

Article

Evaluation of Ecological Rehabilitation Models for Abandoned Mines Using Analytic Hierarchy Process–Entropy Method and Sustainable Development Strategies

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Abstract: This study focuses on the ecological restoration of abandoned mines to develop an evaluation model and propose policy recommendations. The research highlights that while mining contributes to economic growth, it also brings numerous abandoned mines and associated environmental issues. Western countries initiated research on abandoned mines earlier, while China continues to explore various restoration approaches. This paper, adhering to the principles of scientific validity, employs the analytic hierarchy process (AHP) and entropy method to construct an evaluation indicator system. Seven indicators were selected, and their weights were determined using both methods to derive the combined weights. The results indicate that factors such as the water source conditions significantly influence the selection of restoration methods, with different approaches yielding varied evaluation scores. Based on this foundation, sustainable development strategies are proposed for development models regarding composite tourism development, geopark development, and ecological greening. These strategies include enhancing resource utilization efficiency, strengthening ecological protection, and promoting the transformation of ecological value, etc. The aim is to align the rehabilitation of abandoned mines with the goal of sustainable development, offering a scientific basis and policy guidance for the ecological rehabilitation of mines while fostering the sustainable development of the region.

Keywords: mine ecological restoration; AHP; entropy method; evaluation indicator system; policy recommendation; sustainable development



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1. Introduction

The resource value inherent in mines has been a driving force for economic development and has made significant contributions to social development. However, in the extraction of mineral resources, there has been an overemphasis on the economic benefits of mining while neglecting the necessity of management, resulting in negative ecological and social impacts. Consequently, the proliferation of abandoned mines has led to severe problems, including land degradation, air, water, and soil pollution, as well as damage to ecosystems [1]. Currently, China has over 100,000 abandoned mines, with a mine reclamation rate below 10%. The cumulative area of land damaged by mining activities has reached 3.868 million ha [2], affecting underground aquifers spanning 5.38 million ha. The accumulated solid wastes have reached 40 billion tons, with the annual wastewater discharge exceeding 4.7 billion m³. Nationwide, geological disasters triggered by mineral resource development have surpassed 26,000 incidents, causing direct economic losses of CNY 39.75 billion. Furthermore, due to outdated mineral processing equipment and technologies, large quantities of tailings produced at the end of mineral processing contain valuable components, leading to severe resource waste. These problems not only threaten

ecosystem stability and biodiversity conservation but also hinder the sustainable growth of local economies and the harmonious development of society. Achieving sustainable development requires balancing economic, social, and environmental considerations. Therefore, the ecological restoration of abandoned mines has become a key task in realizing sustainable regional development. Through an in-depth discussion of the ecological restoration model of abandoned mines, this study aims to develop a scientific and robust evaluation framework to support the formulation of effective policies, thereby guiding ecological restoration efforts toward sustainable development.

2. Literature Review

There are approximately one million abandoned mines in the world [3]. In response to issues arising from active mining operations and those persisting after mine abandonment, major mining nations such as the US, Canada, and Australia have intensified regulatory oversight of mining activities at legal, organizational, and technical levels while enhancing environmental management. The US initiated ecological restoration projects on mines in 1935, with restoration technologies primarily targeting soil, water, and vegetation [4]. Canada's approach to mine ecological restoration adheres to the principles of site-specific adaptation, employing diverse restoration methods based on the unique topography and extent of ecological damage at each abandoned mine. For instance, abandoned open-pit mines can be repurposed as fish ponds or water reservoirs, while those with distinctive landscape features and favorable transportation access can be developed into mining parks [5]. Mine ecological restoration in Australia primarily aims to reinstate the original environment, with restoration measures integrated throughout the entire mining lifecycle. In the preliminary stages, comprehensive surveys are conducted on the types, quantities, and distribution of the flora, fauna, and microorganisms in the mining area. Based on the anticipated impacts, protective transplantation of vegetation is implemented, along with topsoil preservation. During the middle stages, measures are taken to prevent and treat acid and heavy metal-contaminated wastewater. In the later stages, phosphates are promptly applied to reduce lead and zinc concentrations in polluted wastewater, followed by technical restoration. Concurrently, Australia has established the Australian Minerals Industry Code for Environmental Management, which mandates mining companies to submit annual public environmental impact reports within specified timeframes, thereby monitoring and regulating the environmental practices of mining enterprises [6]. In addition to these studies on national policies, foreign scholars have also conducted relevant research. As early as 1982, European scholar Ferderer proposed understanding the profile of national abandoned mines through the available mineral resources system (MAS) and geographic information system (GIS) [7]. Concerning the sustainable development of abandoned coal mines, there is a noted lack of operational approaches that can be replicated and modeled. Krzemień et al. suggested implementing environmental risk management strategies for the underground space of abandoned coal mines and provided an information framework to support their sustainable development [8]. Michael discussed the safety risks associated with coal mines post-closure and proposed a methodology for risk assessment [9]. Furthermore, J. Stacey et al. explored the sustainable development of abandoned mines from a socio-economic perspective, conducting a literature review and summarizing experiences related to the socio-economics of these mines [10]. In the Republic of Korea, Song J et al. assessed the potential for developing wind and photovoltaic power generation in abandoned mines, conducting a strength study of several sites as a means to further explore the feasibility of utilizing renewable energy sources for the sustainable development of abandoned mines [11,12].

China's research on abandoned mines began relatively late, evolving from spontaneous exploration of mine restoration and reclamation in the mid-20th century to the enactment of relevant laws such as the "Land Reclamation Regulations", and subsequently to the reclamation of historical mine sites and the introduction of policies for new construction land [13]. Over the years, significant efforts have been made in mine restoration.

Considering China's specific mining conditions, domestic experts and scholars have proposed various restoration models, including vegetation reconstruction, landscape design, and composite tourism development. These approaches aim to expand the potential economic and social benefits of mine ecological restoration, striving for a balance among the social, economic, and ecological benefits [14]. The study of models for abandoned mine restoration has consistently been a focal point in academia and in practical applications. In recent years, numerous scholars have conducted in-depth analyses of these methods. In 2011, Zhang Qiuxia et al. conducted a comprehensive study on the ecological restoration of wetlands in coal mining areas [15]. This paper summarized the research advantages of the three main techniques and objectives for wetland restoration in these regions: wastewater treatment, landscape ecosystem establishment, and fish culture. It emphasized that ecosystem restoration should be tailored to regional characteristics, leading to the construction of wetland parks and integrated ecosystems. In 2016, Kai Lei et al. researched the landscape approach to ecological restoration and sustainable development in mining areas [16]. They studied and analyzed the principal techniques of ecological restoration and landscape ecology that are applicable to mine restoration processes, aiming to enhance restoration efforts and ensure long-term effectiveness. Wu et al. addressed nine aspects of the environmental issues associated with mines, thus providing a comprehensive solution for mine ecological restoration [17]. Liu et al. summarized ecological restoration models for abandoned open-pit mines in Shandong Province and achieved a synergy of ecological, social, and economic benefits through the remediation of geological environments and ecological restoration [18]. Sun et al. examined three ecological restoration models for abandoned mines: natural restoration, a combination of natural and artificial restoration, and purely artificial restoration, offering scientific guidance for the ecological restoration of abandoned mines [19]. Zhu et al. studied the ecological restoration projects associated with abandoned open-pit mines in the Yangtze River Economic Belt within Guizhou Province and proposed two models: vegetation greening and reclamation utilization, which improved the ecological environment and fostered sustainable development [20]. Employing the analytic hierarchy process, Wang et al. developed an evaluation model of ecological restoration for abandoned mines and determined the weights of evaluation indicators across five restoration models, including ecological greening and land reuse, thus providing a quantitative basis for selecting appropriate restoration approaches [21]. Wu et al. explored a mine ecological restoration model based on the value realization of ecological products, enhancing ecosystem services and converting ecological value into economic benefits [22]. Li et al. proposed a development-oriented model for the geological environments of mines, introducing new concepts for mine environmental protection and ecological restoration through approaches such as the utilization of residual resources [23]. Liu et al. introduced the "mine ecological restoration+" model and emphasized comprehensive development and utilization in abandoned mines that are ecologically restored [24]. Wang et al. examined the model of social capital participation in mine ecological restoration in Guangdong, providing valuable insights into social capital involvement in mine restoration efforts [25].

Overall, China has achieved significant progress in the research and implementation of abandoned mine restoration. This progress is characterized by diversity, systematic approaches, scientific methodologies, and regional characteristics. There has been continuous innovation in the models for social capital participation and the exploration of pathways to realize the value of ecological products, thus providing strong support and assurance for the ecological restoration and sustainable development of abandoned mines. In the future, it is essential to further develop technical standards, establish robust systems for long-term monitoring and evaluation, and promote cross-regional experience exchanges and dissemination to strengthen the sustainable development of abandoned mine rehabilitation.

3. Research Methods

3.1. Analytic Hierarchy Process

The analytic hierarchy process (AHP) is a decision-making methodology that integrates quantitative and qualitative analysis. It enables the treatment of complex problems characterized by multi-objective decisions as systems. Based on a comprehensive analysis of the essence, influencing factors, and interrelationships within complex problems, AHP calculates single rankings and overall rankings through fuzzy quantification of qualitative indicators. This provides a convenient and effective evaluation approach for indicator assessment [26]. The primary steps are as follows:

(1) Establish a hierarchical structure model

Based on the analysis above, the models for ecological restoration of abandoned mines were selected and examined hierarchically. A corresponding hierarchical structure model was constructed according to the research objectives and the influencing factors at each level, as illustrated in Figure 1. This model comprises three levels: the goal level (A), the criteria level (B), and the alternative level (C).

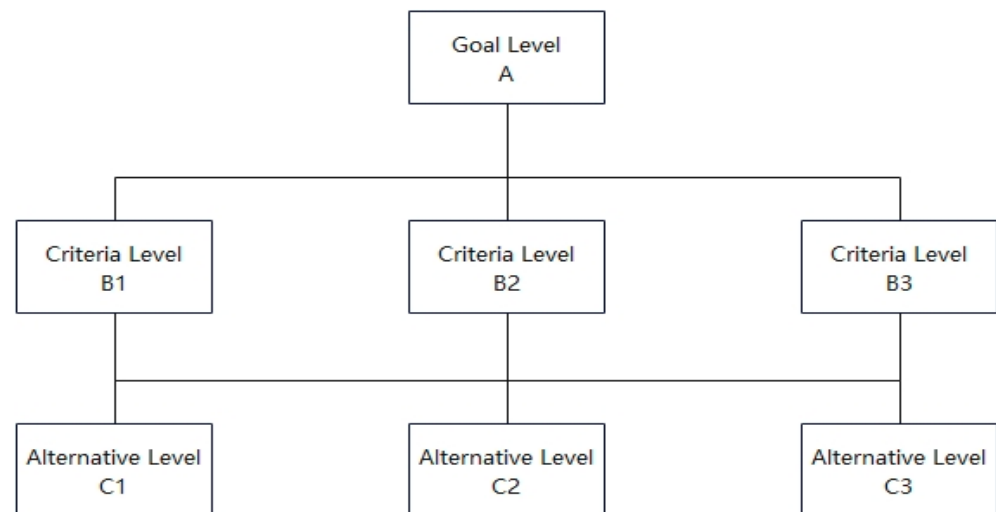


Figure 1. Recursive Hierarchical Model.

(2) Construct pairwise comparison matrices

With the 1–9 scale method, different influencing factors at the same level are compared in pairs. Specifically, the relative importance of the i -th factor compared to the j -th factor, with respect to the factor at the preceding level, was assigned a value. This process determines the relative weights of each factor, as denoted by a_{ij} . Definitions of comparison values are presented in Table 1.

Table 1. Standards for setting comparison values.

Comparison Value	Result
1	Factors i and j are equally important relative to the factor in the upper level
3	Factor i is slightly more important compared to factor j
5	Factor i is clearly more important compared to factor j
7	Factor i is strongly more important compared to factor j
9	Factor i is extremely more important compared to factor j
2, 4, 6, 8	Intermediate values between the adjacent judgments above
$1/a_{ij}$	Reciprocal comparison between factors i and j

For the hierarchical structure model presented earlier, a judgment matrix $A = (a_{ij})_{n \times n}$ was constructed, where the criteria-level factors were evaluated relative to the goal-level

factors. In this matrix, n represents the number of factors being compared pairwise. With this method, judgment matrices for subsequent levels can be similarly constructed. This formula functions to decompose the complex multi-factor evaluation problem into relative importance judgments based on pairwise comparisons of each factor. This approach provides essential data for subsequent weight calculations, thereby facilitating the construction of the entire evaluation system.

$$\begin{bmatrix} A & B1 & B2 & B3 \\ B1 & 1 & b_{12} & b_{13} \\ B2 & \frac{1}{b_{12}} & 1 & b_{23} \\ B3 & \frac{1}{b_{13}} & \frac{1}{b_{23}} & 1 \end{bmatrix} \quad (1)$$

(3) Weight calculation and consistency check

Single ranking involves calculating the maximum eigenvalue λ_{max} and eigenvector W for each level's judgment matrix, then deriving the relative weights of each indicator. The following methods were employed to calculate the weights, eigenvector W , and maximum eigenvalue λ_{max} . The weight calculation formula was employed to derive the relative weight of each index from the judgment matrix, thereby clarifying the significance of each factor in the overall evaluation. The consistency test formula functions as a 'gatekeeper' mechanism, ensuring the reasonableness of expert judgments during the initial stages. This process mitigates potential deviations in the evaluation results caused by subjective factors and enhances the accuracy and effectiveness of the entire AHP evaluation process.

(1) Calculate weights and eigenvector W

$$W_i = \frac{\overline{W_i}}{\sum_{i=1}^n \overline{W_i}} \quad (2)$$

$$W = \begin{Bmatrix} W_1 \\ W_2 \\ \dots \\ W_n \end{Bmatrix} \quad (3)$$

(2) Calculate the maximum eigenvalue λ_{max}

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^n \frac{(AW)_i}{W_i} \quad (4)$$

In practical applications, the calculation results of each matrix will inevitably contain some degree of inconsistency. Therefore, to enhance the scientific validity and rationality of the judgment matrix, the following method was used to perform a consistency check.

(1) Calculate the consistency index (CI)

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (5)$$

If $CI = 0$, it indicates perfect consistency in the matrix; if CI approaches 0, it suggests good consistency in the matrix.

(2) Determine the random (consistency) index (RI) to better assess the consistency ratio of the matrix (Table 2).

Table 2. Random index.

Order	2	3	4	5	6	7	8
RI	0	0.52	0.89	1.12	1.26	1.36	1.41

- (3) Calculate the consistency ratio (CR).

If CR is less than 0.1, the judgment matrix passes the consistency check; otherwise, the judgment matrix requires adjustment.

$$CR = \frac{CI}{RI} \quad (6)$$

- (4) After performing single rankings for each level, derive the comprehensive weights w_j for each indicator using AHP.

3.2. Entropy Method

The entropy method is an analytical approach employed under objective conditions. Utilizing the entropy method minimizes the subjective influence of factor weights on evaluation results, aligning them more closely with objective reality.

- (1) Construct judgment matrix

Based on the data provided, we constructed a judgment matrix comprising m alternatives and n evaluation indicators.

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1m} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nm} \end{bmatrix} \quad (7)$$

- (2) Data standardization

We applied the extremum method to standardize the original data. Equation (8) was used for processing positive indicators, while Equation (9) was used for negative indicators, ultimately yielding a standardized matrix that eliminates differences in measurement units among indicators.

$$r_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \quad (8)$$

$$r_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \quad (9)$$

In these equations, x_{ij} represents the j -th indicator value of the i -th sample ($i = 1, 2, \dots, m; j = 1, 2, \dots, n$), and r_{ij} is the standardized data. To prevent situations where standardized data have low or negative values, a translation process is applied as follows:

$$r'_{ij} = r_{ij} + H \quad (10)$$

where H represents the magnitude of indicator translation, typically set at 0.0001.

The purpose of the formula is to pre-process the data by eliminating interference caused by differences in index scale and order of magnitude. This step is crucial for the subsequent objective determination of weights based on the characteristics of the data, serving as an important antecedent to ensure the accuracy of the entropy weighting method.

- (3) Determine the entropy value of evaluation indicators

These formulas collaboratively establish the weights of the indicators by considering the intrinsic characteristics of the data. This approach complements the weight determination derived from expert experiences in the analytic hierarchy process (AHP) method. Consequently, the entire evaluation system can incorporate subjective expertise while adhering to the principles of objective data analysis, thereby enabling a more comprehensive and accurate assessment of the ecological restoration model for abandoned mines.

- (1) Normalize the standardized matrix.

$$p_{ij} = \frac{r'_{ij}}{\sum_{i=1}^m r'_{ij}} \quad (11)$$

- (2) Calculate the information entropy value e_j of the j -th evaluation indicator.

$$e_j = -\frac{\sum_{i=1}^m p_{ij} \ln(p_{ij})}{\ln(m)} \quad (12)$$

- (3) Calculate the difference coefficient g_j of indicator j .

$$g_j = 1 - e_j \quad (13)$$

- (4) Calculate the weight v_j of the j -th indicator.

$$v_j = \frac{g_j}{\sum_{j=1}^n g_j} \quad (14)$$

3.3. AHP–Entropy Method

The AHP–entropy method involves assigning both subjective and objective weights to each indicator using AHP and the entropy method, respectively. These two weights are then combined to derive an indicator weight that is more rational and objective. In order to enhance the accuracy and scientific validity of the indicator weights, Equation (15) was employed to calculate the combined weight of each evaluation indicator:

$$w_j^* = \frac{w_j v_j}{\sum w_j v_j} \quad (15)$$

where w_j represents the weight derived from AHP, and v_j represents the weight obtained through the entropy method.

Equation (15) integrates the weights calculated by the analytic hierarchy process (AHP) and the entropy weight method, reflecting the empirical judgments of experts regarding the factors associated with the ecological restoration of abandoned mines. The entropy weight method, in contrast, determines weights based on objective information, such as the degree of data dispersion. Each method has its distinct advantages, and this formula effectively combines them. This formula serves to integrate the results of two weight calculation methods, thereby creating a comprehensive weight system. This system provides essential parameters for the thorough and accurate assessment of various ecological restoration models for abandoned mines, thereby enhancing the scientific rigor and reliability of the overall evaluation model.

4. Constructing the Indicator System of Ecological Restoration for Abandoned Mines

4.1. Factors Influencing the Selection of Ecological Restoration Models for Abandoned Mines

Through our literature review and analysis of restoration factors from case studies regarding mine restoration, and in accordance with established evaluation principles, 12 evaluation indicators were identified. These indicators are presented in Table 3.

The size of the mine and the terrain conditions not only affect the scale and difficulty of restoration projects but are also closely related to the sustainability of subsequent land use. Large mines with complex topography may require more resources for restoration; however, with strategic planning, they can offer opportunities for diverse, sustainable uses, such as developing large-scale eco-agriculture or constructing integrated eco-parks.

Soil conditions, vegetation, and biodiversity are central to ecosystem sustainability. High-quality soil serves as the foundation for vegetation growth and ecosystem stability, while robust vegetation cover can help prevent soil erosion, regulate the climate, and absorb carbon dioxide (carbon sequestration). These processes contribute to the ecological

balance, biodiversity conservation, and the provision of long-term ecosystem services, such as water conservation and soil improvement, which are essential for maintaining regional ecological sustainability.

Table 3. Indicators and their attributes.

Indicator Layer	Attribute
Mine area	Positive
Topography	Positive
Soil conditions	Positive
Historical and cultural significance	Positive
Accessibility	Positive
Climate regulation	Positive
Water resources	Positive
Carbon sequestration	Positive
Vegetation cover	Positive
Biodiversity	Positive
Cumulative restored area	Positive
Local residents	Positive

Water conditions are closely related to water conservation and the sustainability of the ecological balance. Adequate, clean water is essential for ecosystems to function properly and plays an indispensable role in vegetation restoration, biological survival, and the prevention of land desertification. Furthermore, water availability significantly influences water supply and the sustainable development of surrounding communities.

Transportation and the surrounding population have significant impacts on economic development and social cohesion (social sustainability). Efficient transportation supports the movement of restoration materials, facilitates tourist access, and streamlines product exports, reducing costs, boosting regional economic growth, creating jobs, and improving local living standards. Addressing the needs of nearby residents—such as minimizing disruptions caused by restoration activities, encouraging community participation in the restoration process, and sharing the benefits of restoration—can foster community harmony and stability. This, in turn, strengthens resident support for the project and ensures its long-term sustainability.

Climate regulation and carbon sequestration highlight the role of abandoned mine rehabilitation in mitigating global climate change and improving the regional ecological environment. Effective ecological restoration measures can enhance the area's climate regulation capacity by stabilizing temperature fluctuations and increasing air humidity, among other benefits. Additionally, vegetation restoration and soil contribute to improved carbon sequestration, reducing greenhouse gas emissions. These efforts are of significant value in addressing global climate change and realizing low-carbon sustainable development.

The cumulative restored area serves as an indicator of the progress and effectiveness of mine rehabilitation efforts and is closely related to the degree of ecological restoration and the sustainable use of land resources within the goals for sustainable development. A continuous increase in the rehabilitated area signifies the rational utilization of more land resources and the gradual recovery of ecosystems, thus establishing a solid foundation for achieving regional ecological, economic, and social sustainability.

The history and culture of mines, in turn, serve as valuable cultural resources for the sustainable development of abandoned mines. By uncovering and utilizing mine history and culture, industries such as cultural tourism and industrial heritage preservation can be cultivated. This not only preserves local cultural heritage and enriches the depth of tourism offerings but also enhances cultural identity and social cohesion. Simultaneously, it drives economic growth, fostering the sustainable integration of cultural and economic development.

4.2. Construction of the Indicator System

Based on this foundation, the membership degree analysis was applied for further refinement. This quantitative screening approach, based on the volume of data, allows for the exclusion of evaluation indicators that are less significant. Consequently, it ensures that the assessments within the evaluation system are more accurate, scientifically sound, and efficient.

$$R_i = \frac{P_i}{n} \quad (16)$$

In this equation, R_i represents the membership degree, P_i represents the total number of times experts select the evaluation indicator under the i -th indicator, and n is the total number of experts.

The principle governing the results of the membership degree is as follows: Indicators with larger membership degrees play a more significant role in the evaluation indicator system and reflect higher expert consensus, indicating stronger representativeness. Conversely, indicators with smaller membership degrees have a lesser role and weaker representativeness.

The membership degree ranges from 0 to 1. This process was completed through expert questionnaires, as illustrated in Table 4.

Table 4. Membership degrees of indicator layer.

Indicator Layer	Membership Degree
Mine area	0.9251
Topography	0.7232
Soil conditions	0.9783
Historical and cultural significance	0.7156
Accessibility	0.8979
Climate regulation	0.8124
Water resources	0.9642
Carbon sequestration	0.7857
Vegetation cover	1
Biodiversity	0.8790
Cumulative restored area	0.8571
Local residents	0.8691

Membership degrees were calculated based on the questionnaire results, and five evaluation indicators were eliminated from the initial screening. The secondary screening retained seven factors as evaluation indicators: mine area, soil quality, water resources, accessibility, vegetation cover, biodiversity, and local residents.

4.3. Weights of Evaluation Indicators for Abandoned Mines Using AHP

4.3.1. Establishment of the Hierarchical Structure Model

To begin with, this study employs AHP to calculate the comprehensive weights for each indicator. Based on the evaluation indicator system previously constructed for selecting ecological restoration models of abandoned mines, a hierarchical structure model was developed, as illustrated in Figure 2.

Composite tourism fully integrates the resources of abandoned mines, such as natural landscapes, historical and cultural assets, and geographic conditions, to deeply explore their tourism potential. By creating diversified tourism offerings, such as mine ruins sightseeing, ecological experiences, cultural exploration, and leisure vacations, it attracts a significant influx of tourists, stimulating the development of related industries such as dining, accommodation, transportation, and retail. This generates substantial economic benefits and supports sustainable economic growth. Throughout the development process, the model prioritizes ecological protection by carefully planning tourism infrastructure to prevent ecological damage from overdevelopment. It ensures the continued functionality

of ecosystem services, safeguarding key elements such as vegetation, water resources, and biodiversity. Simultaneously, tourism operations create ample employment opportunities for local residents, increasing household incomes, improving community infrastructure and social services, and strengthening social cohesion. This approach transforms abandoned mines into exemplary regions for the harmonious development of ecology, economy, and society, thereby serving as a model for sustainable growth.

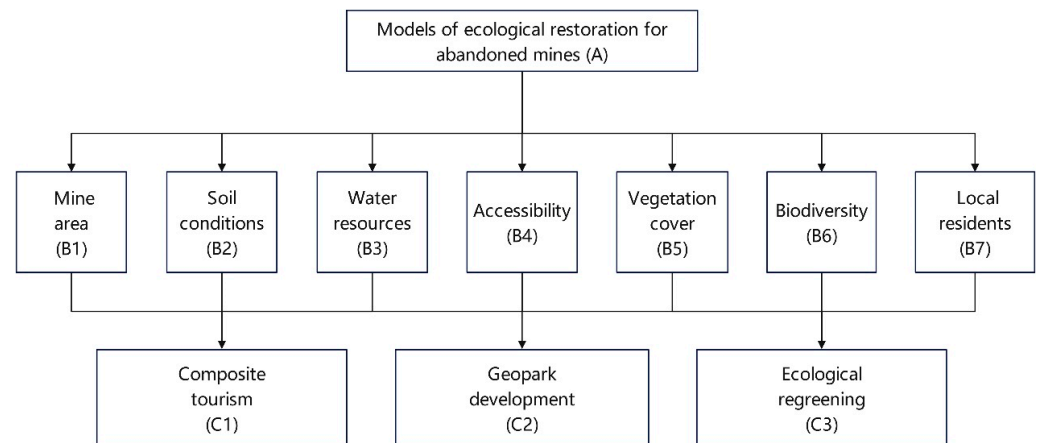


Figure 2. Hierarchical structure model for selecting ecological restoration models of abandoned mines.

Geopark development focuses on utilizing the geological relics and landscapes of abandoned mines as its core, implementing scientific planning and development to establish a geopark that serves as a center for science education, research, and tourism. This model holds significant value in scientific research, providing field study locations for geologists, facilitating the dissemination and innovation of geoscientific knowledge, enhancing public scientific awareness, and promoting the sustainable development of science and culture. In terms of tourism, the geopark attracts geology enthusiasts, students, and general tourists, boosting local tourism and generating economic benefits. From an ecological perspective, the model carefully regulates the scope and intensity of development activities to protect the geological and ecological environment, preserve ecosystem stability, and ensure the long-term conservation and sustainable use of geological relics. Moreover, the construction and operation of the geopark offer local employment opportunities, foster community development, and deepen residents' understanding of geological heritage and ecological conservation, thereby achieving a balance of economic, social, and ecological sustainability.

Ecological greening focuses on restoring the ecological environment of abandoned mines as its primary goal, using ecological restoration techniques such as vegetation restoration and soil enhancement to revitalize the area. As the ecological environment improves, it creates opportunities for the development of green industries, such as eco-agriculture and eco-forestry, ensuring the sustainable use of land resources, increasing economic income, and supporting long-term economic growth. In addition, ecological greening enhances the living conditions of local residents, providing spaces for leisure and recreation, fostering environmental awareness, and promoting the harmonious relationship between the community and nature. This approach ensures the sustainable development of society while improving the quality of life for the surrounding populations.

4.3.2. Construction of Judgment Matrices

Based on AHP, evaluation indicators for ecological restoration models were decomposed into seven interrelated factors. The 1–9 scale method was employed.

Based on the difference among the comparison values of the evaluation indicators above, experts were invited and used the seven indicators to score and assess the importance of alternative level: C1 (composite tourism), C2 (geopark development), and C3 (ecological greening). The following results were obtained:

Composite tourism (C1) is deemed suitable for abandoned mines with favorable ecological conditions, advantageous geographical locations, and significant resource development potential. After scoring by experts, the judgment matrix was derived, as presented in Table 5.

Table 5. The judgment matrix for composite tourism.

C1	B1	B2	B3	B4	B5	B6	B7
B1	1	1/4	1/5	1/8	1/6	1/2	1/7
B2	4	1	2	3	4	5	3
B3	5	1/2	1	1/2	3	4	4
B4	8	1/3	2	1	6	7	2
B5	6	1/4	1/3	1/6	1	2	1/3
B6	2	1/5	1/4	1/7	1/2	1	1/4
B7	7	1/3	1/4	1/2	3	4	1

Geopark development (C2) is appropriate for abandoned mines featuring excellent geological conditions, unique topography, and favorable development potential, along with easy landscape creation. The judgment matrix derived from expert scoring is presented in Table 6.

Table 6. The judgment matrix for geopark development.

C2	B1	B2	B3	B4	B5	B6	B7
B1	1	1	7	2	3	9	6
B2	1	1	4	1	4	9	3
B3	1/7	1/4	1	1/4	1/6	2	2
B4	1/2	1	4	1	4	6	2
B5	1/3	1/4	6	1/4	1	4	5
B6	1/9	1/9	1/2	1/6	1/4	1	1/5
B7	1/6	1/3	1/2	1/2	1/5	5	1

Ecological greening (C3) is suitable for abandoned mines with robust hydrological conditions and high soil resilience, and where the surrounding environment has not suffered severe degradation. The judgment matrix obtained from expert scoring is shown in Table 7.

Table 7. The judgment matrix for ecological greening.

C3	B1	B2	B3	B4	B5	B6	B7
B1	1	1/7	1/9	1/5	1/9	1/2	1/3
B2	7	1	1	4	1	7	6
B3	9	1	1	3	1/3	7	5
B4	5	1/4	1/3	1	1/5	4	3
B5	9	1	3	5	1	8	7
B6	2	1/7	1/6	1/4	1/8	1	1/3
B7	3	1/6	1/5	1/3	1/7	3	1

4.3.3. Weight Calculation

Based on the matrix results above, weights for different matrices were calculated. The row vectors of each matrix were normalized using the sum-product method to derive the weights and characteristic vector W for each evaluation indicator, as presented in Table 8.

Table 8. Weights and characteristic vectors of evaluation indicators.

W	Composite Tourism C1	Geopark Development C2	Ecological Regreening C3	Comprehensive Weight W_i
Mine area B1	0.031098813	0.293223359	0.024177912	0.116167
Soil conditions B2	0.296062517	0.235941512	0.252059387	0.261354
Water resources B3	0.185232437	0.053154334	0.210626887	0.149671
Accessibility B4	0.242594037	0.194645054	0.095500066	0.17758
Vegetation cover B5	0.075390138	0.132266283	0.330513636	0.17939
Biodiversity B6	0.04175135	0.024903151	0.03305335	0.033236
Local residents B7	0.127870708	0.065866307	0.054068763	0.082602

4.3.4. Consistency Check

A consistency check was conducted on the results. First, the maximum eigenvalue λ was calculated, as shown in Table 9, then it was determined whether they could pass the one-time check, as shown in Table 10 below.

Table 9. Maximum eigenvalues for three mine restoration models.

Composite Tourism C1	Geopark Development C2	Ecological Regreening C3
7.78	7.80	7.38

Table 10. Results of consistency check.

	Composite Tourism C1	Geopark Development C2	Ecological Regreening C3
CR	0.095919705	0.098611744	0.04750102
	CR < 0.1, Passed	CR < 0.1, Passed	CR < 0.1, Passed

4.4. Evaluation Indicator Weights for Abandoned Mines Using the Entropy Method

The entropy method is used to calculate weights based on the dispersion of the data, thus avoiding the imbalance between subjective and objective judgments that often result from subjective scoring. This approach significantly reduces the impact of subjective judgment on evaluation results, making the construction more accurate and comprehensive. Additionally, the entropy method demonstrates high applicability across various data types, offering greater versatility.

4.4.1. Constructing Scores

This study employs five-level scoring criteria within the entropy method to evaluate 294 indicators for different models of mine restoration. The scoring scale ranges from 5 to 1. Ten experts and scholars conducted professional assessments, which yielded the following results, as presented in Table 11.

Table 11. Scoring results of evaluation indicators.

Evaluation Indicator	Composite Tourism C1	Geopark Development C2	Ecological Regreening C3
Mine area B1	3	3.91	2
Soil conditions B2	3.17	4	4.1
Water resources B3	3.2	3.12	4
Accessibility B4	4.1	3.9	2.9
Vegetation cover B5	2.7	3.5	4.3
Biodiversity B6	2.5	4	4.3
Local residents B7	3.2	2.7	2.5

4.4.2. Comprehensive Scores

The entropy method involves the following steps:

- (1) We performed dimensionless processing on the original data to eliminate the influence of physical quantities and calculate the feature weight of the n -th restoration model under the j -th indicator. In order to address potential issues with low or negative values in the standardized data, a uniform translation process was applied, where $H = 0.0001$. The results are shown in Table 12.
- (2) We calculated the information entropy e_j and difference coefficient g_j (Table 13).

Table 12. Matrix of standardized evaluation indicators 306 and weight v_j .

Evaluation Indicator	Composite Tourism C1	Geopark Development C2	Ecological Regreening C3
Mine area B1	0.0001	1.0001	0.9012
Soil conditions B2	0.0001	0.892573	1.0001
Water resources B3	0.091009	0.0001	1.0001
Accessibility B4	1.0001	0.833433	0.0001
Vegetation cover B5	0.0001	0.5001	1.0001
Biodiversity B6	0.0001	0.833433	1.0001
Local residents B7	1.0001	0.285814	0.0001

Table 13. Indicator weights of restoration models under the entropy method.

Evaluation Indicator	Information Entropy e_j	Difference Coefficient g_j	Weight v_j
Mine area B1	0.630184	0.369816	0.117048
Soil conditions B2	0.629948	0.370052	0.117122
Water resources B3	0.262091	0.737909	0.23355
Accessibility B4	0.627667	0.372333	0.117844
Vegetation cover B5	0.58	0.42	0.132931
Biodiversity B6	0.627667	0.372333	0.117844
Local residents B7	0.482912	0.517088	0.16366

4.4.3. Combined Weights Under the AHP–Entropy Method

Based on the previous calculations of evaluation indicator weights for selecting the restoration model using both AHP and the entropy method, the combined weights for each evaluation indicator were calculated by integrating these two weights according to Equation (15), as presented in Table 14.

Table 14. Combined indicator weights of restoration models under the AHP–entropy method.

Evaluation Indicator	AHP Weight w_j	Entropy-Based Weight v_j	Combined Weight w_j^*
Mine area B1	0.630184	0.117048	0.106383948
Soil conditions B2	0.629948	0.117122	0.214079338
Water resources B3	0.262091	0.23355	0.244469004
Accessibility B4	0.627667	0.117844	0.146355545
Vegetation cover B5	0.58	0.132931	0.166775122
Biodiversity B6	0.627667	0.117844	0.027392009
Local residents B7	0.482912	0.16366	0.094545034

4.5. Analysis of Research Results

This study derived the comprehensive evaluation of different mine restoration models for using the current weighted method. In this context, r_{ij}' represents the standardized value after the translation of sample data, and w_j^* represents the combined weight of each indicator (Tables 15 and 16).

$$z_i = \sum_{j=1}^n w_j^* r_{ij}' \quad (17)$$

Table 15. Rankings of combined weights for each indicator.

Evaluation Indicator	Combined Weight w_j^*	Ranking
Mine area B1	0.106383948	5
Soil conditions B2	0.214079338	2
Water resources B3	0.244469004	1
Accessibility B4	0.146355545	4
Vegetation cover B5	0.166775122	3
Biodiversity B6	0.027392009	7
Local residents B7	0.094545034	6

Table 16. Comprehensive evaluation of different restoration models.

	Composite Tourism	Geopark Development	Ecological Regreening
Comprehensive evaluation	0.318923	0.552734	0.652815

Firstly, based on the combined weights of evaluation indicators, the highest weight was assigned to water conditions, highlighting that, within the framework of sustainable development, ensuring a stable water supply is fundamental to the ecological restoration of abandoned mines. This is crucial for maintaining the ecosystem balance and supporting the sustainability of agricultural and other economic activities. Good soil conditions facilitate vegetation growth and ecosystem stability, thus promoting the sustainable use of land resources. The condition of vegetation is not only important for ecological aesthetics but also plays a vital role in regulating the climate, conserving soil and water, and providing other essential ecological services for sustainable development. Transportation accessibility influences the economic vitality of rehabilitated mines and facilitates community interaction, both of which are crucial for the sustainable development of the regional economy and society. While the size of the mine carries a relatively lower weight, rational planning for its utilization can still impact resource efficiency and guide the trajectory of sustainable development. The consideration of local residents reflects social equity and harmony, which are key aspects of the social dimension of sustainable development. Finally, as a critical indicator of ecosystem integrity, biodiversity plays an indispensable role in ensuring the long-term stability and sustainability of ecosystems.

Further analyzing values of the comprehensive evaluation for different development plans reveals composite tourism at 0.318923, geopark development at 0.552734, and ecological regreening at 0.652815. It is evident that ecological regreening exhibits the highest overall assessment value. This is because it effectively enhances ecosystem quality and function through measures such as vegetation restoration and soil improvement while ensuring essential ecological services like biodiversity protection, climate regulation, and water and soil conservation. Additionally, it lays the groundwork for future ecological and economic development, including eco-tourism and eco-agriculture. The higher assessment value of geopark development is attributed to its ability to generate economic and social benefits while simultaneously preserving geological relics. This aligns with the principles of sustainable development, which advocate for the coordinated development of the economy, society, and environment. Geopark development not only conserves valuable geological resources but also enhances public awareness of geoscience through educational initiatives, tourism, and other activities. It drives local tourism development, stimulates economic growth, and creates employment opportunities for the community, fostering a mutually beneficial outcome. The lower assessment value of composite tourism suggests that, under its current framework, it may not fully optimize resource utilization, ecological conservation, and social coordination. There is a need for further refinement and optimization. For instance, the integration and utilization of resources may be insufficient, measures of ecological conservation may be lacking, or there may be shortcomings in

coordinating the interests of the surrounding community, all of which impact its potential for sustainable development.

5. Policy Recommendation

5.1. Regarding Composite Tourism

(1) Enhancing resource utilization efficiency

Policies should focus on encouraging developers to use sustainability tools, such as life-cycle assessments, to comprehensively analyze the resource consumption and environmental impacts associated with the construction and operation of tourism projects. This approach helps optimize resource allocation. For example, based on the assessment results, decisions can be made regarding which abandoned buildings are suitable for conversion into low-carbon, environment-friendly accommodation facilities and which areas are ideal for low-energy tourism activities. Additionally, developers should be supported in collaborating with scientific research institutions to innovate applications, such as using mine waste to create tourism souvenirs. This not only reduces the need for raw material extraction but also facilitates resource recycling, promotes sustainable economic growth, and alleviates environmental pressures, aligning with sustainable development principles.

(2) Strengthening consideration of key indicators

The government should establish a clear set of sustainability indicators that address ecological (e.g., targets for increasing vegetation cover, standards for water resource protection), economic (e.g., expected growth in tourism revenues, number of jobs created), and social (e.g., results from resident satisfaction surveys, measures of community participation) aspects. It should also increase investments in green transportation infrastructure, such as installing charging piles and promoting electric tour buses, to improve visitor accessibility while reducing carbon emissions. Additionally, regulations on vegetation protection and restoration should be strengthened, requiring developers to create long-term vegetation management plans and regularly monitor the health of vegetation to ensure ecosystem stability. This will enhance the attractiveness of tourism and foster the harmonious development of both the economy and the environment.

(3) Coordinating multiple interests

It is important to establish a cooperative mechanism based on the principle of sustainable development, such as the “Coordinating Committee for the Interests of Composite Tourism Development in Abandoned Mines”. This mechanism should involve the government, developers, local residents, and social organizations in the decision-making process. The government should introduce policies that ensure residents’ rights to be informed, participate in, and benefit from tourism development. For example, developers could be required to share a portion of tourism revenue with residents for community environmental improvements and public service enhancements. Residents should also be encouraged to participate in tourism-related skills training and take up jobs in the sector to boost their income, reduce social conflicts, and foster sustainable community development, ensuring tourism development in a stable and harmonious social environment.

5.2. Regarding Geopark Development

(1) Strengthening ecological protection

We should formulate strict and detailed regulations for the protection of geological sites, clearly defining protected areas and prohibited activities while enhancing law enforcement to ensure effective preservation. Additionally, it is important to implement sustainable monitoring tools, such as eco-sensor networks, to track real-time changes in the geopark’s ecosystem, including geomorphological stability, vegetation growth, and biodiversity. With the monitoring data, protection strategies should be adjusted as necessary, and scientific ecological restoration techniques, such as biological soil crust technology, should be em-

ployed to restore damaged soils. This will help maintain ecosystem health and stability, providing a solid foundation for the geopark's long-term sustainable development.

(2) Enhancing science education

The government has implemented policies encouraging geoparks to establish enduring partnerships with scientific research institutions to collaboratively conduct geoscientific research projects and translate research findings into educational and public science resources. A dedicated fund for science popularization should be established to support the development of modern, interactive science museums within geoparks. These museums can feature advanced exhibition technologies, such as VR experience zones, to vividly illustrate geological evolution processes. Additionally, a comprehensive training program for science education professionals should be developed to enhance staff expertise and ensure high-quality educational experiences. These measures aim to deepen public understanding of geoscience, foster environmental awareness, promote the preservation and growth of scientific and cultural heritage, and fully realize the sustainable and educational value of geoparks.

(3) Promoting regional cooperation

The government has spearheaded the formulation of the regional sustainable development plan, integrating the geopark with nearby tourism assets to establish a comprehensive tourism destination. A regional tourism cooperation alliance should be formed to market tourism products jointly, enabling resource sharing and complementary advantages. For instance, the collaborative promotion of itineraries such as "geological wonders + historic cultural towns + natural ecological reserves" can attract diverse visitor interests. Within this cooperation, emphasis should be placed on the coordinated protection of the ecological environment by establishing unified ecological protection standards and monitoring mechanisms to prevent overdevelopment. Additionally, inter-regional economic collaboration should be strengthened through joint investments in tourism infrastructure, enhancing the service quality and fostering the sustainable growth of the regional tourism economy.

5.3. Regarding Ecological Regreening

(1) Long-term monitoring and management

A comprehensive ecological regreening monitoring system has been established, employing diverse, sustainable tools such as satellite remote sensing, drone-based aerial photography, and ground sampling surveys. These tools enable regular and thorough monitoring of key indicators, including vegetation restoration status, soil quality improvements, and biodiversity trends. Scientific and well-defined monitoring metrics and assessment standards should be established, with clear targets set for different stages of the regreening process. Based on monitoring results, developers should promptly adjust techniques and management practices, such as enhancing soil quality or introducing more suitable plant species in areas with suboptimal vegetation. To encourage excellence, the government recognizes outstanding developers with awards like the "Ecological Regreening Pioneer Award" and offers policy incentives to sustain their investment in regreening practices. These measures ensure consistent ecosystem restoration and support the long-term sustainability of ecological benefits.

(2) Guiding ecological product development

The policy encourages developers to integrate sustainability principles into the creation of eco-products, such as establishing eco-agriculture initiatives, cultivating organic crops tailored to local soil and climate conditions, and adopting farming practices of eco-friendly poultry and livestock. Developers are also supported in utilizing plant resources from regreened areas to produce environment-friendly handicrafts and sustainable building materials. To enhance success, the government offers technical training and marketing assistance, helping developers build strong brands and improve the added value and market competitiveness of their products. Initiatives include organizing exhibitions and

sales fairs for eco-products and creating e-commerce platforms to boost sales. By promoting eco-product development, the policy enables the economic transformation of ecosystem services, driving sustainable economic growth while supporting ongoing ecosystem protection and enhancement.

(3) Converting ecological value

The government should establish a robust ecological compensation mechanism by setting fair compensation standards based on ecosystem service function assessments, providing financial compensation to developers or neighboring communities undertaking ecological protection responsibilities during the greening process. For instance, compensation can be linked to indicators such as the volume of carbon sequestration achieved through vegetation restoration or improvements in water conservation capacity. Additionally, we should actively explore sustainable applications like carbon trading and payments for ecosystem services to convert the ecological value of greened areas into tangible economic benefits. This could include encouraging private investment in projects that transform ecological value, such as funding eco-tourism infrastructure or partnering with developers on eco-agriculture projects. These efforts diversify funding sources, foster synergy between ecological, economic, and social development, and ensure the comprehensive sustainability of ecological greening development.

6. Results and Prospects

The ecological restoration of mines is of paramount significance for sustainable development in China. Historically, mining has driven economic growth; however, it has also resulted in numerous abandoned mines, which contribute to a range of issues, including land degradation and environmental pollution. These challenges have significantly hindered the balanced development of regional economies, societies, and ecosystems. The AHP–entropy evaluation model developed in this study serves as a scientific foundation for selecting appropriate ecological restoration strategies for abandoned mines, marking a significant advancement in the quantification of sustainability in this context. By applying the AHP–entropy method, we have conducted a comprehensive analysis of the various factors influencing mine ecological restoration. The results of our study indicate that the ecological greening development model achieves a notably high evaluation value, primarily due to its exceptional performance in areas such as water, soil, and vegetation restoration. Through effective vegetation recovery and careful soil management, this model enhances ecosystem services, including water conservation, soil preservation, and biodiversity enhancement. Consequently, it establishes a robust foundation for ecological sustainability. Furthermore, it creates opportunities for industries such as eco-agriculture and eco-tourism, which, in turn, stimulate employment, drive economic growth, and promote sustainable socio-economic development. In essence, it illustrates the potential to transform abandoned mines into sustainable resources.

The geopark development model, which focuses on the preservation of geological relics, effectively integrates science education and tourism. This approach not only protects ecosystems but also enhances public scientific literacy. By promoting cultural heritage and facilitating scientific dissemination, it stimulates local economies and fosters the harmonious coexistence and development of ecology, economy, and society. This underscores the effectiveness of integrated strategies in achieving sustainable development. Although the composite tourism development model exhibits a relatively lower assessment value, it provides valuable insights. Our comprehensive analysis of the data indicates that the key to improving its performance lies in enhancing resource utilization efficiency and carefully addressing key performance indicators. By optimizing resource integration and utilization, strengthening ecological conservation measures, and better coordinating the interests of the surrounding community, this model can potentially align more closely with the overarching goals of sustainable development. Looking ahead, national policies will play a crucial role in advancing restoration efforts. This requires increased capital investment, improved regulations, and more stringent oversight. Local governments must also take proactive steps

to coordinate resources, implement restoration projects, and encourage private investor participation. The findings of this study, combined with collaborative efforts, can serve as a valuable reference for other regions in their pursuit of both comprehensive restoration and sustainable utilization of abandoned mine ecosystems. This will support regional development and contribute to the creation of a prosperous and sustainable environment.

To enhance the depth and innovation of our conclusions, future research could focus on several fronts. Firstly, a more granular analysis of the relationships among various evaluation indicators could be conducted. For instance, investigating how changes in water resources directly affect vegetation cover and biodiversity over time could yield more detailed insights into the ecological restoration process. Secondly, incorporating long-term time-series data could help identify trends and patterns that may not be evident in the current cross-sectional analysis. This approach could facilitate predictions regarding the long-term effectiveness of different restoration models and inform adaptive management strategies. Additionally, further investigation into socio-economic aspects could involve conducting in-depth interviews with local residents and stakeholders to gain a more comprehensive understanding of their perceptions and behaviors. This qualitative data could be integrated with quantitative analyses to develop contextually relevant and sustainable restoration strategies. Finally, exploring the potential for interdisciplinary approaches—such as combining ecological restoration with emerging technologies like artificial intelligence for monitoring and prediction—could open new avenues for innovation in mine ecological restoration.

In conclusion, while our current study has made significant progress in evaluating mine ecological restoration models, ample opportunities for further exploration and improvement remain. By delving deeper into the data and adopting more innovative research methods, we can continue to refine our understanding and contribute to the development of more effective and sustainable restoration practices.

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