frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 08 January 2024
DOI 10.3389/fenvs.2023.1337518



OPEN ACCESS

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RECEIVED 13 November 2023
ACCEPTED 19 December 2023
PUBLISHED 08 January 2024

CITATION
Lin W, Wu P and Zhao G (2024), Identification and analysis of influencing factors of green mining construction based on DPSIR model and Fuzzy-DEMATEL approach.
*Front. Environ. Sci.* 11:1337518.
doi: 10.3389/fenvs.2023.1337518



# Identification and analysis of influencing factors of green mining construction based on DPSIR model and Fuzzy-DEMATEL approach

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Green mining construction (GMC) is a sustainable mining development model with the potential of realizing synergistic development of resources, environment, society, and economy. At present, the green mining strategy has yielded some successes, but there is still a significant gap between theoretical research and practical promotion, owing to the complexity of the green mining system and the diversity of influencing factors. Therefore, in the context of current pressure to normalize environmental protection, how to promote the construction of green mines while taking into account the premise of economic development has become an important issue. Inspired by the form of Drive-Pressure-State-Impact-Response (DPSIR) model, this paper constructs a DPSIR model of the driving mechanism of green mining construction. Using the fuzzy-DEMATEL method, each critical factor and influencing mechanism of GMC is explored, and the network relationship of the critical factors is established. The results show that many factors affect GMC from the perspective of the ecological environment, and 11 critical factors are obtained in varying degrees. Among them, green technology and supervision and long-term mechanism are the most important and influencing factors. Based on the transmission mechanism among these factors, improvement suggestions, and specific strategies are put forward. This research effectively identifies and analyzes the critical factors of GMC from the perspective of driving and response mechanisms, which is helpful to support the construction of ecological civilization and the sustainable development of mining industry.

KEYWORDS

**green mining construction, factor analysis, DPSIR model, Fuzzy-DEMATEL, mining industry**

## 1 Introduction

Mineral resources are an important safeguard for infrastructural development, large-scale urbanization, and accelerated industrialization, as well as an important component of the industrial economy (Zhu et al., 2018). Since humanity entered into the industrial civilization, the economy and society have grown swiftly, and the demand for mineral resources has skyrocketed. Mineral resources have fueled social and economic development and aided human progress; nevertheless, mining activities have also led to increasingly serious ecological and environmental problems, adversely affecting people's lives and hindering the construction of ecological civilization (Dong et al., 2019; Brodny and Tutak, 2023). In addition, the global call for environmental protection brings real pressure on resource and environmental issues. In this context, promoting the green development of mining industry has become a critical practical problem to be solved. Green mining construction (GMC) has been presented as an important technique for achieving environmental preservation and sustainable mine development since the early nineteenth century in Europe and America (European Union, 2010; Mission, 2016), which refers to ensuring the stability of socio-economic benefits, the safety of the ecosystem, and the balance between resources and the environment through the establishment of a scientific management system and the adoption of innovative green mining technologies throughout the life cycle. It is a kind of mining development model that can realize the harmonious unity of resources, environment, economy, and social benefits and aims at reconciling the contradiction between resource exploitation and environmental protection.

In contemporary times, the issue of resources has become a major constraint to the growth of all countries around the world. Considering green mining provides both economic and social benefits, many governments and organizations have taken measures to encourage the construction of green mines. The Canadian Mining Association (MAC) proposed a strategy of Towards Sustainable Mining (TSM) in 2004, which requires mine environmental protection measures to adhere to the principle of prevention at the source and priority on resource recycling (The Mining Association of Canada, 2015). The Australian Government's Department of Industrial Innovation and Science started the mining industry's Leading Practice Sustainable Development Program (LPSDP) in 2006 to promote sustainable mining whose connotation is the same as green mining (Wu et al., 2022a). The Chinese government introduced the concept of green mining in 2003 and it has since proceeded to implement relevant legislation and raise relevant requirements. It was defined by the Ministry of Land and Resources of China and enacted in 2009, that green mines should carry out scientific and orderly mining, control the ecological environment disturbance in the mining area and the surrounding area within a controllable range, and finally realize the scientific mining method, the efficient utilization of resource, the digitization of management information, and the harmony of the mining community (Ministry of Natural Resources of China, 2023). In addition, in 2012, the Chinese government proposed to build 600 green mines within 3 years as demonstration projects and then required the promotion of demonstration experience across the country, which has now achieved initial achievements (Wu et al., 2022b). In 2018, The green mine construction standards of nine major industries were proposed, and the green mine construction began to be standardized. However, GMC is a system project involving a wide range of aspects and rich contents, which includes many stages such as resource exploitation, waste treatment, recycling, land reclamation, and community harmony, so there are many influencing factors and complex influencing mechanisms. Despite decades of theoretical research foundation and mine construction practice, the progress of GMC is still slow (Marimuthu et al., 2022). Identifying and exploring the relationship and the driving response mechanism between critical factors are of practical significance for optimizing the green mine construction process and accelerating the construction speed.

In the process of green mine construction, due to the differences in policy environment, technical level, management system, and other factors, there will be obvious gaps in the progress and effect of green mine construction. Scholars have mainly carried out relevant research from these three aspects. In terms of policy, scholars have affirmed its motivating effect, Qi et al. (2020) believes that the effective deployment of green mining policies is a necessary prerequisite for China to meet its 2025 GMC objective. Luo et al. (2023) proposed that the government could urge the promotion of demonstration projects through supporting policies such as land, taxation, and capital. Furthermore, some scholars have analyzed the existing policies and made suggestions for improvement. For example, Qi et al. (2019) simulated the sustainable effects of GMC policy tools, namely environmental taxes and environmental subsidies, and proposed that the negative consequences of environmental regulation should be compensated by other policy measures. Wu et al. (2022a) suggested that the government could support green mining by formulating standardized and institutionalized long-term mechanism policies. In terms of technology, Sánchez and Hartlieb (2020) elaborated on the important role of technological innovation activities in the mining industry and argued that technological innovation can improve process efficiency and reduce costs, and is also a tool to meet the growing social and environmental concerns of communities and authorities. The research of GMC-related technologies mainly includes two directions: ecological protection and resource conservation. Ecological protection, in particular, focuses on air, soil, and water resource pollution control (Li et al., 2022), disaster prevention and early warning monitoring technology (Dales et al., 2017; Li et al., 2019), and land reclamation and vegetation restoration technology (Jafarpour and Khatami, 2021). Resource conservation includes technologies such as no-waste or low-waste mining and comprehensive utilization of resources (Wang et al., 2019). Comprehensive utilization of resources is a critical aspect of GMC. Taking tail waste resources as an example, mature tailings consolidation and filling technologies (Cao et al., 2022), preparation of glass-ceramics from tailings (Okereafor et al., 2020), and tailings as building materials (Lemougna et al., 2019) have been developed, which not only conserve resources, but also control pollution, and extend the industrial chain. Management research is primarily concerned with environmental control and the creation of socio-economic benefits. Dong et al. (2014) believe that expanding coordination channels among stakeholders, improving the information transparency of mining enterprises, demonstrating corporate social responsibility, and building public trust are effective media to promote the green development goal of mining industry. Shang et al. (2015) argue that the balance between reserves and risks in GMC is dependent on the application of technical equipment, cost control, and competitiveness enhancement. Liu et al. (2023) recommends that mining enterprises should design mining innovation management systems, coordinate the development, review, and improvement of specific regulations related to the construction of mine management systems, and establish evaluation and incentive mechanisms. Existing studies

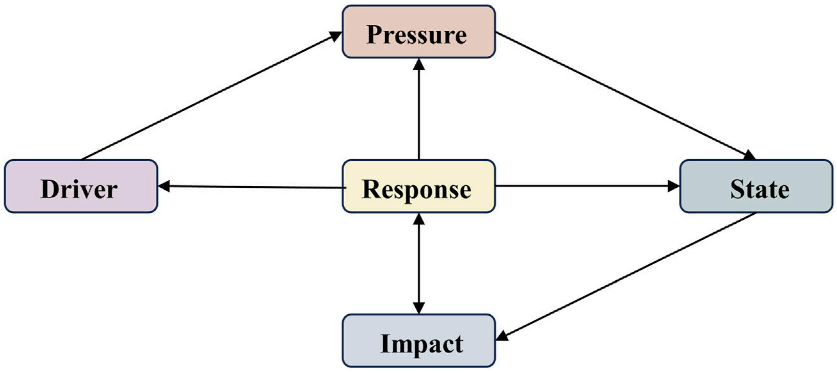


FIGURE 1
The DPSIR model.

have shown that policy, technology, and management all have an important impact on green mine construction, but in the mining system, there is no specific study on the impact degree of each factor and the driving force mechanism between factors. Therefore, this study identifies and refines the critical factors of green mine construction, clarifies the interaction between the factors, further defines and utilizes the critical factors to promote the green development of mines, and puts forward suggestions for the practical needs of green transformation of mining enterprises. In this study, we first establish the system of influencing factors for GMC with the DPSIR model. Then, a fuzzy DEMATEL approach is proposed to determine the critical factors as well as the influencing mechanism of related factors, and the critical factors are analyzed comprehensively. Finally, this research summarizes 11 critical factors that have been validated.

As far as we know, this research fills a void in previous research on green mining in which the driving force mechanism between various factors has rarely been analyzed. Additionally, analyzing the problem from both the factor-to-outcome and factor-to-factor perspectives provides a useful reference for future research. The findings of this research can help stakeholders (government, mining enterprises, scientific research institutions) make correct decisions to promote the development of the green mining industry.

# 2 Analysis of the factors influencing GMC

## 2.1 The DPSIR model

The DPSIR conceptual model emerged from the PSR conceptual model, which is a fundamental and effective paradigm for studying resources, environment, society, and economy (Soltani et al., 2023). As shown in Figure 1, The DPSIR model is a complex circular system that includes five components: driver (D), pressure (P), state (S), impact (I), and response (R). It fully considers the resource, environmental, social, economic, and technological factors influencing green development, as well as their linkages. The model, which mainly emphasizes the causal relationship between human economic activities and environmental changes, has been widely used in research fields involving resource-environmental systems, such as climate change (Hu and He, 2018), carbon emissions (Shi et al., 2018), and marine ecology (Du and Li, 2022), and has achieved positive results. For the mining industry, the exploitation of mineral resources not only promotes economic development but also changes the original state of the mining environment and brings great pressure to the local ecological environment. The environmental change in the mining area will have an even greater impact on the lives and development of the people in the region. Humans will take measures to adapt to these changes in order to achieve sustainable resource and environmental development. The application of the DPSIR model in mining field can reflect not only the impact of economic development on mining ecology but also the feedback of the ecological environment on social life.

GMC, as a complex system engineering, is influenced by many factors such as economy, society, resources, environment, and technology, which fits well with the conventional application scope of the DPSIR model mentioned above. At the same time, the analytical model can reflect the driving force mechanism of GMC influencing factors to a certain extent. Therefore, the DPSIR model was chosen for the construction of the hierarchy of influencing factors to pave the way for further critical factor identification and in-depth analysis of the interrelationships between factors.

## 2.2 GMC factor analysis based on DPSIR

Based on the preceding literature assessment, it is clear that the GMC not only contains a large number of systematic factors, but it is also complex in terms of mechanism. When analyzing the complex GMC system, it is necessary to consider all of the factors of the operation and functioning of green mines at the same time, which involves different aspects of society, economy, and environment as well as resources, and can be affected by legal policies, science and technology, resource environment, socio-economics, supervision, and management, in addition to several uncertainty factors. The Ministry of Land and Resources in China has established strict requirements for GMC, but the standards are only used as a

**TABLE 1** GMC influencing factors hierarchy index table.

| Dimension | Factor | Index | Index interpretation | Source |
|---|---|---|---|---|
| D | $f_1$ | Policy support | National or local policies to support the GMC | Li et al. (2023) |
| | $f_2$ | Standard system | The standard system determines the standardization of GMC | Hu and He (2018) |
| | $f_3$ | Financial inputs | Specialized funds for GMC invested by the State and localities | Luo et al. (2023) |
| | $f_4$ | Environmental awareness of enterprises | Ecological environmental protection consciousness of mining enterprises | Ministry of Natural Resources of China (2023) |
| P | $f_5$ | Environmental pollution | The negative impact of the traditional extensive model on resources and the environment | Shen et al. (2015) |
| | $f_6$ | Resource consumption | The demand for mineral resources is great | Du and Li (2022) |
| | $f_7$ | Resource shortage | Mineral resources are not renewable, and the waste of resources is serious | Hu and He (2018) |
| | $f_8$ | Public pressure | The public's quest for a better ecological environment | Okereafor et al. (2020) |
| S | $f_9$ | Green technology | The extent to which mining technology is scientific and environmentally friendly | Zhu et al. (2018) |
| | $f_{10}$ | Comprehensive utilization rate of resources | Utilization efficiency of mine ore, waste, and other resources | Wu et al. (2022b) |
| | $f_{11}$ | Ore recovery ratio | The recovery rate of ore reflects whether the mining method is reasonable | Chen et al. (2020) |
| | $f_{12}$ | Mine reclamation | Area of mine reclamation and vegetation restoration | Wang et al. (2020) |
| | $f_{13}$ | Tailings stock | Reflect the mine tailings production and utilization degree | Deveci et al. (2023) |
| I | $f_{14}$ | Industrial chain | Promote the development of green mining-related industries and promote new models | Li et al. (2019) |
| | $f_{15}$ | Mineral product income | Total annual output value of mines | Lemougna et al. (2019) |
| | $f_{16}$ | Mine disaster | Losses caused by natural or man-made disasters in a certain period | Wang et al. (2022) |
| | $f_{17}$ | Mine environment improvement | The pollution of air, soil, and groundwater in the mining area has been significantly improved | Lemougna et al. (2019) |
| | $f_{18}$ | Profit rate | The ratio of profits to investment in green mining construction | Ministry of Natural Resources of China (2023) |
| R | $f_{19}$ | Smart mine construction | By the relevant technical specifications, build an informationized and intelligent mine | Jiskani et al. (2023) |
| | $f_{20}$ | Mine management system | Scientific management of mineral resources, and safe production management | Liang et al. (2019) |
| | $f_{21}$ | Supervision and long-term mechanism | Strengthen supervision and punishment of highly polluting mines | Ardejani et al. (2022) |
| | $f_{22}$ | Popularization of science and demonstration | Carry out science popularization and publicity activities to accelerate the demonstration and popularization of green mines | Dong et al. (2014) |

reference for the initial stage of GMC, and the factors for systematic evaluation of GMCs have not been fully clarified. Given that the DPSIR model contains resource, environmental, social, economic, and technological aspects of green development, it aligns well with the GMC. Therefore, based on the perspectives of resources, environment, society, economy, and technology included in DPSIR model, this study takes drive, pressure, state, impact, and response as the guideline for constructing the hierarchical structure system, and collects existing relevant research categories, and finally establishes the evaluation factor table of GMC as shown in Table 1, with 5 categories and 22 influencing factors, which contains the source of each factor and the explanation of specific factors.

Drivers (D). It is a potential motivation for mining enterprises to carry out the GMC, and there are various sources of motivation for different stakeholders, which can come from the government, scientific research institutions, enterprises, and the public, as well as the factors that encourage enterprises to improve economic efficiency.

Pressures (P). It is the impact of traditional mining operations on resources, ecology, and the environment of the local community, and it is a major component that leads directly to GMC. Pressure is both a specific human activity and a natural process that is mostly manifested in mining resource consumption and the impact of mine production activities on the ecological environment.

State (S). It refers to the state attained by mining enterprises following a period of combined driving force and pressure, which can be manifested as a growth in the proportion of green technology and the *status quo* of environmental improvement, pollution reduction, and resource conservation.

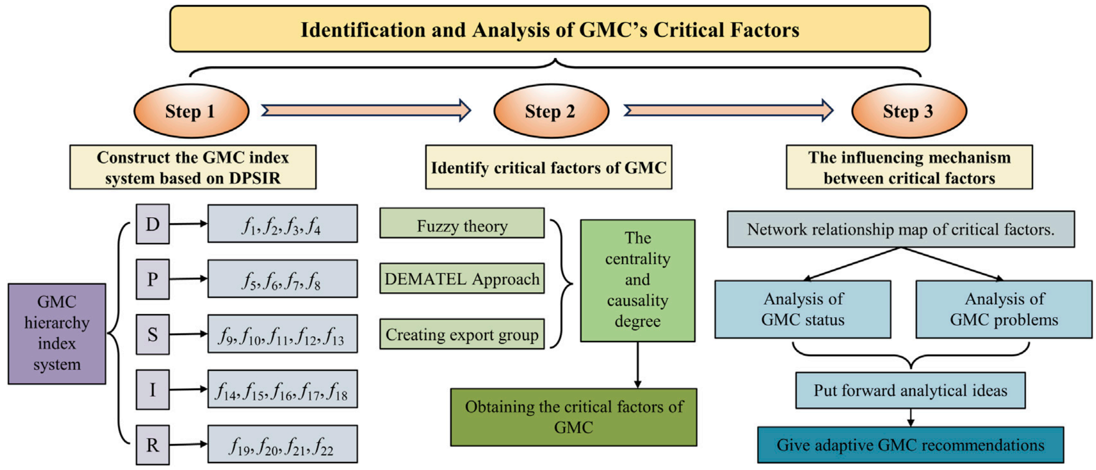


FIGURE 2
Flowchart of the study.

Impact (I). It is the effect of the status of the green mine system on the mining region as well as the surrounding environment, which primarily relates to the embodiment of environmental and social life following environmental improvement. It is the consequence of the interaction of the three parameters mentioned above, and it represents the impact on the corporate image resulting from GMC.

Responses (R). It refers to the incentive and correction procedures implemented to better control the driving factors to encourage GMC, ease existing pressure, preserve a good *status quo* of resources and the environment, or make improvements to make the entire system evolve in a virtuous cycle.

# 3 Method and processing

This research is mainly divided into three steps, as shown in Figure 2. They are as follows: (Zhu et al., 2018) Summarizing and sorting out the influencing factors of GMC, and constructing a hierarchical index system (Dong et al., 2019); Calculating the degree of causality and centrality and identifying critical factors using the fuzzy-DEMETAL method (Brodny and Tutak, 2023); Analyzing the influencing mechanism among critical factors and put forward adaptive recommendations.

## 3.1 Fuzzy-DEMATEL approach

### 3.1.1 DEMATEL method

Although DPSIR has been widely applied to various environmental problems, the causal relationship it reveals is very vague when the system is overly complex. In order to analyze causal relationships between factors more deeply, the model needs to be integrated with other tools. In this paper, DEMATEL is used as a complementary tool to reveal the dynamic correlations between the influencing factors related to GMC. The DEMATEL method is a methodological approach to systems science, using graph theory and matrix tools for systems analysis, and developed by the Battelle Institute in Geneva between 1972 and 1976 (Gabus and Fontela, 1972).

This method is able to express the overall effect of factors, visualize causal relationships, and analyze dependent factors (Du and Li, 2021). Based on the three main advantages of the DEMATEL method, it assists the decision-making process by identifying critical factors and constructing causal diagrams. Uygun et al. have applied the DEMATEL concept to different academic fields and have proved to be an effective tool for analyzing problems related to influential factors.

However, due to the uncertainty of most situations in the real world, the DEMATEL approach will be inapplicable or inappropriate for handling multifactor variables under uncertainty. Therefore, it is necessary to apply fuzzy theory to establish an extended DEMATEL method.

### 3.1.2 Fuzzy theory

Many conceptions in the real world are fuzzy. Fuzzy theory refers to the use of fuzzy mathematical methods to deal with decision-making problems that contain fuzzy concepts (Aaldering et al., 2018), which mainly includes fuzzy sets, fuzzy membership functions, and fuzzy comprehensive evaluation models. Fuzzy theory was developed on the mathematical basis of fuzzy set theory founded by American professor L.A. Zadeh (1965) in 1965. Fuzzy set extends the membership relationship in ordinary sets so that the membership value range of elements can be extended to any value [0,1], to realize the quantification of fuzzy things or phenomena. The mathematical expression is $\mu_A(x)$: $X\rightarrow[0,1]$.

Fuzzy systems frequently involve complex relationships, and variables that cannot be accurately assigned and are extremely subjective, and these variables are fuzzy factors. Processing methods such as ranking and fuzzy evaluation must be utilized at this phase. Fuzzy decision theory is a very practical tool for dealing with these fuzzy and complex problems.

TABLE 2 Linguistic scale for Fuzzy-DEMATEL.

| Linguistic terms | Relative scale | Linguistic values | | |
|---|---|---|---|---|
| | | *l* | *m* | *u* |
| Very high influence | 4 | 0.75 | 1.00 | 1.00 |
| High influence | 3 | 0.50 | 0.75 | 1.00 |
| Medium influence | 2 | 0.25 | 0.50 | 0.75 |
| Low influence | 1 | 0.00 | 0.25 | 0.50 |
| No influence | 0 | 0.00 | 0.00 | 0.25 |

### 3.1.3 Description of Fuzzy-DEMATEL

The F-DEMATEL method must be developed according to expert opinions and language variables. Practice has proved that this fuzzy decision-making method can effectively gather the views of professionals, so as to provide more reliable information. F-DEMATEL has been widely used in many fields. Fuzzy-DEMATEL is employed in this research to convert the GMC complicated system into structural causality. The fuzzy theory can decrease the uncertainty of expert subjective evaluation and increase the representativeness and credibility, the DEMATEL approach can identify the GMC system's main flaws and improvement directions, the steps of this method are briefly described below (Liu et al., 2019; Quezada et al., 2023):

**Step 1:** Construction of direct influence fuzzy matrix. In the established hierarchical structure system, experts are asked to judge the degree of direct influence between each pair of factors in each subsystem on a relative scale of 0–4. In other words, 0, 1, 2, 3, and 4 respectively represent "no influence ", "low influence ", "medium influence ", "high influence " and "very high influence ". Then, according to the fuzzy language scale designed in Table 2, the ambiguous values above are converted into triangular fuzzy numbers (*TFN*). A direct influence fuzzy matrix *A* can be constructed according to the converted triangular fuzzy number.

$$A_p(l,m,u) = \begin{bmatrix} 0 & a_{12}(l,m,u) & \cdots & a_{1n}(l,m,u) \\ a_{21}(l,m,u) & 0 & \cdots & a_{2n}(l,m,u) \\ \vdots & \vdots & 0 & \vdots \\ a_{n1}(l,m,u) & a_{n2}(l,m,u) & \cdots & 0 \end{bmatrix} \forall p \notin P$$

**Step 2:** Construction of total influence fuzzy matrix. The direct influence fuzzy matrix is averaged to obtain an initial average matrix *X*, by normalizing matrix *X*, the regular influence fuzzy matrix *N* is obtained directly. Then, the total influence fuzzy matrix *T* is calculated. As shown in the formula, $T(l)$ can be obtained. In the same step, $T(m)$ and $T(u)$ can be obtained.

$$X(l,m,u) = \frac{1}{P}\sum_{p=1}^{P} A_p(l,m,u)$$

$$N(l) = \frac{X(l)}{s_l}\, where, s_l = \max\left(\max_{1\le i\le n}\sum\nolimits_{j=1}^{n} x_{ij}(l)\ \max_{1\le j\le n}\sum\nolimits_{i=1}^{n} x_{ij}(l)\right)$$

$$T(l) = \sum_{i}^{\infty} N(l)^i = N(l)(I - N(L))^{-1}$$

**Step 3:** Calculation of causality and centrality degrees. De-fuzzifying the total in-fluence fuzzy matrix, the degree of influence ($R_i$), and influence by factors ($D_i$) are calculated for each factor in total influence matrix. The degree of centrality is the sum of Ri and Di and is written as $M_i$ ($R_i + D_i$), and the degree of causality is written as $C_i$ ($R_i$ - $D_i$).

$$T = \frac{1}{6}(T(l) + 4T(m) + T(u))$$

$$R_i = \sum\nolimits_{j=1}^{n} T_{ij}; D_i = \sum\nolimits_{i=1}^{n} T_{ij}$$

**Step 4:** Plotting of centrality-causality distributions. The centrality-causality relationship is represented by a two-dimensional graph with $C_i$ on the horizontal axis and $M_i$ on the vertical axis. The centrality-causality distribution graph can simplify complex causal relationships into an easy-to-understand structure, providing a direction for a deeper understanding of the problem. With the help of this graph, decision-makers can obtain the critical factors of the system and make rational decisions based on the causal relationships.

## 3.2 Critical factor identification

### 3.2.1 Direct influence analysis

Since GMC is a complicated system, an effective strategy for identifying critical factors must be chosen. Fortunately, the Fuzzy-DEMATEL approach can significantly reduce the subjectivity of GMC factor identification, accurately reflect the types of influencing factors, and reasonably analyze the hierarchy, so it is suitable for handling the problem of critical factor identification in such complex systems. The Fuzzy-DEMATEL approach is utilized for GMC critical factor identification after building the hierarchical structure indicated in Table 1; Figure 2.

The expert group is requested to judge the degree of direct influence between the factors in Table 1 and the direct influence fuzzy matrix *A* is constructed according to the converted triangular fuzzy number. By transforming the matrix *A* into a normalized direct influence matrix, the total influence fuzzy matrix *N* is calculated. By de-fuzzifying the total influence fuzzy matrix *N*, the total influence fuzzy matrix *T* is obtained. *T* is drawn as a correlation heat map, as shown in Figure 3.

### 3.2.2 Identify the critical factors

According to the total influence matrix *T*, the degree of influence ($R_i$), the degree of influence by factors ($D_i$), the degree of centrality $M_i$, and the degree of causality $C_i$ of each factor are calculated (Table 3). $M_i$ indicates the influence of factors on the GMC system, $C_i$ represents the degree to which a factor is affected by other factors, if $C_i > 0$, it is the contributing factor, otherwise, it is a resulting factor. According to the centrality and causality degree of each factor, the centrality-causality degree diagram is drawn. As shown in Figure 4, factors in quadrants I and IV have great influence, factors in quadrants I and II are contributing factors, and factors in quadrants III and IV are resulting factors.

According to the relevant literature [45], factors with a high degree of centrality or causality would be regarded as critical factors. The critical factors are identified as $F = \{(r_i + d_i \ge 6.0) \vee (r_i - d_i \ge 0.5)\}$

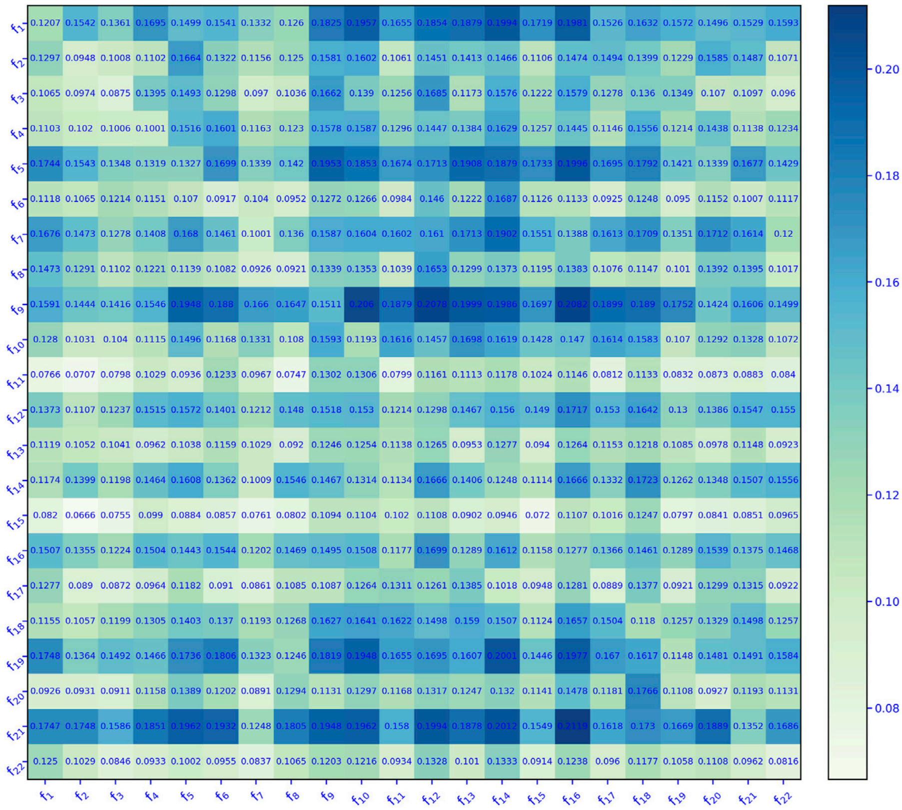


FIGURE 3
Correlation heat map of matrix *T*.

**TABLE 3 The degree of centrality and causality of factors in the GMC system.**

| Factor | $R_i + D_i$ | $R_i$ - $D_i$ | Ranking | Factor | $R_i + D_i$ | $R_i$ - $D_i$ | Ranking |
|---|---|---|---|---|---|---|---|
| $f_1$ | 6.4066 | 0.7234 | 7 | $f_{12}$ | 6.5350 | −0.2043 | 4 |
| $f_2$ | 5.4801 | 0.3531 | 14 | $f_{13}$ | 5.5696 | −0.7377 | 13 |
| $f_3$ | 5.2569 | 0.2959 | 19 | $f_{14}$ | 6.4328 | −0.3917 | 6 |
| $f_4$ | 5.7081 | 0.0893 | 12 | $f_{15}$ | 4.7858 | −0.7349 | 22 |
| $f_5$ | 6.6789 | 0.4819 | 5 | $f_{16}$ | 6.4919 | −0.2800 | 5 |
| $f_6$ | 5.4674 | −0.4725 | 15 | $f_{17}$ | 5.3615 | −0.4976 | 18 |
| $f_7$ | 5.7946 | 0.9041 | 11 | $f_{18}$ | 6.2035 | −0.1554 | 9 |
| $f_8$ | 5.3709 | −0.0056 | 17 | $f_{19}$ | 6.1967 | 0.8674 | 10 |
| $f_9$ | 7.1334 | 0.5655 | 1 | $f_{20}$ | 5.4507 | −0.3290 | 16 |
| $f_{10}$ | 6.2784 | −0.3639 | 8 | $f_{21}$ | 6.7866 | 0.9864 | 2 |
| $f_{11}$ | 5.0399 | −0.7228 | 20 | $f_{22}$ | 5.0065 | −0.3716 | 21 |

and including $\{f_1, f_5, f_7, f_9, f_{10}, f_{12}, f_{14}, f_{16}, f_{18}, f_{19}, f_{21}\}$ based on the distribution of each factor in the centrality-causality diagram. The overall centrality ranking of critical factors is $f_9 > f_{21} > f_5 > f_{12} > f_{16} > f_{14} > f_1 > f_{10} > f_{19} > f_{18} > f_7$, causality ranking is $f_{21} > f_7 > f_{19} > f_1 > f_9 > f_5 > f_{18} > f_{12} > f_{16} > f_{10} > f_{14}$. Therefore, 11 critical factors need to be highlighted in GMCs, marked with a solid red diamond in Figure 4.

# 4 Discussion and recommendation

## 4.1 Discission

According to the results obtained in Section 3.2.2, policy support ($f_1$), environmental pollution ($f_5$), resource shortage ($f_7$), green technology ($f_9$), comprehensive utilization rate of resources ($f_{10}$),

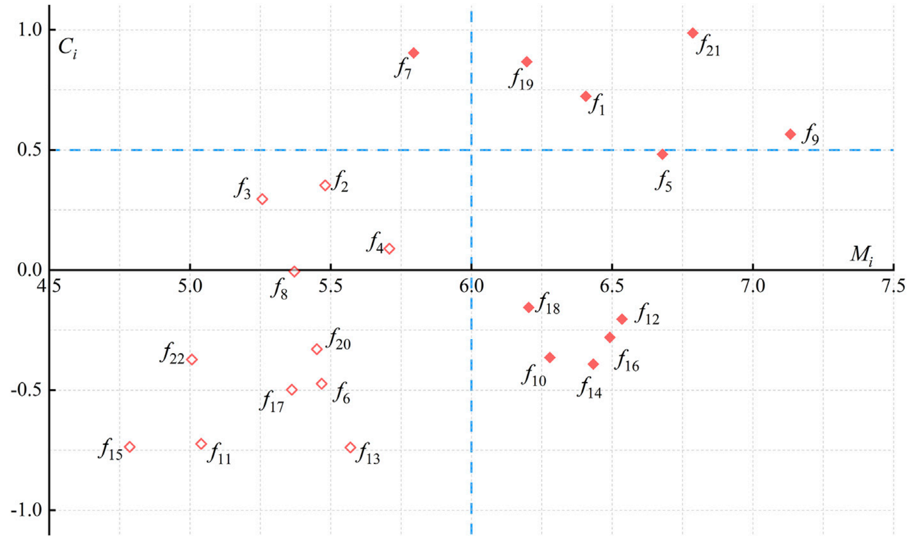


FIGURE 4
The Centrality–Causality degree distribution diagram.

mine reclamation ($f_{12}$), industrial chain ($f_{14}$), mine disaster ($f_{16}$), profit rate ($f_{18}$), smart mine construction ($f_{19}$), supervision and long-term mechanism ($f_{21}$) are critical factors. To achieve a comprehensive GMC, it is necessary to clarify the mechanism of influence among critical factors, and pay special attention to the more important critical factors. Therefore, the 11 critical factors are divided into two categories, in which $f_1$, $f_5$, $f_7$, $f_9$, $f_{19,}$ and $f_{21}$ are the critical contributing factors, among which $f_9$ is the most important contributing factor, and $f_{21}$ is the most influential contributing factor. In addition, $f_{10}$, $f_{12}$, $f_{14}$, $f_{16}$, and $f_{18}$ are critical resulting factors, and there is little difference between how important they are and how affected they are. It is well known that critical contributing factors play a dominant role in the development of GMC systems because they have a greater influence on other factors. Therefore, in GMC project, we should prioritize the critical contributing factors to maximize their positive effects. On the other hand, the critical resulting factors need to be closely monitored and considered as early warning and feedback information reflecting the GMC's situation.

In recent decades, with the development of green mining theory research and the accumulation of GMC practical experience in China, some measures have been taken to address the issues related to the critical contributing factors. In terms of policy support ($f_1$), in recent years, national and local governments have issued several policies and standards, such as the Implementing Opinions on Accelerating the Construction of Green Mines and the Specifications for the Construction of Green Mines, which have clarified the goals of the GMC in terms of the construction pattern, the development mode, and the working mechanism. In the face of resource shortages ($f_7$), a deep well mining strategy is proposed, and deep well mining, deep well cooling, and deep well-lifting technologies are developed. In terms of green technology ($f_9$), with the deepening of cooperation with universities, scientific research and innovation capabilities have been strengthened, and technologies such as efficient mining, full tailings filling, high-value tailings utilization, and ecological reconstruction have been developed. In terms of smart mine construction ($f_{19}$), unmanned mining equipment, intelligent scheduling systems, and intelligent monitoring systems have all been piloted. In terms of supervision and long-term mechanism ($f_{21}$), the specific goals of green mine development have been gradually determined, the supervision mechanism is being established, and the technical specifications and operational specifications have been unified. At the same time, the aforementioned measures still have some difficulties at this point (Zhu et al., 2018). It is difficult to unify the evaluation criteria of green mine construction due to regional economic development differences, mine scale and mineral species differences, and local policy differences (Dong et al., 2019). Most of China's green mines are still in the trial operation or construction pilot stage, and traditional mining methods are still widely used (Brodny and Tutak, 2023). Green mining technology is an emerging and developed technology, which has not yet been applied on a large scale, and the promotion of technology still has a long way to go (European Union, 2010). The lack of risk prevention and control management and whole-process supervision makes it difficult for enterprises to control potential negative environmental and social impacts.

The most intuitive resulting factors that demonstrate the influence of GMC are $f_{10}$, $f_{12}$, $f_{14}$, $f_{16}$, and $f_{18}$. Contributing factors influence resulting factors, and if contributing factors are not adequately regulated, the influence of resulting factors will be less effective, further hindering GMC. For example, if no corresponding measures are taken to improve the level of green technology ($f_9$), the factors it influences such as the comprehensive utilization rate of resources ($f_{10}$) and the industrial chain ($f_{14}$) may also be at a low level. The comprehensive utilization rate of resources ($f_{10}$) is an important indicator of the level of mineral resource development, technical economics, and production management, and a low level of comprehensive utilization rate of resources will make GMC difficult to sustain. Pulling the industrial chain ($f_{14}$) not

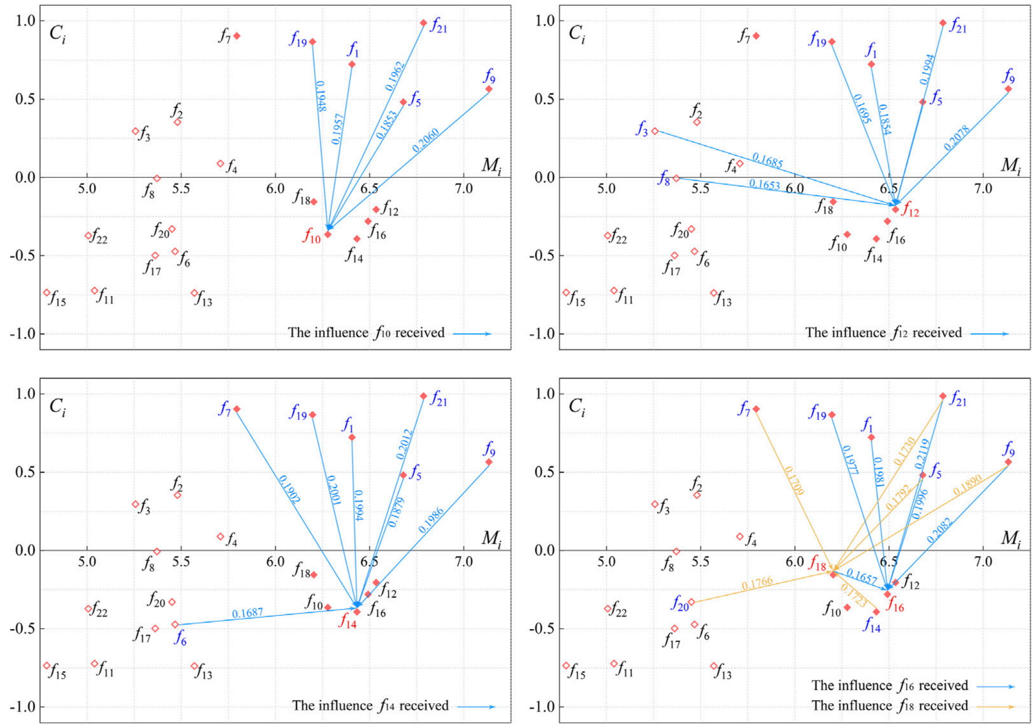


FIGURE 5
The network relationship map of the critical factors.

only reduces mining waste accumulation but also increases employment and contributes to social welfare. On the other hand, when critical resulting factors are ignored, it will also directly affect the GMC. For example, profit margin ($f_8$) influences the investment of mining enterprises in environmental protection, so it is related to the economic and environmental functions of GMC. When the profit space is limited, due to the presence of uncertain risks, high investment costs, and long construction cycle, enterprises are not enthusiastic about GMC, the GMC can only rely on mandatory policies, which are obviously not as effective and sustainable as simulating the enthusiasm of enterprises.

For the above 5 critical factors, when the critical resulting factors are at an abnormal level, the government and enterprises can learn from advanced experience by adjusting the factors which influence them to fix the critical resulting factors. Based on the results of this research, a network relationship Map (NRM) was drawn to represent the specific influence relationships related to critical resulting factors ($f_{10}$, $f_{12}$, $f_{14}$, $f_{16}$, $f_{18}$), as shown in Figure 5.

Since there are many influence relationships involved, a threshold value is set according to relevant literature (Tzeng and Huang, 2012; Kusi-Sarpong et al., 2016; Bai et al., 2017; Marimuthu et al., 2021), and only influence relationships larger than this threshold are drawn. The threshold, calculated by adding the mean of the matrix $T$ plus the standard deviation, is 0.1644. Figure 5 depicts a path of influence mechanisms that can be used to give corrections for certain factors in GMC. For example, when the profit rate is low, known as $f_9$, $f_{20} \rightarrow f_{18}$, we can improve mining technology, optimize the management system, and achieve a higher profit rate. If the mine land is seriously damaged, with $f_3$, $f_{21} \rightarrow f_{12}$, we can increase special funding for governance and strengthen land supervision. Several studies have also been undertaken to confirm some of the effects described here. For example, the implementation of policy support can encourage the expansion of the industrial chain ($f_1 \rightarrow f_{14}$) in order to boost the economic impact of GMC [47]. Green technology contributes to the improvement of the living environment in mining areas ($f_9 \rightarrow f_{18}$), so as to bring out the social benefits of GMC [48,49].

## 4.2 Recommendation

GMC is the only way for the sustainable development of the mining industry. Based on the above analysis, to achieve this goal, we should pay attention to the more important critical factors and focus on contributing factors and resulting factors in different ways. As for the contributing factors, the focus is to analyze the problems existing in China's GMC and learn from advanced experience to take corresponding measures. As for the resulting factors, the government and enterprises should attach great importance to them in the supervision and management. Specifically, when they are at abnormal levels, measures are taken to correct the relevant contributing factors. Based on the results of this study, specific suggestions for Chinese GMC from three aspects of policy, technology, and supervision are proposed as follows:

Regarding the three factors of $f_1$, $f_5$, and $f_7$, since maintaining of ecological environment ($f_5$) and reasonable development of resources ($f_7$) are the primary goals of GMC, these two factors are not discussed in detail. In terms of policy support ($f_1$), since GMC involves multiple departments, the government should improve the relevant environmental laws and regulations of the mine and surrounding areas, clarify the powers and responsibilities of the relevant departments, and gradually decompose the implementation of policies and regulations from the government to the localities and then to the mine so as to ensure the source control, pollution prevention, and ecological restoration. Further, it is necessary to improve the national standard of GMC from an international perspective, strengthen the legal regulation of GMC, and establish a dynamic management mechanism for the green mine list to cope with the changes in economic environmental conditions.

In terms of technology, given $f_9$ and $f_{19}$, relevant organizations should promote the formation of a systematic and standardized green mining technology system, formulate technical specifications, and develop efficient and low-waste mining equipment and mining methods. It is necessary to give full play to the residual value of tailings and realize low-waste mines through full tailings filling technology and high-value utilization technology of tailings. On the other hand, it is necessary to establish a multi-level and all-round intelligent information system through cross-disciplinary integration and optimize the system continuously in application and practice. At the same time, a national communication platform is needed for scientific research, technological development, and practical innovation.

In terms of supervision and long-term mechanism $f_{21}$, in order to ensure GMC's long-term development, the binding force of the law and the guiding role of standards must be fully utilized. The government, enterprises, the public, associations, and other parties should work together to establish a social supervision system and a third-party evaluation mechanism, and improve the information disclosure mechanism of green mining enterprises. It is recommended that mining enterprises that satisfy the green mine requirements receive essential supporting incentive measures, whereas mines that fail to achieve the standards face punitive measures. Fully realize policy potential, encourage mining enterprises to adhere to innovation-driven and enhance scientific and technology investment, and strengthen enterprise internal ability to construct green mines.

Combined with the influence path shown in Figure 5, we can correct certain resulting factors when they reach abnormal levels. For example, the comprehensive utilization rate of resources is mainly affected by five factors ($f_1$, $f_5$, $f_9$, $f_{19}$, $f_{21}\rightarrow f_{10}$), among which technical greenness ($f_9$) and supervision and long-term mechanism ($f_{21}$) have a greater impact. The poor comprehensive utilization rate of mine resources will result in significant resource waste and environmental degradation. Now it can be corrected from two aspects, on one hand, mining enterprises can improve the index by improving the technical level. On the other hand, the relevant departments can put forward the hard index requirement (f10) of the comprehensive utilization rate of resources in the supervision process, and force mining enterprises to improve it.

## 5 Conclusion

GMC is a national strategy to realize the sustainable development of mining industry in China, which is a realistic necessity. At the same time, GMC is also a complex systematic project due to a variety of internal and external factors. According to the current situation of GMC in China, this study adopts DPSIR model and fuzzy DEMATEL method to identify and analyze the relationship between the critical factors of GMC and puts forward some concrete improvement measures. Based on this, the government and mining companies can prioritize the factors that affect GMC and the areas that need to be focused on. The main contributions of this study are summarized as follows:

Firstly, the DPSIR model is selected and adopted to systematically group the influencing factors of GMC since it fits well with the purpose of GMC influencing factor analysis. Further, based on previous literature, 22 influencing factors are summarized and sorted out, and a hierarchical index system including drivers, pressures, states, impacts, and responses is constructed. Secondly, in order to make up for the shortcomings of DEMATEL method which is too subjective, the fuzzy DEMATEL method is constructed in combination with fuzzy theory to calculate the degree of causality and centrality, and 11 critical factors affecting China's GMC are obtained. Thirdly, the critical factors are classified, in view of the critical contributing factors that China has taken measures, this study analyzes the difficulties that still exist; For the critical resulting factors that are easily ignored, the possible impact is summarized. Based on the previous actual evaluation and the relationship analysis among the critical factors, the analysis path of the influence mechanism between the contributing factors and the resulting factors is established to provide a reference for the formulation of solutions to specific problems. Finally, this study proposed recommendations containing concrete measures in terms of policy, technology and long-term mechanisms.

The implications of this paper are three main points (Zhu et al., 2018). Most of the existing studies summarize the hierarchical structure from an independent perspective when establishing the system of influencing factors. This study summarized and expanded the influencing factor system of GMC, divided the factors into five aspects from the perspective of driving to response logic connection, enriched the influencing factor system, and established the relationship link among the influencing factors at the criterion level (Dong et al., 2019). According to the influence mechanism of critical factors established, the paper puts forward the main path to realize the optimization of green mine construction from two aspects of critical contributing factors and critical resulting factors, aiming at promoting the realization of green mines by establishing driving force and response mechanism (Brodny and Tutak, 2023). The DPSIR model established in this study and the analysis conclusions of influencing factors have enriched the theory of green mine construction, and have practical reference significance for the decision-making of mining enterprises and the policy formulation of the government to promote green mine construction.

This research conclusion is only applicable to the present stage of green mine construction and development in China. With the continuous improvement of the degree of sustainable development of the mining industry and the deepening of international cooperation and exchanges in the mining field, the influence relationship between various factors will also change. Therefore, in the future, we should conduct a dynamic comparative analysis of the influencing factors of GMC from an international perspective.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Author contributions

WL: Conceptualization, Data curation, Writing–review and editing. PW: Conceptualization, Methodology, Software, Writing–original draft. GZ: Funding acquisition, Project administration, Supervision, Writing–review and editing.

## Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This research was funded by the National Key Research and Development Program of China (2018YFC0604606).

## Acknowledgments

The authors would like to express their sincere gratitude towards the industrial experts. The authors are grateful for the valuable comments of reviewers, who helped to improve the manuscript greatly.

## Conflict of interest

Author WL was employed by the company Changsha Inst Min Res Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note



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