COMPREHENSIVE EFFECTIVENESS EVALUATION OF ECOLOGICAL RESTORATION IN OPEN-PIT COAL MINES USING ENTROPY WEIGHT-TOPSIS: A CASE STUDY FROM CHINA

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(Received 19th Apr 2025; accepted 11th Jun 2025)

Abstract. As environmental concerns over open-pit coal mining increase, the need for effective ecological restoration assessment methods becomes critical. This study presents a novel framework that combines the Entropy Weight Method and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for evaluating the ecological restoration effectiveness of five representative open-pit coal mines in China. The Entropy Weight Method objectively quantifies the weights of multiple indicators, including soil erosion rate, vegetation coverage, and water quality, ensuring a balanced and data-driven assessment. TOPSIS is then applied to rank the mines based on their closeness to the ideal restoration level. Case study results demonstrate that this combined approach can accurately reflect the real-world effectiveness of different restoration measures, with mines exhibiting higher vegetation cover and improved environmental quality receiving higher rankings. The integration of entropy-based weighting and multi-criteria decision analysis provides an objective and practical tool for evaluating restoration outcomes. This method assists decision-makers and practitioners in identifying best practices, optimizing strategies, and promoting sustainable land use in mining areas, and is adaptable to similar ecological restoration assessment scenarios elsewhere.

Keywords: *entropy weighting, TOPSIS method, indicator selection, mining site restoration, performance ranking*

Introduction

Background

As a common mining method, open-pit coal mining has had many impacts on the ecological environment (Xu et al., 2023b). First, a large amount of land is needed for open-pit coal mining, which leads to the serious destruction and reduction of land resources. Large areas of vegetation are cleared, the soil is destroyed, resulting in soil erosion of the land, and the ecosystem recovery needs a very long time (Bai et al., 2018; Liu et al., 2023; Zhao et al., 2017). Secondly, open-pit coal mining will produce a large amount of waste and slag, which not only pollutes the soil and water but also may have a long-term impact on the ecosystem of the surrounding area (Xu et al., 2023b). In addition, the ore dust and gas pollutants produced by open-pit coal mining, such as sulfur dioxide and nitrogen oxides (Pandey et al., 2014), and PM 2.5 (Wang et al., 2022c), have caused serious pollution to the atmospheric environment, affecting the air quality of the surrounding areas, and may also lead to the formation of acid rain and acid water (Zhang et al., 2023b), which may further aggravate the deterioration of the ecological environment.

Ecological restoration plays a vital role in the development of mine. First, ecological restoration can help restore damaged land and vegetation and accelerate the rebuilding and stabilization of ecosystems (Song et al., 2016; Wang et al., 2016). By planting suitable vegetation and taking soil protection measures, soil erosion can be reduced, soil quality can

DOI: http://dx.doi.org/10.15666/aeer/2304_75677582

be improved, and the ecological function of land can be restored. Secondly, ecological restoration can reduce the negative impact of mining on the surrounding environment (Lei et al., 2016). Through the establishment of wetlands, artificial forests, and other ecological protection areas, water pollution can be reduced, air quality can be improved, and the damage to the surrounding environment caused by mining can be reduced (Ahirwal et al., 2016; Zhang et al., 2011). In addition, ecological restoration can also provide local communities with new economic development models such as ecotourism, leisure, and entertainment, and promote sustainable development (Brock, 2023; Pau et al., 2022). Therefore, ecological restoration can not only help mining enterprises achieve sustainable management but also help to protect and improve the surrounding ecological environment and promote the development of the regional economy.

To sum up, how to take the appropriate ecological restoration strategies in open-pit coal mines and how to correctly evaluate the effect of mine ecological restoration are crucial to the ecological environment management in mining areas.

Literature review

Ecological restoration of open-pit coal mine

The environmental damage caused by open-pit coal mining has long been a concern. In order to reduce the negative impact of mining on the environment, the ecological restoration of finished coal mines has become an urgent task. At present, a variety of technical means and strategies have emerged for ecological restoration in open-pit coal mines. Vegetation restoration is an important measure, through the replanting of vegetation or the introduction of plant species adapted to the local environment, to gradually restore the vegetation cover in the mine area, and reduce soil erosion and water erosion (Sun et al., 2021; Wang et al., 2022b; Ye, 2021). Land reclamation is also an important means of ecological restoration, through the treatment and reuse of the land affected by mining, it can be reintegrated into the local ecosystem and restore its agricultural functions (Galanina et al., 2020; Li et al., 2022; Skousen and Zipper, 2021). In addition, technical means like water resources management and soil restoration have also been widely used in the ecological management or restoration of mines (More et al., 2020; Pinto et al., 2020; Rosarina et al., 2021; Yinli et al., 2020).

Evaluation methods for ecological restoration effectiveness of open-pit coal mines

A variety of evaluation methods have been adopted to evaluate the ecological restoration effectiveness of open-pit coal mines. The evaluation method of the mine ecological restoration effect has experienced the development process from qualitative to quantitative, from single indicator to multi-indicator. Early evaluation methods mainly rely on qualitative observation and experience, the evaluation indicator were simple. With the development of science and technology, a series of quantitative evaluation methods have appeared. Remote sensing technology plays an important role in the evaluation of mine ecological restoration effect. Through the acquisition of high-resolution remote sensing image data, the quantitative analysis of vegetation cover and land use in the mine area can be realized (Yang et al., 2023; Zhang et al., 2023a; Zhu et al., 2020). Change detection using NDVI time-series or land use classification can timely understand the dynamic change of vegetation cover, evaluate the restoration process of ecosystems, and provide a scientific basis for subsequent management and decision-making. The evaluation method of the ecological indicator is one of the important means to evaluate the effect of ecological restoration in mines. Through the measurement and analysis of soil quality (Wang et al., 2022a), vegetation structure (Wei and Yanjun, 2022; Xu et al., 2021), animal community (Bruno Rocha Martins et al., 2020; Taddeo and Dronova, 2018), and other ecological indicators, the restoration of the mining ecosystem can be objectively assessed. In addition, the method of ecosystem service value assessment also provides a new way to evaluate the effect of mine ecological restoration. By analyzing various social effects provided by the ecosystem, such as regional economic growth (Worlanyo and Jiangfeng, 2021), etc., the effect of mine ecological restoration and its contribution to human society can be assessed.

Research questions and objectives

As discussed above, through the comprehensive application of remote sensing technology, ecological indicator evaluation method, ecosystem service value evaluation method, and other evaluation methods, the effect of ecological restoration in open-pit coal mines can be comprehensively and objectively evaluated, and a scientific basis and reference can be provided for relevant decision-making. Ecological restoration in open-pit coal mines is an important issue in the field of the mining industry, as well as environmental protection, but how to evaluate the effect of ecological restoration comprehensively and objectively is a complex and challenging problem. Traditional evaluation methods are often too one-sided, relying only on a simple indicator or experience judgment. Therefore, it is necessary to explore a comprehensive consideration of various environmental indicators and socially beneficial indicators of the evaluation system, for a more comprehensive and scientific evaluation of the effect of the mine’s ecological restoration.

To solve the above problems, the entropy weight method and the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method are adopted to establish a comprehensive evaluation system and carry out a unified evaluation of environmental indicators and socially beneficial indicators. The entropy weight method can determine the weight of an indicator according to its information entropy, avoiding the problem of subjective weighting. The TOPSIS method can rank and evaluate the effectiveness of mines based on the relative closeness to the ideal solution. The purpose of this article mainly includes two aspects: one is to evaluate the necessity of ecological restoration in coal mines and to highlight the urgency and importance of ecological restoration through systematic evaluation of the damage to the ecological environment in mines; The second is to improve the scientific rigor and accuracy of ecological restoration evaluation in open-pit coal mines, and establish a scientific and objective evaluation system by introducing the evaluation method combining entropy weight method and TOPSIS method, to provide scientific basis and decision support for ecological restoration in mines.

In summary, the objective of this study is to develop a scientifically robust and comprehensive evaluation framework that integrates the Entropy Weight Method and the TOPSIS method, to objectively assess the effectiveness of ecological restoration in open-pit coal mines and to support decision-making for sustainable environmental management. The Entropy Weight Method ensures objectivity in determining the importance of each indicator by quantifying information entropy, while the TOPSIS method enables effective ranking of ecological restoration outcomes based on their relative closeness to an ideal solution. This combination provides a more scientific and comprehensive tool for evaluating the effectiveness of ecological restoration efforts in open-pit coal mines.

Methods

Principle and procedure of the entropy weight method

Entropy is an important concept in information theory, which is used to measure the uncertainty of information or the average measure of information (Sullivan, 2015). The higher the value of information entropy, the higher the uncertainty of information. The smaller the value of information entropy, the higher the certainty of information (Li et al., 2018). The entropy weight method is a weight determination method based on information entropy theory. In the entropy weight method, information entropy is used to quantify the difference or weight between various indicators. The calculation process is as follows:

- Identify indicators and their value. First of all, it is necessary to identify the various indicators involved in the evaluation, as well as the specific value for these indicators. These indicators can be environmental indicators, economic indicators, social indicators, etc.
- Calculate the probability of each indicator. For each indicator, calculate the proportion or proportion of its data as the probability of the indicator. This step is to convert the value of the indicator into a probability distribution for subsequent information entropy calculations.
- Calculate the information entropy of each indicator. The probability of each indicator is substituted into the information entropy calculation equation to obtain the information entropy value of each indicator.
- Calculate the weight of each indicator. According to the calculation result of information entropy, the information entropy value of each indicator is normalized, and the weight of each indicator is obtained. Generally, the larger the information entropy, the smaller the weight of the indicator; The smaller the information entropy, the greater the weight of the indicator.
- Normalization processing. The weights of the obtained indicators are normalized to ensure that the sum of weights is equal to 1, so as to conduct subsequent comprehensive evaluation or decision analysis.

Through the above steps, the entropy weight method can quantify the importance of different indicators and provide a scientific basis for subsequent evaluation, analysis, and decision-making.

Principles and procedure of the TOPSIS method

The TOPSIS method was first proposed and developed by Hwang and Yoon (Hwang and Yoon, 1981; Hwang et al., 1993). It is used in multi-attribute decision analysis. This method takes the distance between the ideal solution and the worst solution as the evaluation standard and considers the closeness of the evaluation object to the ideal solution and the worst solution (Amin et al., 2019; Hanine et al., 2016). The TOPSIS method has been widely used in the fields of management science, engineering technology, and environmental management, and is considered as a simple and effective multi-attribute decision-making method. The steps of the TOPSIS method are as follows:

- Determination of the ideal solution and the worst solution. In the TOPSIS method, the ideal and worst solutions need to be determined first. The ideal solution refers to the evaluation object with the best performance on each indicator, while the worst solution is the evaluation object with the worst performance on each indicator.

- The distance between the evaluation object and the ideal solution or the worst solution is calculated. For each evaluation object, it is necessary to calculate its distance to the ideal solution and the worst solution. The distance here can be Euclidean distance, Manhattan distance, or some other distance measure. Under normal circumstances, the smaller the distance from the evaluation object to the ideal solution, the better, or the larger the distance from the worst solution, the better.
- Calculation of relative closeness. After calculating the distance from the evaluation object to the ideal solution and the worst solution, the relative closeness of each evaluation object needs to be calculated according to these distance values.

According to the calculation result of relative closeness, each evaluation object can be sorted to determine the final evaluation result. The higher the relative closeness of the evaluation object, the better the comprehensive evaluation, and the higher the ranking. Through the above steps, the TOPSIS method can effectively evaluate the comprehensive performance of each evaluation object and sort it to provide a scientific basis for decision-making.

Effectiveness evaluation method for ecological restoration of open-pit coal mines based on entropy weight-TOPSIS method

Evaluation indicator system

Taking into account various factors such as the Effectiveness of geological hazard control, Soil remediation effectiveness, Water Quality, Vegetation and Wildlife Recovery Status, Air Quality, and Social Benefits in the mining area, a comprehensive evaluation indicator system for the ecological restoration effect of open-pit coal mines, as shown in *Table 1,* has been formulated.

Based on the normalized data and entropy calculations, the weights of all 26 evaluation indicators can be determined using the Entropy Weight Method. These weights reflect the relative importance of each indicator in the overall assessment process and were used in the subsequent TOPSIS-based ranking.

Data collection

The various indicators in *Table 1* require obtaining their respective values through different methods. In general, the methods for data collection include the following:

(1) Field sampling and laboratory analysis: For many ecological and soil-related parameters, representative samples were collected on-site and subsequently analyzed in the laboratory using standard procedures. Indicators obtained through this approach include *Soil Organic Matter Content*, *Soil Heavy Metal Content*, *Soil Available Nutrient Content*, *Soil Microbial Biomass (SMB)*, *Water Heavy Metal Concentration*, *pH Value*, *Dissolved oxygen (DO)*, *Chemical Oxygen Demand (COD)*, *Total Phosphorus (TP)*, *Total Nitrogen (TN)*, *PM 10*, *PM 2.5*, *Concentration of* SO_2, *Concentration of* NO_x, *Concentration of* VOC_s, *Total Suspended Particulate (TSP) Concentration*, *Vegetation Coverage*, *Normalized Difference Vegetation Indicator (NDVI)*, *Shannon-Wiener Diversity Indicator of Plants*, and *Shannon-Wiener Diversity Indicator of Animals*.

(2) Questionnaire survey: Data collection through presenting a series of questions to respondents to gather their opinions, views, experiences, or feedback. The indicators

collected through questionnaire surveys include the *Satisfaction Rate of Surrounding Residents*.

(3) Statistical data review: Collecting data by accessing existing statistical materials, reports, literature, or databases. Data sources include historical data, government-published statistical reports, datasets used in academic research, etc. The data obtained through this method include *Coverage Rate of Hazard Prevention and Control* Engineering, *Frequency of Geological Disasters*, *Soil Erosion Rate*, *Number of New Job Positions Create*d, and *Increased Economic Output*.

Table 1. *Evaluation indicator system for the ecological restoration effectiveness of open-pit coal mines*

Level-1 indicator	**Level-2 indicators**	**Names of level-3 indicators**	**Meanings of level-3 indicators**
Ecological restoration effectiveness of open-pit coal mine	Effectiveness of geological hazard control	Coverage rate of hazard prevention and control engineering	The percentage of the area covered by geological hazard prevention and control engineering in potential geological hazard-prone areas of the mining area, %
		Frequency of geological disasters	Frequency of geological disasters (such as landslides, collapses, etc.), times/year
		Soil erosion rate	The percentage of soil mass eroded by water or wind during a certain period compared to the original soil mass within the same period, t/km^2•year
	Soil remediation effectiveness	Soil organic matter content	The content of organic matter in soil, including organic matter and humus, g/kg
		Soil heavy metal content	The concentration of heavy metal elements in soil, mg/kg
		Soil available nutrient content	The content of nutrients available for plant uptake in soil, including major nutrients such as N, P, K, as well as trace elements like Fe, Zn, Mn), mg/kg
		Soil microbial biomass (SMB)	Soil Microbial Biomass (SMB) refers to the biomass of microorganisms (such as bacteria, fungi, protozoa, etc.) in soil, g/kg wet soil
	Water quality	Water heavy metal concentration	The concentration of heavy metal elements (such as lead, cadmium, mercury, etc.) in water, mg/L
		pH Value	Water acidity or alkalinity
		Dissolved oxygen (DO)	The content of dissolved oxygen in water, mg/L
		Chemical oxygen demand (COD)	The amount of organic and oxidizable inorganic substances (such as sulfides, nitrites, etc.) in water that demand oxygen, mg/L
		Total phosphorus (TP)	The concentration of phosphorus in water, mg/L
		Total nitrogen (TN)	The concentration of nitrogen in water, mg/L
	Vegetation and wildlife recovery status	Vegetation coverage	The percentage of the surface area covered by vegetation compared to the total surface area, %

		Normalized difference vegetation indicator (NDVI)	An indicator of vegetation growth calculated based on remote sensing data. Its values range from -1 to + 1, with higher values indicating denser vegetation coverage and more vigorous growth
		Shannon-Wiener diversity indicator of plants	Used to assess the diversity and evenness of plant communities
		Shannon-Wiener diversity indicator of animals	Used to assess the diversity and evenness of animal communities
	Air quality	Total suspended particulate (TSP) concentration	The concentration of particulate matter with aerodynamic diameter ≤ 100 μm in environmental air, μg/m^3
		PM 10	The concentration of particulate matter with an aerodynamic diameter ≤ 10 μm in air, μg/m^3
		PM 2.5	The concentration of particulate matter with an aerodynamic diameter 2.5 μm in air, μg/m^3
		Concentration of SO_2	The concentration of sulfur dioxide (SO_2) in the atmosphere, μg/m^3
		Concentration of NOx	The concentration of nitrogen oxides (NOx) in the atmosphere, μg/m^3
		Concentration of VOCs	The concentration of volatile organic compounds (VOCs) in the atmosphere, μg/m^3
	Social benefits	Satisfaction rate of surrounding residents	Satisfaction rate of surrounding residents with ecological restoration projects, %
		Number of new job positions created	The number of new job positions created during ecological restoration and operation processes
		Increased economic output	The added value of relevant industries after ecological restoration implementation, US dollars

Effectiveness evaluation model

The TOPSIS method is a commonly used approach in multi-objective decision analysis in systems engineering. It is known for its efficiency in computation and the scientific rationality of its results, making it widely applicable to evaluation and decision-making problems across various domains. Leveraging the characteristics of the TOPSIS method, the objective-weighted entropy method is combined to establish the entropy-weighted TOPSIS model for evaluating the ecological restoration effectiveness of open-pit coal mines. The specific steps for evaluating the model are as follows:

Step 1: Assuming the evaluation of m ecological restoration mines with n evaluation indicators, the initial decision matrix $A = (a_{ij})_{m\times n}$ can be established. In the matrix, a_{ij} represents the value of the j-th indicator for the i-th mine (where $i = 1, 2, ..., m$; $j = 1, 2, ..., n$).

Step 2: Normalize the initial decision matrix to obtain a standardized matrix $R = (r_{ij})_{m\times n}$. For indicators where higher values are preferable, *Equation 1* can be used for the normalization.

$$r_{ij}=\frac{a_{ij}-\min\limits_{j}a_{ij}}{\max\limits_{j}a_{ij}-\min\limits_{j}a_{ij}} \quad \text{(Eq.1)}$$

For indicators where lower values are preferable, *Equation 2* can be used for the normalization.

$$r_{ij}=\frac{\max\limits_{j}a_{ij}-a_{ij}}{\max\limits_{j}a_{ij}-\min\limits_{j}a_{ij}} \quad \text{(Eq.2)}$$

In *Equations 1* and *2*, r_{ij} is the normalized value of a_{ij}, ranging from 0 to 1; a_{ij} represents the value of the *j*-th indicator for the *i*-th mine; $\max\limits_{j}a_{ij}$ and $\min\limits_{j}a_{ij}$ is the maximum and minimum value of indicator *j* across all mines to be evaluated.

For indicators where moderate values a_{best} are preferable, *Equations 3* and *4* can be used for the normalization.

$$M=\max\left(|a_{ij}-a_{best}|\right) \quad \text{(Eq.3)}$$

$$r_{ij}=1-\frac{|x_i-x_{best}|}{M} \quad \text{(Eq.4)}$$

In *Equations 3* and *4*, a_{best} is the optimal (moderate) value of indicator *j*, i.e., the ideal target value.

Step 3: Use *Equation 5* to calculate the entropy value for each indicator.

$$H_j=-\frac{1}{\ln m}\sum_{i=1}^{m}f_{ij}\ln f_{ij} \quad \text{(Eq.5)}$$

In *Equation 5*, H_j is the information entropy value of the indicator *j*. $f_{ij}=\frac{r_{ij}}{\sum\limits_{i=1}^{m}r_{ij}}$. If $f_{ij}=0$, then $f_{ij}\ln f_{ij}=0$. *m* is the total number of mines to be evaluated.

Step 4: Determine the entropy weight for each indicator according to *Equation 6*.

$$\omega_i=\frac{1-H_j}{n-\sum\limits_{j=1}^{n}H_j},\ 0\leqslant\omega_j\ll 1,\ \sum_{j=1}^{n}\omega_j=1 \quad \text{(Eq.6)}$$

In *Equation 6*, ω_j is the weight of indicator *j*; *n* is the number of indicator numbers.

Step 5: The weighted standardized matrix $Y=(y_{ij})_{m\times n}$ is obtained by multiplying the standardized matrix $R=(r_{ij})_{m\times n}$ by the weights calculated using the entropy weighting method. Where:

$$y_{ij}=r_{ij}\times\omega_j \quad \text{(Eq.7)}$$

In *Equation 7*, y_{ij} is the weighted normalized value for indicator j of mine i; ω_j is the weight of indicator j.

Step 6: Determine the ideal solution and the worst solution. In the weighted standardized matrix: the maximum value of the positive indicator and the minimum value of the negative indicator are selected to form an ideal solution (*Eq. 8*). Conversely, the minimum value of the positive indicator and the maximum value of the negative indicator are selected to form a negative ideal solution (*Eq. 9*).

$$Z^+ = \left(\max_{1 \leq i \leq m} y_{ij} \mid j \in j^+,\ \min_{1 \leq i \leq m} y_{ij} | j \in j^- \right) = (Z_1^+,\ Z_2^+,\ ...,\ Z_n^+) \tag{Eq.8}$$

$$Z^- = \left(\min_{1 \leq i \leq m} y_{ij} \mid j \in j^+,\ \max_{1 \leq i \leq m} y_{ij} | j \in j^- \right) = (Z_1^-,\ Z_2^-,\ ...,\ Z_n^-) \tag{Eq.9}$$

In *Equations 8* and *9*, Z_j^+ and Z_j^- are the ideal solution (best value) and negative ideal solution (worst value) for indicator j, respectively.

Step 7: The Euclidean distance from each ecological restoration of open-pit coal mines to the positive and negative ideal solution is calculated separately.

$$D_i^+ = \sqrt{\sum_{j=1}^{n} (y_{ij} - z_j^+)^2} \qquad (i = 1, 2, ..., m) \tag{Eq.10}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} (y_{ij} - z_j^-)^2} \qquad (i = 1, 2, ..., m) \tag{Eq.11}$$

In *Equations 10* and *11*, y_{ij} is the weighted normalized value for indicator j of mine *i;* D_i^+ and D_i^- are the Euclidean distances to the ideal and negative ideal solutions, respectively; Z_j^+ and Z_j^- are the ideal solution (best value) and negative ideal solution (worst value) for indicator j, respectively.

Step 8: Calculate the relative closeness to the positive ideal solution of each repaired open-pit coal mine by *Equation 12*.

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{Eq.12}$$

In *Equation 12*, C_i is the relative closeness of mine i to the ideal solution; D_i^+ and D_i^- are the Euclidean distances to the ideal and negative ideal solutions, respectively. The value of C_i ranges from 0 to 1. The closer the value of C_i is to 1, the closer the solution is to the positive ideal solution.

Case studies and results

Selection of mines to be studied

To verify the effectiveness of ecological restoration in open-pit coal mines proposed based on the combination entropy weight method and TOPSIS method, 5 open-pit coal mines with relatively similar scale and geological conditions were selected as cases to calculate their ecological restoration effectiveness. These 5 coal mines are all located in the northwestern part of China. One of the selected mines, #D Coal Mine, is illustrated in *Figure 1* to provide a visual reference for the study area.

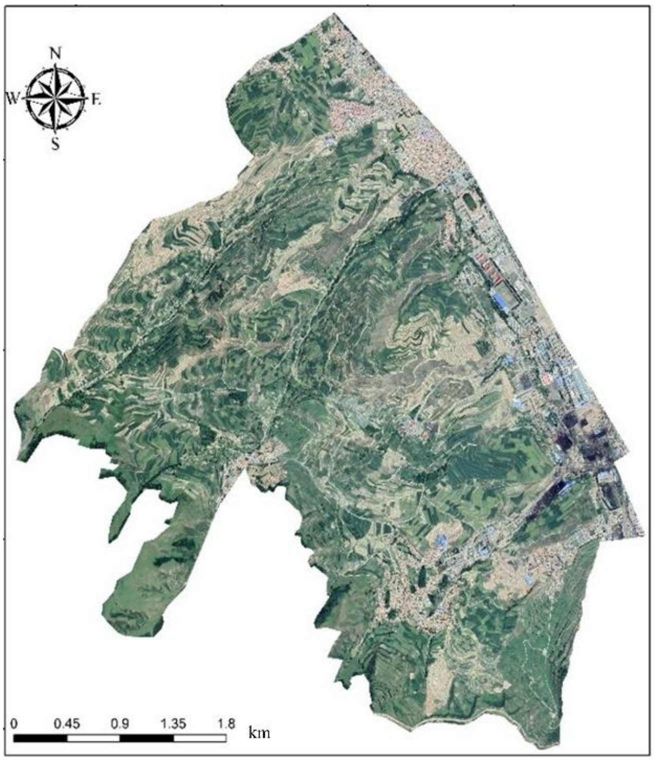

Figure 1. *#D Coal mine is one of the 5 coal mines to be studied*

Data collection and processing

The data used in this study were collected from five ecologically restored open-pit coal mines located in northwestern China. The data collection period spanned from May 2024 to October 2024. A mixed-method approach was adopted, including:

- Field sampling and laboratory analysis. For physical and chemical indicators such as soil organic matter, heavy metals, microbial biomass, water pH, DO, COD, and particulate matter concentrations, field samples were collected and analyzed in certified environmental laboratories following national standard procedures.
- Questionnaire surveys. Information such as the satisfaction rate of surrounding residents was obtained through structured questionnaires distributed to local community members.
- Official reports and monitoring data. Certain indicators, such as the frequency of geological disasters, job creation, and economic output were extracted from local government environmental impact assessment reports and company-provided restoration documentation.

These data sources were triangulated to ensure consistency and reliability. Detailed indicator values are summarized in *Table 2*.

Table 2. *3-Level indicator values of 5 coal mines to be studied*

Level-3 indicator	Unit	Mine #1	Mine #2	Mine #3	Mine #4	Mine #5
Coverage rate of hazard prevention and control engineering	%	55	78	66	59	80
Frequency of geological disasters	times/year	2	1	3	4	4
Soil erosion rate	t/km^2•year	2.3	3.5	2.1	4.0	1.8
Soil organic matter content	g/kg	3.8	5.2	4.5	6.1	4.9
Soil heavy metal content	mg/kg	45	55	38	60	42
Soil available nutrient content	mg/kg	120	150	135	110	125
Soil microbial biomass (SMB)	g/kg	250	280	265	230	275
Water heavy metal concentration	mg/L	0.08	0.11	0.09	0.07	0.12
pH Value	/	6.5	7.2	6.8	7.0	7.3
Dissolved oxygen (DO)	mg/L	8.3	7.9	8.1	8.5	8.0
Chemical oxygen demand (COD)	mg/L	15	20	18	16	22
Total phosphorus (TP)	mg/L	0.020	0.0	0.025	0.018	0.035
Total nitrogen (TN)	mg/L	0.5	0.4	0.6	0.45	0.55
Vegetation coverage	%	40	45	42	38	47
Normalized difference vegetation indicator (NDVI)	/	0.65	0.72	0.68	0.70	0.75
Shannon-Wiener diversity indicator of plants	/	4.2	4.5	4.3	4.6	4.8
Shannon-Wiener diversity indicator of animals	/	3.8	4.0	3.9	4.2,	4.1
Total suspended particulate (TSP) concentration	μg/m³	25	30	28	22	32
PM 10	μg/m³	15	18	16	20	14
PM 2.5	μg/m³	10	12	11	9	13
Concentration of SO_2	μg/m³	25	35	30	20	40
Concentration of NOx	μg/m³	75	90	80	70	100
Concentration of VOCs	μg/m³	50	60	55	45	65
Satisfaction rate of surrounding residents	%	75	80	78	72	85
Number of new job positions created	/	50	65	60	55	70
Increased economic output	US Dollar	1000000	1250000	1200000	1100000	1300000

Calculation and evaluation

According to the 26 indicator values of the 5 ecologically restored mines in *Table 2,* we carried out a step-by-step calculation and analysis to evaluate their ecological restoration effectiveness using the Entropy Weight-TOPSIS method. This process includes the following steps:

Step 1: Constructing the Initial Decision Matrix. The values of all 26 evaluation indicators for each of the 5 mines we collected first, form an initial decision matrix ***A***. This matrix summarizes all relevant ecological, environmental, and social benefit aspects of each mine.

$$A=\begin{bmatrix} 55\% & 2 & 2.3 & 3.8 & 45 & 120 & 250 & 0.08 & 6.5 & 8.3 & 15 & 0.020 & 0.5 & 40 & 0.65 & 4.2 & 3.8 & 25 & 15 & 10 & 25 & 75 & 50 & 75 & 50 & 1000000 \\ 78\% & 1 & 3.5 & 5.2 & 55 & 150 & 280 & 0.11 & 7.2 & 7.9 & 20 & 0.030 & 0.4 & 45 & 0.72 & 4.5 & 4.0 & 30 & 18 & 12 & 35 & 90 & 60 & 80 & 65 & 1250000 \\ 66\% & 3 & 2.1 & 4.5 & 38 & 135 & 265 & 0.09 & 6.8 & 8.1 & 18 & 0.025 & 0.6 & 42 & 0.68 & 4.3 & 3.9 & 28 & 16 & 11 & 30 & 80 & 55 & 78 & 60 & 1200000 \\ 59\% & 4 & 4.0 & 6.1 & 60 & 110 & 230 & 0.07 & 7.0 & 8.5 & 16 & 0.018 & 0.45 & 38 & 0.70 & 4.6 & 4.2 & 22 & 20 & 9 & 20 & 70 & 45 & 72 & 55 & 1100000 \\ 80\% & 4 & 1.8 & 4.9 & 42 & 125 & 275 & 0.12 & 7.3 & 8.0 & 22 & 0.035 & 0.55 & 47 & 0.75 & 4.8 & 4.1 & 32 & 14 & 13 & 40 & 100 & 65 & 85 & 70 & 1300000 \end{bmatrix}$$

Step 2: Data Normalization. Equations 1, 2, 3, and *4*, are used to standardize the initial decision matrix ***A***, and the standardized matrix ***R*** can be obtained. This converts each indicator to a comparable scale between 0 and 1, accounting for whether a higher, lower, or moderate value is better for each indicator.

$$R=\begin{bmatrix} 0.00 & 0.67 & 0.77 & 0.00 & 0.68 & 0.25 & 0.40 & 0.80 & 0.00 & 0.67 & 1.00 & 0.43 & 0.50 & 0.22 & 0.00 & 0.00 & 0.00 & 0.70 & 0.83 & 0.75 & 0.75 & 0.83 & 0.75 & 0.23 & 0.00 & 0.00 \\ 0.92 & 1.00 & 0.23 & 0.61 & 0.23 & 1.00 & 1.00 & 0.20 & 0.60 & 0.00 & 0.29 & 1.00 & 1.00 & 0.78 & 0.70 & 0.50 & 0.50 & 0.20 & 0.33 & 0.25 & 0.25 & 0.33 & 0.25 & 0.62 & 0.75 & 0.83 \\ 0.44 & 0.33 & 0.86 & 0.30 & 1.00 & 0.63 & 0.70 & 0.60 & 0.60 & 0.33 & 0.57 & 0.29 & 0.00 & 0.44 & 0.30 & 0.17 & 0.25 & 0.40 & 0.67 & 0.50 & 0.50 & 0.67 & 0.50 & 0.46 & 0.50 & 0.67 \\ 0.16 & 0.00 & 0.00 & 1.00 & 0.00 & 0.00 & 0.00 & 1.00 & 1.00 & 1.00 & 0.86 & 0.49 & 0.75 & 0.00 & 0.50 & 0.67 & 1.00 & 1.00 & 0.00 & 1.00 & 1.00 & 1.00 & 1.00 & 0.00 & 0.25 & 0.33 \\ 1.00 & 0.00 & 1.00 & 0.48 & 0.82 & 0.38 & 0.90 & 0.00 & 0.40 & 0.17 & 0.00 & 0.00 & 0.25 & 1.00 & 1.00 & 1.00 & 0.75 & 0.00 & 1.00 & 0.00 & 0.00 & 0.00 & 0.00 & 1.00 & 1.00 & 1.00 \end{bmatrix}$$

Step 3: Calculating Entropy Weights. The entropy method was applied to objectively calculate the weight of each indicator based on the variability in the data for all mines. The entropy weight of each indicator ω_j can be calculated by using *Equations 5* and *6*.

$$\omega_j=\begin{pmatrix} 0.0447, 0.0676, 0.0368, 0.0353, 0.0370, 0.0396, 0.0310, 0.0389, 0.0314, 0.0458, 0.0353, 0.0378, 0.0373, \\ 0.0397, 0.0351, 0.0418, 0.0373, 0.0417, 0.0327, 0.0373, 0.0373, 0.0327, 0.0373, 0.03876, 0.037, 0.0327 \end{pmatrix}$$

Step 4: Weighted Normalized Matrix. By multiplying the normalized values by their corresponding entropy weights, a weighted normalized matrix *Y* for all indicators and mines can be obtained by *Equation 7*.

$$Y=\begin{bmatrix} 0 & 0.045 & 0.028 & 0 & 0.025 & 0.010 & 0.012 & 0.031 & 0 & 0.031 & 0.035 & 0.016 & 0.019 & 0.009 & 0 & 0 & 0 & 0.029 & 0.027 & 0.028 & 0.028 & 0.027 & 0.028 & 0.009 & 0 & 0 \\ 0.041 & 0.068 & 0.008 & 0.022 & 0.008 & 0.040 & 0.031 & 0.008 & 0.019 & 0 & 0.010 & 0.038 & 0.037 & 0.031 & 0.246 & 0.021 & 0.019 & 0.008 & 0.011 & 0.009 & 0.009 & 0.011 & 0.009 & 0.024 & 0.028 & 0.027 \\ 0.020 & 0.023 & 0.031 & 0.011 & 0.037 & 0.025 & 0.022 & 0.023 & 0.019 & 0.015 & 0.020 & 0.011 & 0 & 0.018 & 0.011 & 0.007 & 0.009 & 0.017 & 0.022 & 0.019 & 0.019 & 0.022 & 0.019 & 0.018 & 0.019 & 0.022 \\ 0.007 & 0 & 0 & 0.035 & 0 & 0 & 0 & 0.039 & 0.031 & 0.046 & 0.030 & 0.018 & 0.028 & 0 & 0.018 & 0.028 & 0.037 & 0.042 & 0 & 0.037 & 0.037 & 0.033 & 0.037 & 0 & 0.009 & 0.011 \\ 0.045 & 0 & 0.037 & 0.017 & 0.030 & 0.015 & 0.028 & 0 & 0.013 & 0.008 & 0 & 0 & 0.009 & 0.040 & 0.035 & 0.042 & 0.028 & 0 & 0.033 & 0 & 0 & 0 & 0 & 0.039 & 0.037 & 0.033 \end{bmatrix}$$

Step 5: Determining Ideal and Worst Solutions. For each indicator, the ideal (best) and negative ideal (worst) values across all mines can be determined. According to *Equations 10* and *11*, the ideal solution and worst solution can be obtained.

$$Z^{+}=(0.045, 0, 0, 0.035, 0, 0.040, 0.031, 0, 0.031, 0.046, 0, 0, 0, 0.040, 0.035, 0.042, 0.037, 0, 0, 0, 0, 0, 0, 0.039, 0.037, 0.033)$$

$$Z^{-}=(0, 0.068, 0.037, 0, 0.03, 0, 0, 0.039, 0, 0, 0.035, 0.038, 0.037, 0, 0, 0, 0, 0.042, 0.033, 0.037, 0.037, 0.033, 0.037, 0, 0, 0)$$

Step 6: Calculating Euclidean Distances. The Euclidean distance of each coal mine to the ideal solution and worst solution can be calculated by using *Equation 12* and *13* respectively, and the relative closeness of each mine to the ideal solution can be calculated by using *Equation 14*. The calculation results of Euclidean distance and relative closeness are listed in *Table 3*.

Discussion

As shown in *Table 3,* Mine #5 achieves the highest closeness coefficient and is therefore evaluated as having the most effective ecological restoration among the five mines studied. This suggests that the restoration strategies implemented in Mine #5, such as extensive vegetation replanting, soil improvement measures, and comprehensive water management, are closest to the optimal benchmark constructed by the Entropy Weight-TOPSIS model. In contrast, Mine #1, with the lowest closeness coefficient, demonstrates relatively weaker performance across multiple ecological and social indicators, highlighting areas where restoration efforts may need to be strengthened.

Table 3. *Euclidean distances and relative closeness between mines and the ideal solution*

No.	D^+	D^-	C_i	Ranking
Mine #1	0.159151	0.057425	0.265148	4
Mine #2	0.12947	0.133137	0.506982	2
Mine #3	0.100484	0.100484	0.5	3
Mine #4	0.132632	0.132632	0.5	3
Mine #5	0.127287	0.165256	0.564894	1

The clear gradation in closeness coefficients among the five mines confirms the model's ability to distinguish differences in ecological restoration effectiveness. More importantly, the outcomes of our analysis correspond well with field observations and independently measured indicators. For example, mines with higher vegetation coverage and improved water quality verified through NDVI and water sampling, and those reporting greater resident satisfaction, consistently ranked higher according to the model. This alignment between model results and real-world conditions not only validates the robustness of the Entropy Weight-TOPSIS approach but also underscores its interpretability for practical applications.

Another strength of the Entropy Weight-TOPSIS method lies in its capacity to objectively integrate diverse and multi-dimensional data. The entropy weighting scheme reduces subjective bias in indicator selection, allowing the most informative variables to play a greater role in the final assessment. This integrated evaluation framework provides a more holistic picture than traditional single-indicator or qualitative assessments and enables decision-makers to pinpoint both strengths and bottlenecks in restoration practice.

From a practical perspective, the use of this method offers valuable support for ecological management and policy formulation. The ranking results not only highlight which mines are performing well, such as Mine #5, but also provide actionable insights for underperforming sites. Managers can analyze leading cases to identify best practices in restoration design, adaptive management, and community engagement. At the same time, weaker sites can use these findings to target specific deficiencies, optimize resource allocation, and set measurable improvement goals.

Overall, this study demonstrates that the Entropy Weight-TOPSIS approach is a reliable and effective tool for evaluating ecological restoration in open-pit coal mines. It bridges the gap between scientific assessment and on-the-ground realities, providing a solid basis for continual improvement of restoration strategies and for promoting sustainable post-mining landscape management. Future research can further enrich this framework by incorporating long-term monitoring data and broader socio-economic indicators, ensuring an even more comprehensive and adaptive evaluation of restoration outcomes.

Conclusions

In conclusion, the methodology presented in this article provides a systematic and quantitative approach to evaluating the effectiveness of ecological restoration efforts in open-pit coal mines. By integrating the Entropy Weight Method and the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS), this framework offers a comprehensive means of assessing restoration initiatives. Through the calculation of information entropy and subsequent ranking using TOPSIS, decision-makers can identify the most effective restoration strategies by considering various ecological parameters such as *Soil Erosion Rate*, *Soil Available Nutrient*, *Water Heavy Metal Content*, *Vegetation Coverage*, *Concentration of* SO_2, and *Increased Economic Output*. The validation of this methodology through a case study for 5 open-pit coal mining regions underscores its applicability and robustness. By conducting field surveys and collecting data, the effectiveness of different restoration techniques was evaluated, demonstrating the utility of the Entropy Weight Method-TOPSIS Method in assessing ecological restoration efforts. This methodology not only aids decision-makers in evaluating current restoration projects but also provides insights for future initiatives aimed at mitigating the ecological impacts of mining activities and promoting sustainable land use practices.

While the proposed methodology offers a promising approach to assessing the effectiveness of ecological restoration efforts in open-pit coal mines, a limitation should be acknowledged to guide future research and improvement: Ecological restoration is a dynamic process that unfolds over time, and the effectiveness of restoration efforts may vary across different temporal scales. Future research could investigate approaches for incorporating temporal dynamics into the assessment methodology to capture long-term ecological trajectories and ensure the sustainability of restoration outcomes.

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