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**Invited Review**

# Multi-criteria decision evaluation of coal gangue resource utilization schemes: A case study of the taigemiao mining area

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## ABSTRACT

Aiming at the multi-objective and multi-criteria decision-making challenges in the process of coal gangue resource utilization, this study takes the Xinjie Taigemiao mining area as a case and proposes an integrated evaluation model combining the analytic hierarchy process (AHP) with min-max normalization. The model is structured around the sustainable goal of coal gangue resource utilization and establishes a multi-dimensional evaluation index system that includes technical feasibility, economic efficiency, environmental impact, resource-use efficiency, management complexity, and social acceptability. The weights of the indicators are determined by AHP, and each alternative is quantitatively assessed using min-max normalization, thereby achieving a systematic ranking and optimization among multiple schemes. The results indicate that low-level grouting technology performs best in terms of resource-use efficiency, environmental impact, and economic performance, and is identified as the optimal technical pathway for coal gangue resource utilization in this mining area. This study provides systematic and quantifiable methodological support for decision-making in coal gangue resource utilization in mining areas, with a certain degree of universality and potential for broader application.

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## 1 Introduction

Coal, as China's primary energy source and important chemical raw material, plays a fundamental and "ballast" role in ensuring national energy security. However, the coal gangue associated with coal mining has become the largest industrial solid waste in China [1]. Statistics show that from 2011 to 2021, the annual new gangue emissions in China's coal industry ranged from 600 to 750 million tons, with a cumulative stockpile exceeding 7 billion tons, forming nearly 1700 gangue hills [2]. These gangues are stockpiled in the open air for a long time, not only occupying a large amount of land resources but also potentially causing environmental and safety problems such as spontaneous combustion, landslides, and water pollution, which have become a persistent problem restricting the sustainable development of mining areas and ecological environmental protection [3, 4].

To promote large-scale, resourceful, and harmless disposal of coal gangue, various technical routes have been developed, mainly including underground backfilling, building material utilization, land reclamation, and thermal energy utilization. Among them, underground backfilling mining has been applied in many mining areas due to its multiple advantages such as large-scale gangue consumption, surface subsidence control, and release of pressed coal under buildings, water bodies, and railways [5, 6]. However, from the overall perspective of resource utilization, different technical routes have significant differences in technical maturity, economic feasibility, environmental friendliness, resource conversion efficiency, and system management complexity [2–8]. How to scientifically and systematically select schemes has become a key decision-making problem in current gangue treatment and green transformation of mining areas [9–11].

In recent years, various decision-making analysis methods have been widely applied in mining engineering. Structured decision-making methods represented by the analytic hierarchy process (AHP) have been systematically applied in investment analysis, engineering design, and planning scenarios. Research shows that under conditions of limited information, subjective probability analysis based on expert experience can provide effective support for decision-making [12]. With the in-depth application of expert systems in the mining field, the effectiveness of expert judgment as a basis for decision-making has gradually attracted attention. Studies have found that even when screening a group of "high-level" experts, there are still significant differences in expert judgments, and the degree of consensus is insufficient to effectively distinguish the superiority or inferiority of schemes [13, 14]. To address this challenge, the academic community has explored improvement paths from multiple perspectives: for the problem of data deficiency, a method combining expert elicitation techniques and gap analysis is adopted to identify key parameters; to overcome the subjectivity of traditional static weighting, a dynamic expert reliability weighting calculation method is introduced; through sensitivity analysis, "variable risks" sensitive to changes in weights are identified, and Gaussian fuzzy numbers are used to describe rock mass heterogeneity to achieve reliable evaluation of risk levels [15–18]. These explorations provide valuable references for decision-making in complex mining conditions.

It is easy to observe that current research mostly focuses on a certain type of technology or relies on expert experience and qualitative analysis. Although they have certain guiding significance [19–21], they often fail to comprehensively integrate the comprehensive performance of multiple dimensions such as technology, economy, environment, resources, and management when facing complex decisions with multiple objectives and attributes, especially lacking a systematic quantitative comparison framework [22–24]. Therefore, constructing a scientific, transparent, and reproducible multi-criteria evaluation system is of great significance for promoting rational decision-making in coal gangue resource utilization.

To this end, this study takes the Xinjie Taigemiao mining area as a case study, and proposes a comprehensive evaluation model combining AHP and min-max normalization method [25, 26] around the overall goal of coal gangue resource utilization. By establishing a multi-level evaluation index system, systematically integrating key dimensions such as resource utilization efficiency, technical feasibility, economy, environmental impact, and management complexity, and using a combination of quantitative and qualitative methods, various utilization schemes are scientifically ranked and optimized, aiming to provide systematic decision support and methodological reference for the selection of utilization paths of coal gangue resource in similar mining areas.

## 2 Theoretical method

AHP is a multi-criteria decision analysis method that combines qualitative and quantitative approaches, proposed by the American operations researcher T.L. Saaty in the 1970s [27, 28]. It considers the subordinate relationships and interactions among various factors, processes them hierarchically and organizationally, and constructs a top-down multi-level structural model. It is particularly suitable for dealing with complex decision problems that are difficult to analyze completely quantitatively. The algorithm is simple and practical, with strong operability and high accuracy, so it is often used in the field of multi-index decision-making. The core of the AHP method is to achieve quantitative decision-making through the following four steps:

### 2.1 Establish a hierarchical structure model

The decision problem is decomposed into a target layer (TL), a criterion layer (CL), and a scheme layer (SL), constructing an orderly hierarchical structure. The target layer is the content to be finally evaluated or determined by the evaluation system; the criterion layer is the specific evaluation criteria or dimensions to be considered to achieve the goal, governed by the target layer, also affecting the scheme layer; the scheme layer is the set of all specific schemes that can solve the problem, to be decided. See Figure 1.

### 2.2 Construct a judgment matrix

Starting from the criterion layer of the hierarchical structure model, for each factor at the same level subordinate to each factor at the upper level, pairwise comparisons are made using a 1–9 scale method to construct a judgment matrix. The choice of the 1–9 range is not arbitrary but based on the human psychological ability to distinguish differences between things. Research shows that when people compare multiple things simultaneously, the number of levels they can effectively distinguish is usually within 7±2, i.e., 5 to 9. Therefore, the 1–9 scale method fits human intuitive judgment well. See Table 1.

For example, through qualitative analysis and judgment, if it is considered that $a_i$ is "significantly more important" than $a_j$, then according to the 1–9 scale method, the corresponding "relative importance" is 5 (Table 1). Therefore, in the judgment matrix, $a_{ij} = 5$, and correspondingly, $a_{ji} = 1/5$; if it is considered that $a_i$ is "strongly more important" than $a_j$, the corresponding "relative importance" is 7, so $a_{ij} = 7$, and $a_{ji} = 1/7$.

To scientifically determine the relative importance of evaluation indicators, this study employs the delphi method, inviting experts in relevant fields to conduct pairwise comparisons and assign scores to the criterion

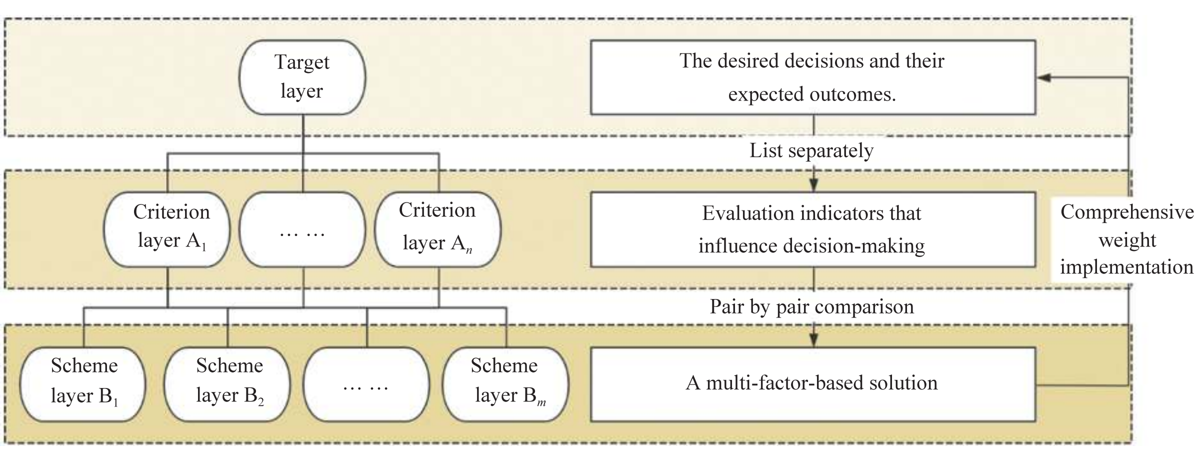


**Figure 1** Hierarchical analysis model

**Table 1** 1 Degree of judgment matrix and its meanings

| Degree indicators | | |
|---|---|---|
| Relative importance | Definition | Explanation |
| 1 | Equal importance | Two factors are equally important |
| 3 | Slightly more important | The former is slightly more important than the latter |
| 5 | Significantly more important | The former is significantly more important than the latter |
| 7 | Strongly more important | The former is strongly more important than the latter |
| 9 | Extremely more important | The former is extremely more important than the latter |
| 2, 4, 6, 8 | Intermediate values between two adjacent judgments | Compromise between the two |
| Reciprocals | | The ratio of the importance of factor $i$ to factor $j$ is $a_{ij}$. The ratio of the importance of factor $j$ to factor $i$ is $1/a_{ij}$ |

layer indicators using the 1–9 scale method (and its reciprocals). By statistically calculating the median and quartiles of the experts' assignment results, the expert opinions are assessed. When opinions are inconsistent, anonymous revisions are carried out iteratively until all assigned scores are consistent; namely, the interquartile range becomes zero.

The median and interquartile range are common statistical measures used to describe the central tendency and dispersion of data distribution, with the following calculation equations:

① Median

After sorting a set of data in ascending order, the value located in the middle is the median. For a dataset with a sample size of $n$,

If $n$ is odd, the median is the value at position $(n+1)/2$.

If $n$ is even, the median is the average of the values at positions $n/2$ and $1+n/2$.

② Quartiles

Quartiles divide the sorted data into four equal parts. The commonly used first quartile ($Q_1$) and third quartile ($Q_3$) are defined as the value below which 25% of the data falls and the value below which 75% of the data falls, respectively.

③ The interquartile range (IQR) is defined as

$IQR = Q_3 - Q_1$

The common calculation method for quartiles (based on positional interpolation) is

Position of $Q_1$: $L_{Q1} = (n+1)/4$;

Position of $Q_3$: $L_{Q3} = 3(n+1)/4$

If the position is an integer, the value at that position is taken; if it is a decimal, linear interpolation is performed between the two adjacent values.

According to the above method, after pairwise comparisons of all factors in the criterion layer, the judgment matrix $\boldsymbol{A} = (a_{ij})_{n\times n}$ can be obtained, as shown in Figure 2, where $a_{ij}$ represents the importance degree of factor $i$ relative to factor $j$.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}$$

**Figure 2** Judgment matrix

## *2.3 Calculate the weight vector and consistency test*

Hierarchical single sorting refers to calculating the relative importance of a factor relative to a factor at the upper level and sorting them according to importance. The root method is the most commonly used calculation method for hierarchical single sorting, i.e., geometrically averaging each row vector of the judgment matrix, then normalizing, and the resulting column vector is the weight vector. The calculation steps of the root method are as follows:

① Calculate the product $M_i$ of each row of the judgment matrix

$$M_i = \prod_{j=1}^{n} a_{ij} \quad i = 1, 2, \cdots, n \tag{1}$$

② Calculate the $n$-th root of $M_i$, denoted as $W_i$:

$$W_i = \sqrt[n]{M_i} \tag{2}$$

③ Normalize the vector $\boldsymbol{W}=[W_1, W_2, \ldots, W_n]^{\mathrm{T}}$:

$$W_i = \frac{W_\mathrm{i}}{\sum_{j=1}^{n} W_\mathrm{j}} \tag{3}$$

The weight vector of the evaluation indicators in the criterion layer is obtained, satisfying $\sum_{j=1}^{n} W_j = 1$ and $W_j \geq 0$, where $W_j$ represents the relative importance of the j-th indicator.

$$W \approx \begin{bmatrix} W_1 \\ W_1 \\ \vdots \\ W_n \end{bmatrix}$$

Perform consistency test on the judgment matrix. If the relative consistency CR of judgment matrix $\boldsymbol{A}$ is less than 0.1, then judgment matrix $\boldsymbol{A}$ is considered feasible and passes the consistency test. Usually, the smaller the CR value (close to 0), the better. If CR is not less than 0.1 and fails the consistency test, return to the step of pairwise comparison to reconstruct a qualified judgment matrix $A$. The calculation of CR is as follows:

$$\begin{cases} \mathrm{CR} = \dfrac{\mathrm{CI}}{RI} \\ \lambda_{\max} = \sum_{i=1}^{n} \dfrac{(AW)_i}{nW_i} \\ \mathrm{CI} = \dfrac{\lambda_{\max} - n}{n-1} \end{cases} \tag{4}$$

where $\boldsymbol{W}$ is the weight vector, and $(AW)_i$ is the vector $\boldsymbol{AW}$ of $i$-th element. The values of RI for 1–9 order judgment matrices are shown in Table 2.

## 2.4 Normalization

Min-max normalization is a commonly used dimensionless data processing method. Its purpose is to map the original indicator data of different schemes ($B_1$–$B_m$) under the influence of various factors in the criterion layer ($A_1$–$A_n$), which have different dimensions, orders of magnitude, and even non-quantifiable original data, into a unified closed interval (usually [0, 1]) through sorting and linear transformation, thereby eliminating the influence of dimensional differences on evaluation results and making the indicators comparable.

Before normalization, all indicators need to be preprocessed. For indicators with clear numerical values, the data are directly used as the original values; for indicators with a numerical range, the median is taken as the original value; for indicators without specific data, a grade score (schemes with similar ranking are given the same grade score) is assigned as the original value based on the grade judgment of the indicator. For example, for 7 different schemes judged to be 5 difficulty levels, values from 1 to 5 are assigned, with 5 being the highest difficulty and 1 the lowest, and schemes with the same grade have the same score.

After obtaining all quantitative data, different linear transformation equations are used according to the different attributes of the indicators:

For benefit-type indicators (larger is better):

$$\mu_i = (x_i - x_{\min})/(x_{\max} - x_{\min}) \tag{5}$$

For cost-type indicators (smaller is better):

$$\mu_i = (x_{\max} - x_i)/(x_{\max} - x_{\min}) \tag{6}$$

where $x_i$ is the original indicator value of scheme $i$, and $x_{\max}$ and $x_{\min}$ are the maximum and minimum values of all schemes under this indicator, respectively. After transformation, all indicator membership degrees $\mu_i$ fall within the [0, 1] interval. For a multi-criteria decision problem containing $m$ schemes and $n$ evaluation indicators, after min-max normalization, the normalized membership matrix $\boldsymbol{B} = (\mu_{ij})_{m \times n}$ is obtained, as shown in Figure 3, where $\mu_{ij}$ represents the normalized membership degree of the $i$-th scheme under the $j$-th indicator.

The advantage of this method is that it reasonably assigns values to factors that cannot be expressed

**Table 2** Average random consistency index value table

| Order $n$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| RI | 0.00 | 0.00 | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 |

$$B = \begin{bmatrix} \mu_{11} & \mu_{12} & \cdots & \mu_{1n} \\ \mu_{21} & \mu_{22} & \cdots & \mu_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \mu_{m1} & \mu_{m2} & \cdots & \mu_{mn} \end{bmatrix}$$

**Figure 3** Normalized matrix of the scheme

quantitatively (such as management difficulty) and retains the relative relationship of the original factors. It is a linear transformation that does not change the distribution characteristics of the data, and the calculation is simple, intuitive, easy to understand and implement.

### *2.5 Calculate the combined weight*

The weights of each layer are combined to obtain the combined weight of the scheme layer relative to the target layer, and the one with the largest weight is the optimal scheme.

## 3 Model construction and evaluation index system

### *3.1 Model and index system construction*

In this study, the target layer is "optimal scheme for coal gangue resource utilization." The result of this decision is the ultimate goal of the hierarchical analysis, and the entire evaluation process revolves around achieving this goal. The criterion layer consists of six key evaluation indicators: gangue treatment capacity, system management difficulty, working face coal output capacity, system investment, additional cost of gangue treatment, and surface subsidence.

The selection of indicators follows the principles of scientificity, systematicness, representativeness, and operability. Initially, indicators closely related to the resource utilization of coal gangue in existing studies were screened out. Then, based on the actual problems that the managers in the Taigemiao mining area were concerned about during the on-site investigation, the final determination was made. Among them, the gangue processing capacity directly measures the absorption scale of the technical scheme and is the "hard constraint" for resource utilization; the difficulty of system management reflects the complexity of project implementation and affects the operational stability; the coal output capacity of the working face measures the impact on coal mining efficiency and reflects the technical coordination; the system investment and the increase in gangue processing costs respectively represent economic feasibility from the perspectives of one-time investment and long-term operation; the surface subsidence volume directly reflects the environmental impact and embodies the requirements of green mine construction.

These indicators together constitute the criterion system for measuring the pros and cons of various backfilling technology schemes. The scheme layer includes seven mainstream backfilling technologies participating in the comparison: fully mechanized solid filling, fully mechanized paste filling, continuous mining and continuous filling, low-level grouting, separated layer grouting, adjacent grouting, and low-level slurry injection. The ultimate goal of AHP is to rank these schemes and select the optimal one, as shown in Figure 4.

Based on the six key evaluation indicators, quantitative data and analysis ranking are performed for coal gangue resource utilization schemes:

1) Gangue treatment capacity (larger is better): low-level grouting (1.33 million t/a) > fully mechanized solid filling (0.88 million t/a) > separated layer grouting (0.79 million t/a) > fully mechanized paste filling (0.68 million t/a) > continuous mining and continuous filling (0.26 million t/a) > adjacent grouting (0.25 million t/a) = low-level slurry injection (0.15 million t/a).

2) System management difficulty (smaller is better): fully mechanized paste filling > fully mechanized solid filling > continuous mining and continuous filling > separated layer grouting ≈ low-level grouting > adjacent grouting ≈ low-level slurry injection. The more new underground engineering, equipment, systems, etc., the more complex the system and the greater the system management difficulty.

3) Working face coal output capacity (larger is better): fully mechanized solid filling (1.18 million t/a) > fully mechanized paste filling (0.88 million t/a) > continuous mining and continuous filling (0.34 million t/a) > low-level grouting = separated layer

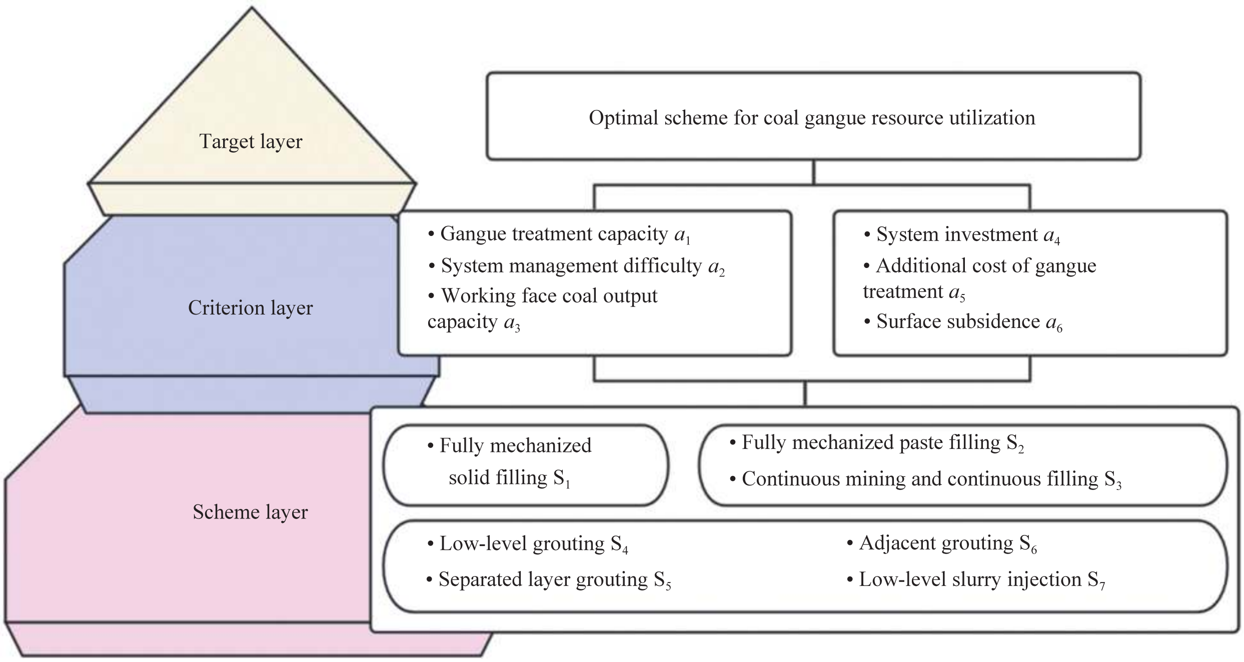


**Figure 4** Optimal scheme for the resource utilization of coal gangue

grouting = adjacent grouting = low-level slurry injection (0 million t/a).

4) System investment (smaller is better): fully mechanized paste filling (CNY 500–600 million) > fully mechanized solid filling (CNY 400–500 million) > continuous mining and continuous filling (CNY 300–400 million) > low-level grouting ≈ separated layer grouting (CNY 200–300 million) > adjacent grouting ≈ low-level slurry injection (CNY 100–200 million).

5) Additional cost of gangue treatment (smaller is better): continuous mining and continuous filling (CNY 120–150/t) > fully mechanized paste filling (CNY 100–120/t) > low-level grouting ≈ separated layer grouting (CNY 80–100/t) > adjacent grouting ≈ low-level slurry injection (CNY 60–80/t) > fully mechanized solid filling (CNY 30–60/t).

6) Surface subsidence (smaller is better): adjacent grouting ≈ low-level slurry injection > separated layer grouting > low-level grouting > fully mechanized solid filling > fully mechanized paste filling ≈ continuous mining and continuous filling.

## 3.2 The judgment matrix

To ensure the scientificity and credibility of the indicator system, in the process of constructing the judgment matrix, this study numbered the 6 different types of evaluation indicators in the criterion layer from a1 to a6 (Table 3), and invited 8 experts (numbered as E1 to E8) who have been engaged in mining, safety, mineral processing, and mine management for more than 10 years, and come from universities, research institutes, and enterprises (Table 4). They adhered to the overall goal of "determining the optimal plan for the resource utilization of coal gangue," and used the 1–9 scale method to evaluate and assign scores to the indicators in the criterion layer.

In order to avoid the influence of authority and groupthink, the experts first, based on the actual

**Table 3** Key evaluation indicators and types

| Number | $a_1$ | $a_2$ | $a_3$ | $a_4$ | $a_5$ | $a_6$ |
|---|---|---|---|---|---|---|
| Indicator | Gangue treatment capacity | System management difficulty | Working face coal output capacity | System investment | Additional cost of gangue treatment | Surface subsidence |
| Type | Benefit | Cost | Benefit | Cost | Cost | Cost |
| Requirement | Larger is better | Smaller is better | Larger is better | Smaller is better | Smaller is better | Smaller is better |

**Table 4** Expert information

| Expert number | Title | Position | Professional field | Years | Institution |
|---|---|---|---|---|---|
| $E_1$ | Professor | Academic leader | Mining engineering | 14 | University |
| $E_2$ | Associate professor | Teaching and research | Mineral processing | 10 | University |
| $E_3$ | Researcher | Laboratory director | Mine solid waste disposal | 11 | Research Institute |
| $E_4$ | Senior engineer | Technical director | Mine backfill technology | 13 | Enterprise |
| $E_5$ | Professor-level senior engineer | Chief engineer | Mine design and planning | 21 | Enterprise |
| $E_6$ | Associate researcher | Key researcher | Mining area ecological restoration | 11 | Research Institute |
| $E_7$ | Engineer | Project manager | Coal mine management | 7 | Enterprise |
| $E_8$ | Associate professor | Teaching and research | Economics and management | 9 | University |

problems that the managers were concerned about during the on-site investigation of Taigemiao mining area, anonymously and independently assigned scores to the importance and operability of the indicators. Then, according to the calculation methods of the median and quartile introduced in Section 2.2 of the text, the first round scoring results of expert consultation were obtained, as shown in Table 5. Due to the first round of scoring, there were significant deviations in the scores given by some experts. This result was then fed back to all the experts for re-examination and adjustment. Finally, all the scores tended to be consistent, thereby confirming the rationality and operability of the above 6 indicators. The basis and assignment results of the importance degree of evaluation indicators compared by experts are as follows:

1) Comparison of gangue treatment capacity $a_1$ with other indicators:

$a_1$ vs. $a_2$ (management difficulty): Treatment capacity is the fundamental prerequisite for achieving "zero emission" and the core measure of project success. System management difficulty, while affecting operational efficiency, is secondary and can be overcome through process optimization. Therefore, treatment capacity is "strongly more important" than management difficulty, assigned 7.

$a_1$ vs. $a_3$ (coal output capacity): In the early stage of mining, there is "no requirement for coal output capacity." This makes the priority of coal output capacity at this stage far lower than the core environmental and production task of treating gangue. Therefore, treatment capacity is "strongly more important" than coal output capacity, assigned 7.

$a_1$ vs. $a_4$ (system investment): Gangue treatment capacity is a direct reflection of the scheme's functionality, while system investment is the economic threshold to achieve that function. In the decision-maker's mind, whether gangue can be effectively treated is more critical than the amount of investment. Therefore, treatment capacity is between "slightly more important" and "significantly more important" than system investment, assigned 4.

$a_1$ vs. $a_5$ (treatment cost): When "selecting the best coal gangue filling technology," both gangue treatment volume and treatment cost should have clear technical indicator requirements, indicating that both are core concerns. But treatment capacity is a prerequisite for the scheme to be valid; without sufficient capacity, no matter how low the cost, it is meaningless. Therefore, treatment capacity is "slightly more important" than treatment cost, assigned 3.

$a_1$ vs. $a_6$ (surface subsidence): In the early stage of mining, there is no special requirement for surface subsidence control. This makes the importance of surface subsidence control minimal. In contrast, treating gangue is a rigid demand. Therefore, treatment capacity is "extremely more important" than surface subsidence, assigned 8.

2) Comparison of system management difficulty $a_2$ with other indicators:

$a_2$ vs. $a_3$ (coal output capacity): Both are not core in the target task, but the impact of management difficulty on the long-term stable operation of the project is considered more important than the temporary coal output requirement. Therefore, the management difficulty is "slightly more important" than coal output

**Table 5** The results of the first round of expert scoring

| Comparison Program | $E_1$ | $E_2$ | $E_3$ | $E_4$ | $E_5$ | $E_6$ | $E_7$ | $E_8$ | Median | Quartiles |
|---|---|---|---|---|---|---|---|---|---|---|
| $a_{12}$ | 7 | 7 | 7 | 7 | 6 | 6 | 8 | 8 | 7 | 1.5 |
| $a_{13}$ | 7 | 7 | 7 | 7 | 6 | 6 | 8 | 8 | 7 | 1.5 |
| $a_{14}$ | 4 | 4 | 4 | 4 | 3 | 3 | 5 | 5 | 4 | 1.5 |
| $a_{15}$ | 3 | 3 | 3 | 3 | 2 | 2 | 4 | 4 | 3 | 1.5 |
| $a_{16}$ | 8 | 8 | 8 | 8 | 7 | 7 | 9 | 9 | 8 | 1.5 |
| $a_{23}$ | 3 | 3 | 3 | 3 | 2 | 2 | 4 | 4 | 3 | 1.5 |
| $a_{24}$ | 1/3 | 1/3 | 1/3 | 1/3 | 1/4 | 1/4 | 1/2 | 1/2 | 1/3 | 0.1875 |
| $a_{25}$ | 1/7 | 1/7 | 1/7 | 1/7 | 1/8 | 1/8 | 1/6 | 1/6 | 1/7 | 0.0238 |
| $a_{26}$ | 3 | 3 | 3 | 3 | 2 | 2 | 4 | 4 | 3 | 1.5 |
| $a_{34}$ | 1/3 | 1/3 | 1/3 | 1/3 | 1/4 | 1/4 | 1/2 | 1/2 | 1/3 | 0.1875 |
| $a_{35}$ | 1/7 | 1/7 | 1/7 | 1/7 | 1/8 | 1/8 | 1/6 | 1/6 | 1/7 | 0.0238 |
| $a_{36}$ | 3 | 3 | 3 | 3 | 2 | 2 | 4 | 4 | 3 | 1.5 |
| $a_{45}$ | 1/3 | 1/3 | 1/3 | 1/3 | 1/4 | 1/4 | 1/2 | 1/2 | 1/3 | 0.1875 |
| $a_{46}$ | 4 | 4 | 4 | 4 | 3 | 3 | 5 | 5 | 4 | 1.5 |
| $a_{56}$ | 8 | 8 | 8 | 8 | 7 | 7 | 9 | 9 | 8 | 1.5 |

capacity, assigned 3.

$a_2$ vs. $a_4$ (system investment): System investment is a huge economic threshold for project initiation and a key factor in technical and economic benefits. Management difficulty belongs to operational-level recurring costs. Obviously, the importance of a one-time huge investment is higher than daily management. Therefore, system investment is "slightly more important" than management difficulty, assigned 1/3.

$a_2$ vs. $a_5$ (treatment cost): Treatment cost directly affects the long-term economic feasibility of the project, while management difficulty is relatively low. Therefore, treatment cost is "strongly more important" than management difficulty, assigned 1/7.

$a_2$ vs. $a_6$ (surface subsidence): The complexity of maintaining system stable operation is more important than the problem of mining surface subsidence. Therefore, management difficulty is "slightly more important" than surface subsidence, assigned 3.

3) Comparison on coal output capacity $a_3$ of working face with other indicators:

$a_3$ vs. $a_4$ (system investment): System investment is a key economic indicator, while the importance of coal output capacity in the early stage is relatively low. Therefore, system investment is "slightly more important" than coal output capacity, assigned 1/3.

$a_3$ vs. $a_5$ (treatment cost): For the decision goal, treatment cost is a key indicator, while coal output capacity is the least important. Therefore, treatment cost is "strongly more important" than coal output capacity, assigned 1/7.

$a_3$ vs. $a_6$ (surface subsidence): Although both are relatively unimportant for the decision goal, coal output capacity is considered slightly higher than surface subsidence. Therefore, coal output capacity is "slightly more important" than surface subsidence, assigned 3.

4) Comparison of system investment $a_4$ with other indicators:

$a_4$ vs. $a_5$ (treatment cost): The weight of treatment cost (0.26) is slightly higher than that of system investment (0.21), indicating that decision-makers believe that recurring operational costs has a more critical impact on the long-term benefits of the project than one-time initial investment. Therefore, treatment cost is "slightly more important" than system investment, assigned 1/3.

$a_4$ vs. $a_6$ (surface subsidence): System investment is a key economic indicator with a higher weight (0.21), while surface subsidence has the lowest weight (0.05) in the early stage. Therefore, system investment is between "slightly more important" and "significantly more important" than surface subsidence, assigned 4.

5) Comparison of additional cost of gangue treatment $a_5$ with other indicators:

$a_5$ vs. $a_6$ (surface subsidence): The additional cost of gangue treatment is a core indicator for decision-making, and compared to the early-stage mine, the difference in importance between the two is huge. Therefore, treatment cost is "extremely more important" than surface subsidence, assigned 8.

The judgment matrix of the six key technical and economic indicators in the criterion layer is obtained as follows:

$$A=\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} \\ a_{41} & a_{45} & a_{45} & a_{45} & a_{45} & a_{46} \\ a_{51} & a_{55} & a_{55} & a_{55} & a_{55} & a_{56} \\ a_{61} & a_{65} & a_{65} & a_{65} & a_{65} & a_{66} \end{bmatrix} = \begin{bmatrix} 1 & 7 & 7 & 4 & 3 & 8 \\ 1/7 & 1 & 1 & 1/3 & 1/7 & 3 \\ 1/7 & 1 & 1 & 1/3 & 1/7 & 3 \\ 1/4 & 3 & 3 & 1 & 1/3 & 4 \\ 1/3 & 7 & 7 & 3 & 1 & 8 \\ 1/8 & 1/3 & 1/3 & 1/4 & 1/8 & 1 \end{bmatrix}$$

## 3.3 Weight vector calculation and consistency test

The root method is used to calculate the weight vector:

① According to Equation (1), the product of each row of the judgment matrix $\boldsymbol{M}_1$ is calculated: $\boldsymbol{M}_1 = 1\times7\times7\times4\times3\times8 = 4704$.

Similarly, $\boldsymbol{M}_2 = \boldsymbol{M}_3 = 0.020408$, $\boldsymbol{M}_4 = 3$, $\boldsymbol{M}_5 = 392$, and $\boldsymbol{M}_6 = 0.000434$.

② According to Equation (2), the 6th roots $\overline{W_i} = \sqrt[6]{M_i}$, $\overline{W_1} = \sqrt[6]{4704} \approx 4.092$, $\overline{W_2} = \overline{W_3} \approx 0.5228$, $\overline{W_4} \approx 1.2009$, $\overline{W_5} \approx 2.705$, and $\overline{W_6} \approx 0.2755$ are calculated.

③ According to Equation (3), the vector $\overline{W}=[W_1, W_2, \ldots, W_n]^{\mathrm{T}}$ is normalized.

The sum is $\sum_{j=1}^{n}\overline{W_j} \approx 4.092+0.5228+0.5228+1.2009+2.705+0.2755=9.319$. Then, $W_1 = 4.092/9.319 = 0.4392$, $W_2 = W_3 = 0.0561$, $W_4 = 0.1289$, $W_5 = 0.2903$, $W_6 = 0.0296$.

The sum is checked: $0.4392 + 0.0561 + 0.0561 + 0.1289 + 0.2903 + 0.0296 = 1.0002 \approx 1$. The weight vector is

$$W \approx \begin{bmatrix} 0.4392 \\ 0.0561 \\ 0.0561 \\ 0.1289 \\ 0.2903 \\ 0.0296 \end{bmatrix}$$

According to the weight vector, the order of importance of the evaluation indicators is gangue treatment capacity > additional cost of gangue treatment > system investment > system management difficulty ≈ working face coal output capacity > surface subsidence, as shown in Figure 5.

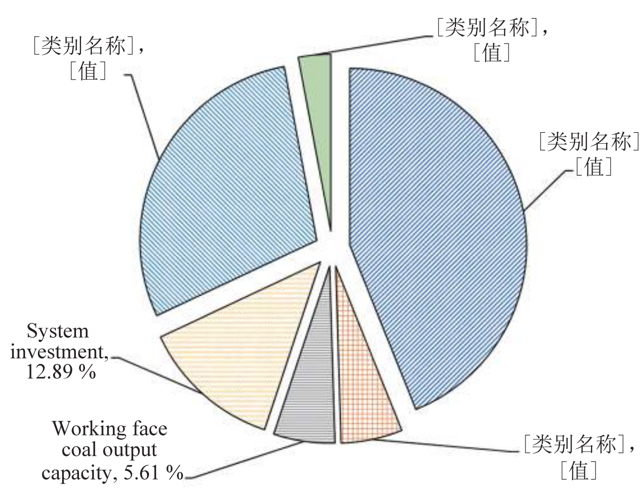


**Figure 5** Quantitative weight distribution of evaluation indicators

④ To test whether judgment matrix $\boldsymbol{A}$ is feasible, consistency test is performed according to Equation (4):

$$AW \approx \begin{bmatrix} 1 & 7 & 7 & 4 & 3 & 8 \\ 1/7 & 1 & 1 & 1/3 & 1/7 & 3 \\ 1/7 & 1 & 1 & 1/3 & 1/7 & 3 \\ 1/4 & 3 & 3 & 1 & 1/3 & 4 \\ 1/3 & 7 & 7 & 3 & 1 & 8 \\ 1/8 & 1/3 & 1/3 & 1/3 & 1/8 & 1 \end{bmatrix} \begin{bmatrix} 0.4392 \\ 0.0561 \\ 0.0561 \\ 0.1289 \\ 0.2903 \\ 0.0296 \end{bmatrix} = \begin{bmatrix} 2.84790 \\ 0.34818 \\ 0.34818 \\ 0.79047 \\ 1.84560 \\ 0.19040 \end{bmatrix}$$

$$\lambda_{\max} = \frac{1}{6}\left(\frac{2.84790}{0.4392}+\frac{0.34818}{0.0561}+\frac{0.34818}{0.0561}+\frac{0.79047}{0.1289}+\frac{1.84560}{0.2903}+\frac{0.19040}{0.0296}\right) = 6.3033$$

$$\mathrm{CI}=\frac{\lambda_{\max}-6}{6-1}=\frac{6.3033-6}{6-1}=0.06066$$

For $n = 6$, from Table 2, RI = 1.24, then,

$$\mathrm{CR}=\frac{\mathrm{CI}}{\mathrm{RI}}=\frac{0.06066}{1.24}=0.04892<0.1$$

Thus, judgment matrix $A$ passes the consistency test, and the weight vector is valid and reliable.

## 3.4 Normalization

Based on the statistical analysis of each utilization scheme of coal gangue resource, combined with the assignment method, for indicators with clear numerical values (gangue treatment capacity, coal output capacity of working face), the treatment volume is directly taken as the original value; for indicators with a numerical range (system investment, additional cost of gangue treatment), the median is taken as the original value; for indicators without specific data (system management difficulty and surface subsidence), according to the analysis, they can be divided into five levels. Among them, fully mechanized paste filling has the greatest difficulty, assigned 5; fully mechanized solid filling is the next, assigned 4; continuous mining and continuous filling is assigned 3; separated layer grouting and low-level grouting is assigned 2 (similar difficulty); adjacent grouting and low-level slurry injection is assigned 1. For surface subsidence, fully mechanized paste filling and continuous mining and continuous filling have the largest subsidence, assigned 5; fully mechanized solid filling assigned 4; low-level grouting assigned 3; separated layer grouting assigned 2; adjacent grouting and low-level slurry injection have the smallest subsidence and are similar, assigned 1. Thus, the original indicator values and the maximum and minimum values under different indicators are obtained, as shown in Table 6.

According to the min-max normalization equations (5) and (6), the benefit-type and cost-type indicators are normalized respectively, obtaining the normalized matrix $\boldsymbol{B}$:

$$B=\begin{matrix}[0.6186 & 0.25 & 1.0000 & 0.25 & 1.0000 & 0.25]\\ [0.4492 & 0.00 & 0.7458 & 0.00 & 0.2778 & 0.00]\\ [0.0932 & 0.50 & 0.2881 & 0.50 & 0.0000 & 0.00]\\ [1.0000 & 0.75 & 0.0000 & 0.75 & 0.5000 & 0.50]\\ [0.5424 & 0.75 & 0.0000 & 0.75 & 0.5000 & 0.75]\\ [0.0847 & 1.00 & 0.0000 & 1.00 & 0.7222 & 1.00]\\ [0.0000 & 1.00 & 0.0000 & 1.00 & 0.7222 & 1.00]\end{matrix}$$

The rows correspond to the seven schemes ($S_1$ to $S_7$)

**Table 6** Quantification and assignment of each scheme under evaluation indicators

| Scheme | No. | Gangue treatment capacity ($10^4$ t/a) | System management difficulty | Coal output capacity of working face ($10^4$ t/a) | System investment (CNY million) | Additional cost of gangue treatment (CNY/t) | Surface subsidence |
|---|---|---|---|---|---|---|---|
| Fully mechanized solid filling | $S_1$ | 88 | 4 | 118 | 4.5 | 45 | 4 |
| Fully mechanized paste filling | $S_2$ | 68 | 5 | 88 | 5.5 | 110 | 5 |
| Continuous mining and continuous filling | $S_3$ | 26 | 3 | 34 | 3.5 | 135 | 5 |
| Low-level grouting | $S_4$ | 133 | 2 | 0 | 2.5 | 90 | 3 |
| Separated layer grouting | $S_5$ | 79 | 2 | 0 | 2.5 | 90 | 2 |
| Adjacent grouting | $S_6$ | 25 | 1 | 0 | 1.5 | 70 | 1 |
| Low-level slurry injection | $S_7$ | 15 | 1 | 0 | 1.5 | 70 | 1 |
| Max | | 133 | 5 | 118 | 5.5 | 135 | 5 |
| Min | | 15 | 1 | 0 | 1.5 | 45 | 1 |

Note: The data are based on the 2026 mine survey and the information provided by the enterprises. To assess the impact of data uncertainty on the results, we conducted an interval endpoint sensitivity analysis on the system investment and processing costs (calculating the minimum and maximum values). The results showed that the low-level grouting remained the optimal solution, indicating that the results were not sensitive to data fluctuations.

and the columns correspond to the six indicators ($a_1$ to $a_6$). The matrix elements represent the normalized membership degree of different schemes under the corresponding indicator, with 1 being the best and 0 the worst.

### *3.5 Calculate the combined weight*

The weight matrixes of the criterion layer and the scheme layer are combined to obtain the combined weight of the scheme layer relative to the target layer. The one with the largest weight is the optimal scheme, as follows:

$$S=B\times W=\begin{bmatrix}0.6186 & 0.25 & 1.0000 & 0.25 & 1.0000 & 0.25\\ 0.4492 & 0.00 & 0.7458 & 1.00 & 0.2778 & 0.00\\ 0.0932 & 0.50 & 0.2881 & 0.50 & 0.0000 & 0.00\\ 1.0000 & 0.75 & 0.0000 & 0.75 & 0.5000 & 0.50\\ 0.5424 & 0.75 & 0.0000 & 0.75 & 0.5000 & 0.75\\ 0.0847 & 1.00 & 0.0000 & 1.00 & 0.7222 & 1.00\\ 0.0000 & 1.00 & 0.0000 & 1.00 & 0.7222 & 1.00\end{bmatrix}\begin{bmatrix}0.4392\\ 0.0561\\ 0.0561\\ 0.1289\\ 0.2903\\ 0.0296\end{bmatrix}=\begin{bmatrix}0.6718\\ 0.3198\\ 0.1496\\ 0.7379\\ 0.5443\\ 0.4615\\ 0.4243\end{bmatrix}$$

Thus, the weights and ranking of the selected schemes are low-level grouting ($S_4$) 0.7379 > fully mechanized solid filling ($S_1$) 0.6718 > separated layer grouting ($S_5$) 0.5443 > adjacent grouting ($S_6$) 0.4615 > low-level slurry injection ($S_7$) 0.4243 > fully mechanized paste filling ($S_2$) 0.3198 > continuous mining and continuous filling ($S_3$) 0.1496, as shown in Figure 6.

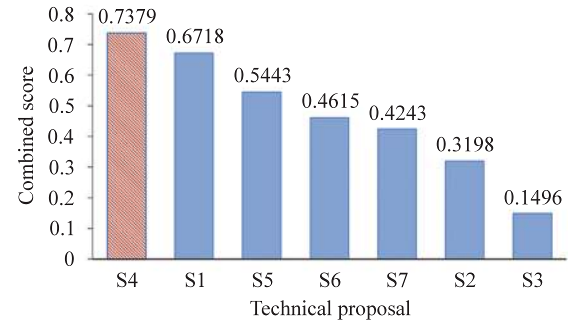


**Figure 6** Technical scheme scores and comprehensive ranking results

## 4 Results analysis and evaluation

### *4.1 Analysis of calculation results*

Through the quantitative calculation of AHP, the consistency test of the judgment matrix is good (CR = 0.04892 < 0.1), indicating that the expert judgment logic is consistent and the weight distribution is reasonable. The min-max normalization effectively eliminates dimensional differences, making indicators of different natures comparable. Finally, "low-level grouting technology" is determined as the optimal choice for utilization of coal gangue resource in this mining area, which is highly consistent with its geological conditions, early construction focus, and environmental protection requirements. This technology can meet the urgent demand for large-scale gangue consumption while balancing investment and complexity, and has strong engineering feasibility and adaptability [29, 30]. However, this result is only applicable to the early construction stage where coal output is not the main focus [31]. Therefore, if the later transitions of the mining area to a formal production stage with "coal output as the main focus," the indicators need to be readjusted for re-evaluation. From the calculation and ranking of combined weights, it can be found:

1) Low-level grouting ($S_4$) has the highest score (0.7379), mainly due to its outstanding performance in gangue treatment capacity (1.33 million t/a), which has the highest weight (0.4392), significantly improving the comprehensive score of this scheme. At the same time, it is at a medium level in system investment, management difficulty, and cost, with no obvious evaluation shortcomings.

2) Fully mechanized solid mining method ($S_1$) demonstrated significant economic advantages in terms of coal output capacity (1.18 million t/a) and cost (CNY 45/t), but due to its complex system management and high investment requirements, it failed to reverse its disadvantages in management and investment on the lower-weight production-related indicators. As a result, it ranked second.

3) Separated layer grouting ($S_5$), adjacent grouting ($S_6$), and low-level slurry injection ($S_7$) are generally weak in gangue treatment capacity and coal output

capacity, but their characteristics of low investment, low cost, and easy management make them perform well in cost-control indicators, especially suitable for mining areas sensitive to initial investment and with small gangue quantities.

4) Fully mechanized paste filling ($S_2$) and continuous mining and continuous filling ($S_3$) rank low, mainly limited by multiple unfavorable factors such as large system management difficulty, high investment, and high cost. Although they have certain advantages in coal output capacity or treatment capacity, they are not enough to offset their significant disadvantages in economic and management indicators.

### 4.2 Analysis of key indicator impact

1) Gangue treatment capacity, as the indicator with the largest weight (0.4392), has a significant impact on the total score. Low-level grouting achieves a full score (1.0) in this item, which is the key to its optimal selection.

2) Cost-type indicators (treatment cost weight 0.2903, system investment weight 0.1289) jointly constrain technical routes with high investment and high operating costs, such as fully mechanized paste filling and continuous mining and continuous filling.

3) Coal output capacity has a low weight (0.0561) in the current evaluation system, reflecting that the mining area's focus in the early stage is on gangue treatment, which is consistent with the project positioning.

### 4.3 Analysis of research limitations

1) Due to the various stages of the mining area's planning, construction, and production, the weight requirements for each evaluation indicator change at different stages. Moreover, AHP involves an evaluation process of quantifying subjective indicators, which means this method also has limitations in conducting dynamic or full life-cycle evaluations. However, for conducting a comprehensive evaluation around a certain decision-making goal and multiple indicator factors and providing the optimal conclusion, the AHP still has certain advancement and practicality.

2) Additionally, this study only discusses the analysis process under a single target scenario, ignoring the dynamic changes in the enterprise's safety, environmental, economic management strategies and goals as the mining area develops. Therefore, in the subsequent research and studies, it is necessary to conduct scenario comparison analyses under different goals and different weightings of indicators, and deeply explore the relationship between weight setting and policy orientation.

3) Although the AHP method has the advantages of clear structure and simple operation, it also has problems such as a strong assumption of indicator independence and inability to handle the interdependence between indicators. Therefore, in the future, we will learn and introduce evaluation models such as the network analytic hierarchy process (ANP) that are more dynamic and systematic.

## 5 Conclusion

This study constructs an optimization model for coal gangue filling technology based on AHP and min-max normalization, and evaluates it with the Xinjie Taigemiao mining area as an example. The main conclusions are as follows:

1) Low-level grouting technology is the optimal scheme. It performs outstandingly in gangue treatment capacity, and has no obvious shortcomings in cost, investment, and management, suitable for the current development needs of the mining area.

2) The model passes the consistency test, the weight distribution is reasonable, the evaluation process is transparent and repeatable, and has strong methodological value.

3) The research results show that in the early stage of the mining area with gangue treatment as the core, treatment capacity should be the primary evaluation indicator, while systems with high investment and high complexity, such as fully mechanized paste filling and continuous mining and continuous filling, have low applicability.

4) This model can provide systematic decision support for the selection of filling technology in mining areas with similar conditions, and also provides a reference case for the application of multi-criteria evaluation in mining engineering.

5) In the future, dynamic evaluation and sustainability dimensions can be further integrated into the

model to improve its applicability and foresight in different stages and policy environments.

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## Author contributions

Lv Hongguang: Project administration, methodology, writing-original draft, and writing-review & editing. Kang Xuegang: Resources, investigation, and data curation. Gu Lin: Investigation and validation. Wang Lu: Data curation and validation. Li Jihui: Supervision, and writing-review & editing. Ma Liqiang: Supervision, conceptualization, and formal analysis.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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