged between 0.70 and 0.88.

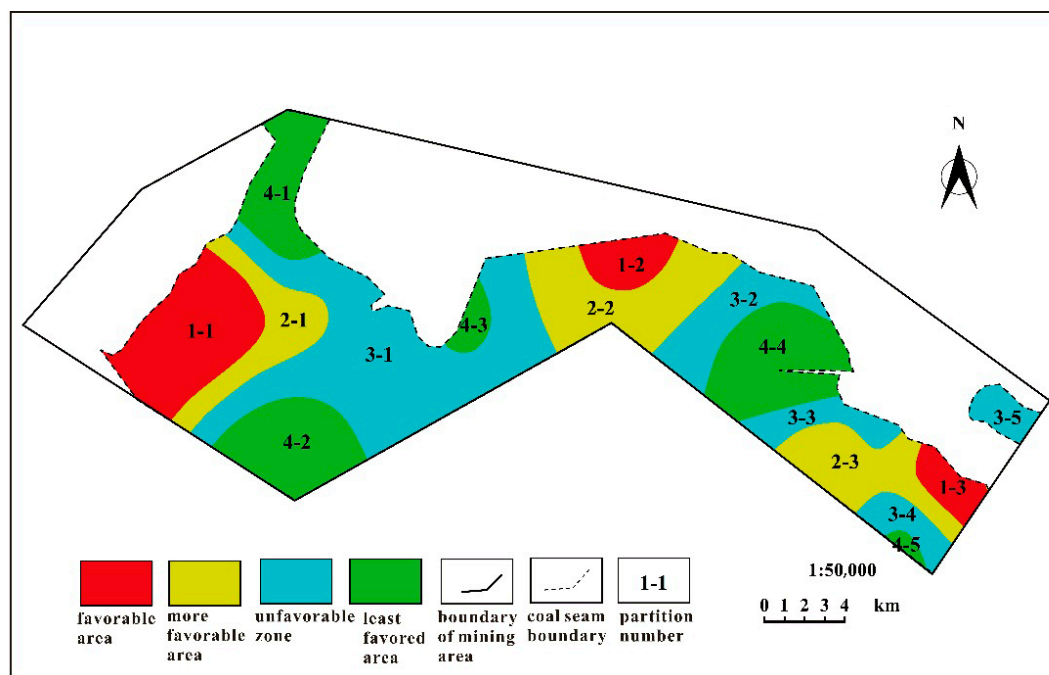


Figure 7. Favorable zoning of in-situ pyrolysis of the No. 9 coal seam.

The more favorable areas were mainly located in blocks 2-1, 2-2, and 2-3 of the mining area, as shown in the yellow region in Figure 7. In general, U1, U2, U4, U5, and U6 were favorable, whereas U3 was moderate. The membership values in these areas fell between 0.60 and 0.70.

The generally favorable areas were primarily distributed in blocks 3-1, 3-2, 3-3, 4-3, and 4-5 of the mining area, corresponding to the blue zone in Figure 6. In these areas, U1, U4, U5, and U6 were favorable, whereas U2 and U3 were moderate. The membership values for these regions ranged between 0.50 and 0.60.

The unfavorable areas were located in blocks 4-1, 4-2, 4-3, 4-4, and 4-5 of the mining area, which are marked in green in Figure 6. Although U1, U4, and U6 were relatively good, U2, U3, and U5 were generally less favorable. The membership values in these zones were all below 0.5.

5. Geological Evaluation of In-Situ Pyrolysis Furnace Target Area in a Favorable Area

5.1. Geological Evaluation of Target Area Optimization of Pyrolysis Furnace

The geological selection for in-situ pyrolysis involved the systematic integration and quantification of geological conditions in the study area, utilizing mathematical evaluation methods to optimize the sub-blocks arranged for pyrolysis furnace deployment and identify suitable units for implementation. Based on the evaluation results of coal seam development potential, the coal seams were divided into four development grades: favorable area, relatively favorable area, relatively unfavorable area, and unfavorable area. The layout of the pyrolysis furnace adhered to the principles of hierarchical management and control. The favorable area should serve as the core deployment zone, representing the preferred development region. The more favorable area should act as a supplementary layout for alternative development, while the relatively unfavorable and unfavorable areas should be strictly excluded owing to geological constraints. However, because a comprehensive evaluation may mask certain critical unfavorable conditions, not all favorable or more favorable zones are necessarily suitable for pyrolysis furnace deployment. Therefore, it is essential to further screen key geological indicators based on the evaluation of favorable areas. Relying on six geological evaluation indices, including coal quality, coal seam occurrence, surrounding rock, sealing, hydrological, and environmental geological conditions, along with pyrolysis performance indicators, including tar yield, high-pressure permeability, and high-pressure porosity, a more refined assessment was conducted.

5.2. Selection of One-Vote Veto Index

According to the comprehensive evaluation of geological conditions for each borehole and experimental results of in-situ pyrolysis physical properties, the poor geological conditions were mainly reflected in coal seam occurrence conditions (U2), surrounding rock engineering characteristics (U3), and hydrogeological characteristics (U5).

The in-situ pyrolysis physical parameters that reflected poor suitability included coal tar yield, high-pressure permeability, and high-pressure porosity. The weak links of the coal seam occurrence condition (U2) were primarily concentrated in coal-measure parameters, such as coal thickness (U21), coal thickness variation coefficient (U26), dip angle (U22), and burial depth (U23). The sub-category geological indicators with poor surrounding rock conditions (U3) were mainly represented by sub-category indicators, such as roof lithology (U31) and floor lithology (U32). In the category of hydrogeological conditions (U5), poor suitability was mainly associated with relative water inflow (U52).

Given the small variation in coal seam dip angle and gentle structural distribution in the study area, the influence of dip angle on the target optimization was minimal. Therefore, it was not used as a one-vote veto index. The coal seam structure in the study area was simple, with 0–4 layers of gangue, a relatively stable medium-thick to thick seam structure, and was fully recoverable. As a result, the coal seam structure was excluded from the one-vote veto index. The one-vote veto index was primarily selected based on coal tar yield, high-pressure permeability, high-pressure porosity, coal thickness, burial depth, coal thickness variation coefficient, and proximity to large normal faults.

(1) Coal tar yield

Coal with a tar yield over 7% is generally classified as oil-rich coal. Before initiating in-situ pyrolysis, it is essential to ensure that the target coal seam meets this threshold. A large number of pyrolysis simulation experiments demonstrated that aliphatic side chains and weak chemical bonds in coal began to break between 400 and 500 °C, resulting in peak tar yields ranging from 1.93% to 3.67%. When the temperature exceeded 500 °C,

the tar underwent secondary cracking into gas, and the tar yield decreased significantly by approximately 31.8% at 600 °C. Therefore, the in-situ pyrolysis temperature could be controlled between 400 and 500 °C to optimize both energy consumption and economic return [35–38]. Accordingly, tar yield below 7% was selected as the one-vote veto index.

(2) Permeability

According to the in-situ pyrolysis simulation experiments and overburden pore permeability tests (Schedule S8), increasing the pyrolysis temperature (for example, up to 600 °C) initially improved the permeability, reaching 537.6 mD. However, under high pressure (2200 psi), the permeability drops sharply to 55.2 mD, representing an 89.7% decrease, indicating that the high-temperature coal exhibited low mechanical strength and increased stress sensitivity. The experimental results showed that a permeability of at least 10 mD was required to ensure the effective migration of pyrolysis products under high pressure. For instance, the permeability of ST400 coal was 25.6 mD at 2200 psi. The low permeability (less than 10 mD) makes it difficult to inject heat carriers, such as steam or gas, uneven heat transfer, and reduced reaction efficiency. Therefore, the permeability less than 10 mD was selected as the one-vote rejection index.

(3) Porosity

In the pyrolysis simulation and overburden porosity–permeability experiments, the volatile matter in the coal began to decompose and form new pores at 400–500 °C, resulting in porosity levels of approximately 18.8% (as in TH400 coal). However, when the temperature reached 600 °C, the semi-coke began to condense and densify, causing the porosity to increase to 26.4%, while the permeability dropped significantly. Hence, the pore formation and structural stability should be balanced. Under high pressure, the in-situ porosity must exceed 15% to ensure sufficient reservoir space. When the porosity fell below 15%, the storage capacity became inadequate, leading to poor enrichment of pyrolysis products and limited resource recovery. Therefore, a porosity below 15% was selected as the one-vote veto index (Schedule S8).

(4) Coal thickness

Thin coal seams with a thickness of less than 1.5 m experienced rapid heat loss and uneven temperature distribution. For example, the thermal efficiency of a coal seam with a thickness of 0.8 m can decrease by 40 percent, which could lead to an insufficient pyrolysis reaction [37]. In contrast, thick coal seams greater than or equal to 1.5 m can form stable pressure gradients, facilitate the uniform diffusion of heat carriers, and help prevent local overpressure or low-pressure zones [38]. Therefore, coal seams with a thickness less than 1.5 m were selected as a one-vote veto index.

(5) Buried depth

When the buried depth is greater than or equal to 500 m, the natural geothermal gradient (typically approximately 3 °C/100 m) can provide a basic heat source in the range of 45 °C to 60 °C, reducing the external heating energy consumption [39]. In deep coal seams, the in-situ pressure exceeded 10 MPa, which required matching with high permeability (greater than or equal to 10 mD) to ensure mass transfer and suppress premature gas release. This behavior aligned with the experimental observations of permeability reduction under high pressure. Therefore, a buried depth less than 500 m was selected as a one-vote veto index.

(6) Coefficient of variation of coal thickness

When the coefficient of variation exceeded 15%, the thickness of the coal seam fluctuated significantly, and the local variation potentially reached 30%. This resulted in uneven

thermal fields, causing overheating in thin zones (leading to tar cracking) and underheating in thick zones (causing incomplete reactions). Uniform coal seams with a variation coefficient less than or equal to 15% were more suitable for designing consistent well layouts and optimizing heating and recovery strategies [40]. Therefore, a coefficient of variation of coal thickness greater than 15% was selected as a one-vote veto index.

(7) Distance from large normal fault

The in-situ stress conditions near major faults can be complex, and injection during pyrolysis may activate fault slip. For instance, microseismic risk increases by a factor of five when the distance to the fault is less than 150 m, which may lead to gas leakage or formation instability [37]. Additionally, faults may act as conduits for low-temperature water, which has been measured at approximately 25 °C at a depth of 500 m, thereby disrupting the thermal balance and reducing the pyrolysis efficiency. Consequently, a distance from large normal faults less than 200 m was selected as a veto index.

Combined with the above analysis, this study adopted coal tar yield, high-pressure permeability, high-pressure porosity, coal thickness (U21), buried depth (U23), coal thickness variation coefficient (U26), and distance from fault (U41) as one-vote veto indicators (Table 9).

Table 9. Indicators of one-vote rejection threshold table.

Type	Index	Scope of Literature Recommendations	Scope of Recommendations in This Article	The Scope Excluded in This Paper
Pyrolysis physical conditions	Coal tar yield (%)	>7% [39]	≥7	<7%
	Permeability (mD)	≥10	≥10	<10
	Porosity (%)	≥15	≥15	<15
Geological condition	Coal seam thickness (m)	≥0.8 [40] or ≥1.5 [38]	≥1.5 [38]	<1.5
	Depth of embedment (m)	≥500 [38]	≥500	<500
	Variation coefficient of coal thickness (%)	<15 [37]	≥15	>15
	Distance from large normal fault (m)	≥150 [37]	≥200	<200

5.3. Pyrolysis Furnace Target Optimization

The coal thickness, coefficient of variation in the coal thickness, and buried depth of each borehole in the No. 9 coal seam within the study area are presented in Schedule S2. The distance from the fault to each borehole is listed in Schedule S4, and the distance from the roof aquifer is shown in Schedule S5. According to the one-vote veto criteria, all boreholes with coal seams exhibiting any of the following conditions were excluded: buried depth (U23) less than 500 m, coal thickness (U21) less than 1.5 m, coal thickness variation coefficient (U26) exceeding 15%, distance from fault (U41) less than 200 m, average tar yield below 7%, high-pressure permeability less than 10 mD, or high-pressure porosity below 15% in favorable and more favorable areas.

Based on the fuzzy mathematics comprehensive evaluation results and the application of the one-vote veto screening method, the final pyrolysis furnace target areas identified in the No. 9 coal seam of the study area were Blocks 1, 2, and 3 (Figure 8).

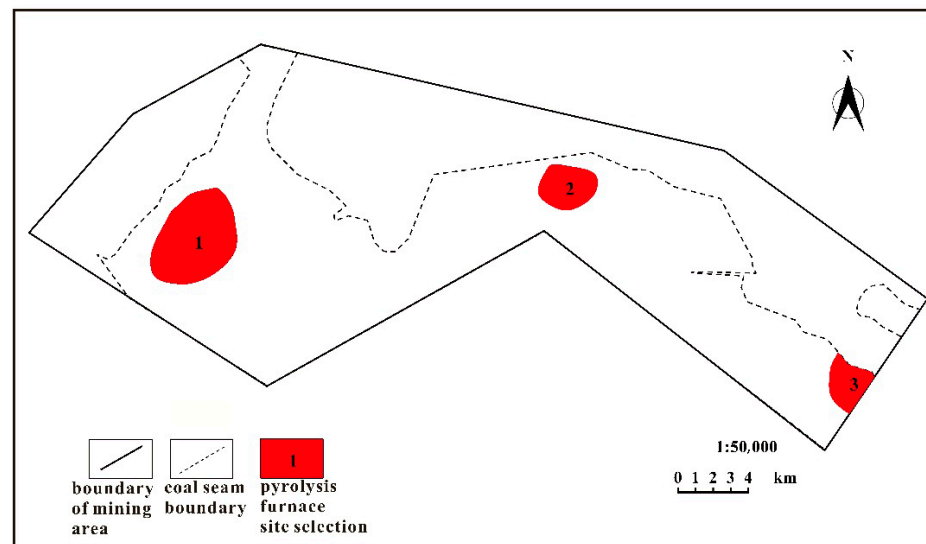


Figure 8. Optimization results of the No. 9 coal seam pyrolysis furnace.

6. Conclusions

The main controlling geological factors of the in-situ pyrolysis of oil-rich coal were analyzed and refined, and geological indices across six categories and nineteen subcategories were established. Based on the AHP and a comprehensive evaluation using fuzzy mathematics, the weights of geological indices were determined. Combined with the geological characteristics of the Tiaohu mining area, a feasibility evaluation index system for in-situ pyrolysis of oil-rich coal was developed. The geological indices in the study area were quantified, and their corresponding comprehensive weights were calculated. Three favorable areas for in-situ pyrolysis of oil-rich coal in the Tiaohu mining area of the Santanghu basin were identified. According to the evaluation results of the 19 geological indicators across six categories, combined with the physical characteristics of coal in the study area, a one-vote veto index system was established. The system included the thresholds for a coal seam thickness greater than or equal to 1.5 m, a buried depth greater than or equal to 500 m, a thickness variation coefficient less than or equal to 15%, a distance from the fault greater than or equal to 200 m, a tar yield greater than or equal to 7%, a high-pressure permeability greater than or equal to 10 mD, and a high-pressure porosity greater than or equal to 15%. Based on this system, three target areas were selected for pyrolysis.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/en18154034/s1>, Schedule S1. Data table of coal rock and coal quality in each borehole of No.9 coal seam in the study area. Schedule S2. The coal seam parameter table of each borehole in No.9 coal seam in the study area. Schedule S3. The lithology table of roof and floor of No.9 coal seam in the study area. Schedule S4. The distance table of No.9 coal seam from fault in the study area. Schedule S5. The relative water inflow table of No.9 coal seam in the study area. Schedule S6. Table of harmful elements content of raw coal in No.9 coal seam in the study area. Schedule S7. The favorable situation membership degree of the second-level geological index of underground pyrolysis of No.9 coal seam in the study area. Schedule S8. The results of the test of the pressure hole permeability test.

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