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# Evaluation of the importance of critical minerals in China

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Critical minerals are the basic resources that support many strategic industries, and the importance of their safety and security cannot be overstated. In recent years, as geopolitical conflicts have intensified, higher demands have been placed on the stable supply of critical minerals. The United States and the European Union have strengthened their mechanisms for securing the supply of critical minerals through the establishment of mineral security partnerships. China, as a large resource consumer, has a long evaluation interval for critical minerals, which needs to be re-examined to guarantee a stable supply of important mineral resources. This study identifies 32 assessed minerals based on China's list of strategic mineral resources, with reference to the lists of critical mineral resources of the United States and the European Union. These minerals are categorized into long-term balanced developmental minerals, national strategic advantage minerals, and national strategic scarce minerals. Then, a comprehensive evaluation of the relative importance of the three types of minerals was carried out using the linear weighted sum method. The results show that among the classified minerals, nickel, gold, potash, chromium, tungsten, arsenic, bismuth, lithium, zirconium, and hafnium are of greater significance, phosphorus, molybdenum, barite, niobium, and tantalum are of lesser importance. Nickel, chromium, lithium, zirconium, and hafnium have a high supply risk. Potash and gold have good economic importance and market prospects, respectively, while tungsten, arsenic, and bismuth have a strong influence. According to the evaluation results, the corresponding suggestions are put forward.

KEYWORDS

**mineral resources, critical minerals, importance evaluation, China, sustainable supply**

## 1 Introduction

Critical minerals play an important role in the global economy, national security, and sustainable development. They are not only pivotal for the advancement of nascent industries but also serve as a crucial foundation for promoting global green and low-carbon development. In the context of global decarbonization, a new round of scientific and technological industrial revolution is forcing industrialized countries to transform their mineral resource structure from traditional energies to critical minerals (Deng and Li, 2023). In order to ensure the stable supply of critical minerals in the transition period, many countries have formulated relevant security measures and carried out international cooperation to coordinate mineral supply (U.S. Geological Survey, 2022;

European Commission, 2023; Critical Minerals Office, 2024). As a large resource country, China ranks first in the world in terms of production, consumption, and trade of various mineral resources. The shortage of critical minerals will challenge the national industrial and supply chain security, hindering the pace of energy transition. Therefore, facing the intricate international situation, it is crucial to conduct a new round of evaluation on China's mineral resources. A scientific evaluation the relative importance of mineral resources not only strengthens the formulation of resource supply security strategies but also serves as a reference for the stable development of enterprises.

Major developed countries and regions around the world, such as the United States, the European Union, Japan, Canada, and Australia, place great importance on the security of critical minerals. They have not only issued lists and catalogs and formulated national strategies but have also jointly formed critical mineral alliances for the whole industrial chain. These economies have also introduced regulations requiring periodic reviews and assessments of critical minerals (National Research Council, 2008; Nassar et al., 2016; Executive Office of the President, 2017; Department of the Interior, 2018), as shown in Table 1. Since 2011, the United States, the European Union, and Japan have held an annual trilateral conference to discuss strategies on how best to ensure an adequate supply of critical materials and promote international cooperation. In 2021, Australia and Canada became new official members (METI, 2021), further expanding the collaboration. Over time, the countries have progressed from initial information sharing to conducting specific research projects and implementing policies. In recent years, the United States has carried out a series of activities related to critical minerals through international organizations such as the G7, OECD, and IEA. In contrast, China's research on critical minerals started relatively late. It proposed to implement protective exploitation of strategic mineral resources in 2001 (Ministry of Natural Resources, 2007), and in 2016, 24 minerals such as oil, natural gas, iron, and copper were listed as strategic minerals (Ministry of Natural Resources, 2016).

With the increasing emphasis on critical minerals in various countries, many scholars have also carried out research on this topic. The definition of critical minerals varies with time and depending on the context (IRTC Round Table, 2018). Chen (2002) summarized mineral resources that are essential for the national economy, social development, and national defense security—but cannot be domestically guaranteed or significantly influence the international market—as strategic mineral resources. Critical minerals not only include minerals with abundant reserves that can impact the international mining market (Chen and Wang, 2007), but also those indispensable for the development of strategic emerging industries as national industries undergo transformation and upgrading (Li J. et al., 2023; Wang A. et al., 2019; Wang D, 2019). Critical minerals carry geopolitical significance (Wang A. et al., 2019) and generally lack relevant substitutes (Griffin et al., 2019). They are of great strategic importance for national development, stability, and international competitiveness (Zhao, 2011).

There are no standardized criteria and methods for assessing the criticality of raw materials (Schrijvers et al., 2020). Schrijvers et al. (2020) adopted aggregation methods to combine various indicators into a unified score or index in order to identify whether a mineral is critical. Hotchkiss et al. (2024) used the geometric mean evaluation method to aggregate three major evaluation indicators of supply risk, production growth, and market dynamics to obtain a final score for each potential target. Li X. et al. (2014) employed a judgment matrix based on expert opinions and an analytic hierarchy process (AHP) to determine the indicator weights. McCullough and Nassar (2017) applied hierarchical cluster analysis to determine minerals that should be identified as potentially critical. Zhao (2011) adopted the conceptual model of pressure–state–response (PSR) to conduct an evaluation study of China's mineral resources and used the gray GM (1,1) model to forecast the gap between the supply and demand of China's mineral resources. Kong et al. (2011) utilized a comprehensive evaluation model based on fuzzy mathematics to obtain the importance level of mineral resources. The weight of each indicator is calculated using the AHP, and the relative importance of each mineral resource is obtained using the multi-indicator linear weighting function method (Chen and Wang, 2007; Li W. et al., 2008). Zhang et al. (2015) constructed a two-dimensional evaluation system based on economic importance and supply risk, using the AHP to calculate the mineral coordinate values. In summary, scholars generally agree that critical minerals refer to those resources with low substitutability, and their supply disruptions will have a significant socio-economic impact. Most scholars have focused on indicators such as supply relations, economic security, production concentration, and market volatility for evaluation (Thomason et al., 2010; Sun and Wang, 2005; Zhou N. et al., 2020; Erdmann and Graedel, 2011). Most of the research studies adopt one or more methods, such as AHP, fuzzy comprehensive evaluation, gray model, and multi-dimensional matrix, to establish an evaluation index system in an all-round and multi-factor way to evaluate the critical minerals. However, the existing studies have not considered the characteristics of different minerals in the evaluation process and failed to judge the priority of development of each mineral. Based on this, this study carries out systematic evaluation according to the characteristics of minerals, divides minerals into three major categories, and designs and builds a differentiated three-dimensional evaluation index system, which can more accurately measure the relative importance among minerals than a single evaluation system. Through directed classification evaluation, valuable insights can be provided for the development of important minerals in enterprises. The mineral classification and differentiated evaluation system in this study introduces a new dimension to critical mineral evaluation research, providing new ideas and methods for related fields. The remainder of this study is structured as follows: Section 2 identifies the targets of this evaluation. Section 3 describes the evaluation indicators and methods. Section 4 presents the results of the various assessments and discusses them in different situations. Section 5 presents relevant measures and suggestions based on the evaluation results.

## 2 Screening and delimitation of evaluation targets

### 2.1 Screening of evaluation scope

Critical minerals are time-sensitive and stage-specific, referring to mineral resources that are extremely important to national

TABLE 1 Critical mineral research in major government departments.

| Country | Year | Agency | Title | Method | Reference |
|---|---|---|---|---|---|
| United States | 1921 | The Army General Staff | Harbord List 1921 | — | Schmidt (2018), Munitions Board (1950) |
| | 1939 | U.S. Congress | Strategic and Critical Materials Stock Piling Act | — | U.S. Congress (1939) |
| | 1979 | U.S. Congress | Strategic and Critical Materials Stock Piling Revision Act of 1979 | — | U.S. Congress (1979) |
| | 2008 | National Research Council | Minerals, Critical Minerals, and the U.S. Economy | Criticality matrix | National Research Council (2008) |
| | 2010 | U.S. Department of Energy | Critical Mineral Strategy | Criticality matrix | U.S. Department of Energy (2010) |
| | 2011 | U.S. Department of Energy | Critical Mineral Strategy | Criticality matrix | U.S. Department of Energy (2011) |
| | 2012 | U.S. Geological Survey | Energy and Minerals Science Strategy | — | U.S. Geological Survey (2012) |
| | 2016 | National Science and Technology Council | Assessment of Critical Minerals: Screening Methodology and Initial Application | Early-warning screening and in-depth analyses | Nassar et al. (2016) |
| | 2017 | Executive Office of the President | A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals | — | Executive Office of the President (2017) |
| | 2018 | Department of the Interior | Final List of Critical Minerals 2018 | NSTC mineral criticality screening tool | Department of the Interior (2018) |
| | 2022 | U.S. Geological Survey | 2022 List of Critical Minerals | Three-path evaluation method | U.S. Geological Survey (2022) |
| Europe | 1975 | Commission of the European Communities | The Community: Supplies of Raw Materials | Examination | Commission of the European Communities (1975) |
| | 2008 | Commission of the European Communities | The Raw Materials Initiative: Meeting Our Critical Needs for Growth and Jobs in Europe | — | Commission of the European Communities (2008) |
| | 2011 | European Commission | Tackling the Challenges in Commodity Markets and on Raw Materials | Criticality methodology | European Commission (2011) |
| | 2014 | European Commission | Report on Critical Raw Materials for the EU | Criticality methodology | European Commission (2014) |
| | 2017 | European Commission | Study on the Review of the List of Critical Raw Materials | EC criticality methodology | European Commission (2017) |
| | 2020 | European Commission | Study on the EU's List of Critical Raw Materials | EC criticality methodology | European Commission (2020) |
| | 2023 | European Commission | Study on the Critical Raw Materials for the EU 2023 | EC criticality methodology | European Commission (2023) |
| Australia | 2019 | Australian Government | Australia's Critical Minerals Strategy 2019 | — | Australian Government (2019) |
| | 2024 | Critical Minerals Office | Australia's Critical Minerals List and Strategic Materials List | — | Critical Minerals Office (2024) |

(Continued on the following page)

TABLE 1 (*Continued*) Critical mineral research in major government departments.

| Country | Year | Agency | Title | Method | Reference |
|---|---|---|---|---|---|
| China | 2001 | Ministry of Natural Resources | National Mineral Resources Planning | — | Ministry of Natural Resources (2007) |
| | 2009 | Ministry of Natural Resources | National Mineral Resources Planning (2008–2015) | — | Ministry of Natural Resources (2009) |
| | 2011 | State Council | Programmer of Action for the Strategy of Finding Mineral Breakthroughs (2011–2020) | — | State Council (2011) |
| | 2016 | Ministry of Natural Resources | National Mineral Resources Planning (2016–2020) | — | Ministry of Natural Resources (2016) |
| Japan | 2012 | Cabinet | Resource Securement Strategies | — | Hatayama and Tahara (2015) |
| | 2018 | Ministry of Economy, Trade and Industry | Critical Minerals Report | — | Su and Hu (2022) |
| United Kingdom | 2008 | Department for Business Enterprise and Regulatory Reform | Material Security: Ensuring Resource Availability for the UK Economy | Eight basic criteria analysis method | BERR (2008) |
| | 2011 | British Geological Survey | Risk List 2011: A New Supply Risk Index for Chemical Elements or Element Groups Which are of Economic Value | Equal weight summation | British Geological Survey (2011) |
| | 2015 | British Geological Survey | Risk List 2015: An Update to the Supply Risk Index for Elements or Element Groups that are of Economic Value | Equal weight summation | British Geological Survey (2015) |
| | 2022 | Department for Business, Trade and Department for Business, Energy and Industrial Strategy | Resilience for the Future: The UK's Critical Minerals Strategy | Weighted summation | Department for Business, Trade and Department for Business, Energy & Industrial Strategy (2022) |
| Canada | 2021 | Natural Resources Canada | Critical Minerals: An Opportunity for Canada | — | Natural Resources Canada (2021) |
| | 2024 | Natural Resources Canada | Canada's Critical Minerals | — | Natural Resources Canada (2024) |
| India | 2016 | Department of Science and Technology, Council on Energy, Environment and Water | Critical Non-Fuel Mineral Resources for India's Manufacturing Sector: A Vision for 2030 | Analysis of criticality methodology | Gupta et al. (2016) |
| | 2023 | Ministry of Mines | Critical Minerals for India | Three-stage approach | Ministry of Mines (2023) |

stability and development within a certain time frame. They not only cover advantageous minerals with global influence but also include resources in short supply for strategic emerging industries. Although China screened critical minerals in 2016, the list of critical minerals needs to be reevaluated urgently due to changes in market demand and the use of mineral resources as a result of technological change and industrial transformation and upgrading. In order to evaluate China's critical minerals more comprehensively, this study takes the 24 minerals screened in China's National Mineral Resources Planning (2016–2020) as the basis (Ministry of Natural Resources, 2016), with additional consideration of the overlapping mineral lists of the EU and the U.S. as the objects of evaluation[1], as shown in Figure 1.

Despite the rapid expansion of clean energy production capacity such as wind and solar energy, fossil fuels still dominate global energy consumption, accounting for 81.5% in 2023 (EI, 2024),

1 In this study, both platinum group metals and rare earth elements are statistically analyzed as broad categories rather than being enumerated as individual elements.

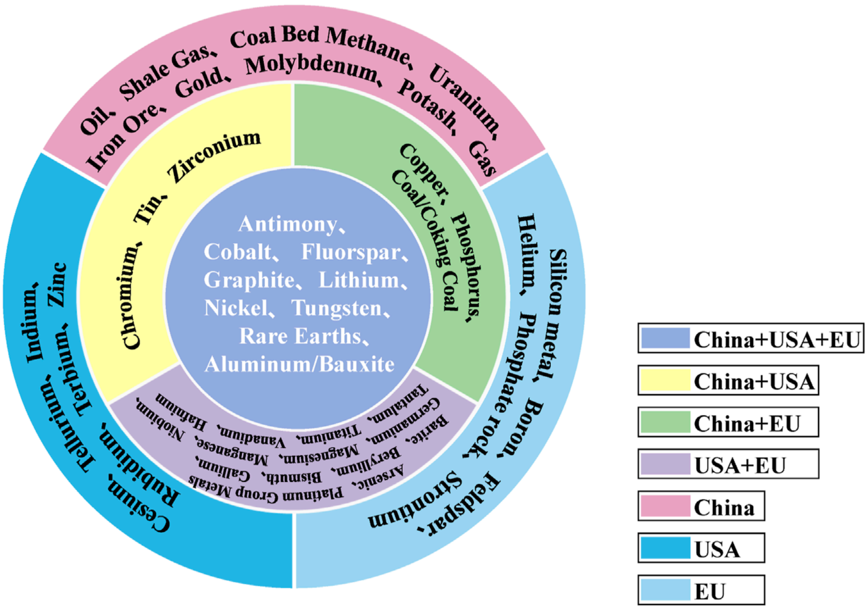


FIGURE 1
List of critical minerals from China, the United States, and the European Union.

and this situation is difficult to change in the short term. In history, resource conflicts have mainly manifested as disputes over fuel minerals such as oil and natural gas. However, since the beginning of the 21st century, the rise of emerging industries, the widespread application of next-generation information technology, and the acceleration of global green transformation have elevated the importance of some non-fuel minerals. In recent years, many countries have strengthened the competition for critical minerals, and the assessment of critical minerals by countries and regions such as Australia, the United States, and the European Union is usually based on non-fuel mineral resources. Therefore, this study will no longer explore the energy minerals but will focus on evaluating the remaining 32 non-energy minerals.

## 2.2 Classification of evaluation objects

The value of bulk minerals and strategic small minerals are different, and the degree of impact on the economy and the ability to resist the risks of minerals are also different (Wang, 2019; Li, 2024; Guo et al., 2021). It needs to be evaluated from different angles, so this study first distinguishes between the bulk minerals and the small minerals in the evaluation object. The 32 minerals are categorized according to different market values and industry types[2] in Figure 2. Minerals with a market value greater than $20 billion are defined as long-term balanced developmental minerals, including iron, manganese, chromium, copper, aluminum, nickel, gold, potash, and phosphorus. Minerals with a market value of less than $20 billion are defined as strategic small minerals. Second, according to the relevant literature research and the definition of critical minerals, the evaluation objects are subdivided into advantage minerals and scarce minerals (Liu Y. et al., 2019; Zhai et al., 2019; Guo et al., 2021; Li J. et al., 2023). Since the long-term balanced developmental minerals are basically shortage minerals (except for phosphorus), no further subdividing is carried out, and the strategic small minerals are subdivided into two categories: one category is national strategic advantage minerals, which have reserves or production rank among the top two in the world and an import reliance of less than 30% (Chen, 2002; Li W. et al., 2008), including vanadium, tungsten, molybdenum, antimony, rare earth elements, germanium, gallium, graphite, fluorspar, arsenic, barite, magnesium, and bismuth. The other category is national strategic scarce minerals (Zhai et al., 2019; Guo et al., 2020), which are highly dependent on foreign countries and cannot meet the needs of economic development. These minerals include titanium, cobalt, platinum group metals (PGMs), lithium, niobium, tantalum, zirconium, hafnium, beryllium, and tin.

2 Since rare earth elements and platinum group metals are collections of metallic elements, they are classified according to the mean value.

# 3 Indicators and methods

The relative importance of mineral resources refers to their significance, compared to others, in terms of political strategy, economic development, national defense, and security within a certain period. For example, lithium ore was previously mainly used in traditional industries that were labor-intensive or manufacturing-oriented. However, with the rapid development of the new energy industry, lithium ore has increased its importance in emerging industries and is known as "white oil" (Zhang et al., 2015). Accordingly, when establishing the relative importance evaluation system, it is not only necessary to take into account the

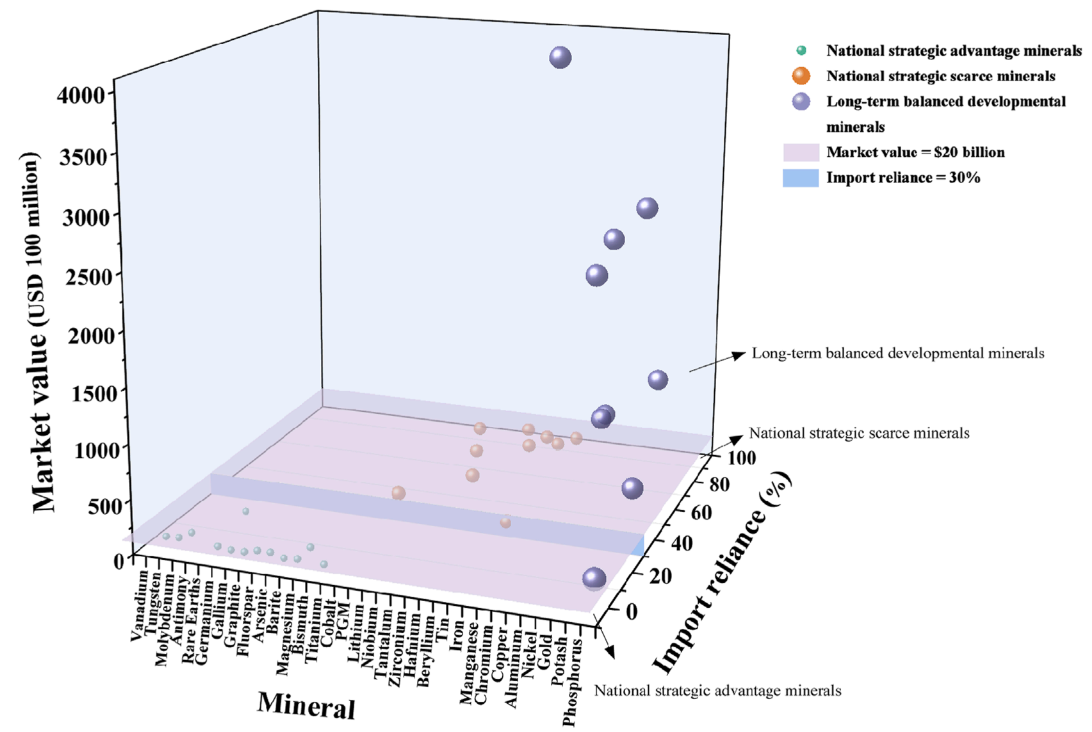


FIGURE 2
Classification chart for evaluating mineral species.

characteristics of mineral types and market dynamic changes but also to define the spatial and temporal scope of the importance of mineral resources and help clarify the order of the relative importance of minerals (Chen and Wang, 2007; Zhang et al., 2015). Referring to previous studies, the evaluation indicators in this study mainly focus on several aspects such as economic importance, strategic importance, supply risk, market prospect, and global influence. Based on the characteristics of various types of minerals, a three-dimensional evaluation system is constructed.

The linear weighted sum method is used in this study (Li X. et al., 2019), and the specific calculation is shown in Equation 1. For each mineral resource, the different indicators of mineral types and their corresponding weights are multiplied, and then they are summed up to obtain the relative importance scores.

$$Y = \sum_{j=1}^{m} W_j X_j. \quad (1)$$

In Equation 1, $Y$ is the relative importance score of the mineral, $X_j$ is the value of the $jth$ evaluation indicator of the mineral, $W_j$ is the weight coefficient corresponding to $X_j$, and $m$ represents the total number of indicators for the mineral, where $0 < W_j < 1$ ($j = 1, 2, \ldots, m$) and $\sum_{j=1}^{m} W_j = 1$.

$W_j$ is determined using the expert scoring method. In the $W_j$ assessment process, candidate indicators are first determined based on existing research. Then, the selected experts in the field of mineral resources screen important indicators according to their academic knowledge, accumulated experience, and professional judgment and determine the weight coefficient of each indicator according to their relative importance. The indicators recognized by more than half of the experts are important indicators, and the average weights of the important indicators are the final weights.

## 3.1 Long-term balanced developmental mineral evaluation system

Long-term balanced developmental minerals are mainly bulk minerals that are characterized by wide applications, large consumption, and high production, and they play a supporting role in China's economic development. Most of these minerals will continue to be consumed at high levels in the future, so the importance of long-term balanced developmental minerals should be assessed primarily in terms of economic importance, supplemented by demand prospects and supply risks (Figure 3).

### 3.1.1 Economic importance

Not only the market value of a mineral but also the price changes affected by supply and demand should be considered in the assessment of economic importance. In a scenario of high demand and high profitability, market expectations improve, while in a scenario of low demand and low profitability, market expectations decline.

① Market value: it refers to the total value of resource consumption, reflecting the economic value that minerals can produce (Zhang et al., 2015). As shown in Formula 2, the consumption of minerals multiplied by the price can better

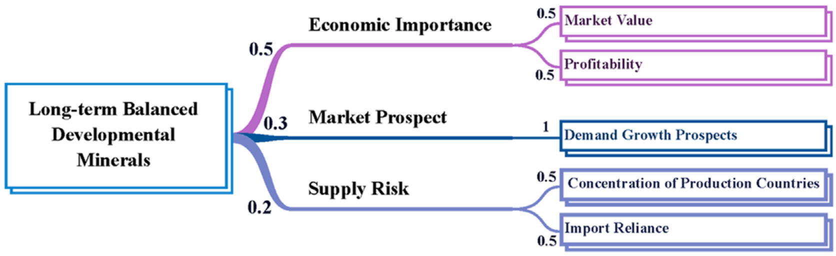


FIGURE 3
Long-term balanced developmental mineral evaluation system.

intuitively show the market value of resources.

$$Q_i = C_i P_i. \tag{2}$$

In Equation 2, $Q_i$ is the market value of the $i$th mineral. $C_i$ is the global consumption of the $i$th mineral in 2022. $P_i$ is the annual average price of the mineral.

② Profitability: this indicator is mainly measured by the average profit margin of a certain mineral. Due to the difficulty of data acquisition, this study selects the average profit margin of leading Chinese enterprises of each mineral type in the past 5 years (2018–2022) for estimation.

In order to eliminate the differences between different variables and improve the efficiency and accuracy of data analysis, this study uses min–max scaling to standardize the indicators, as shown in Equations 3, 4.

$$\acute{x}_{ij} = \frac{x_{ij} - \min_i \{x_{ij}\}}{\max_i \{x_{ij}\} - \min_i \{x_{ij}\}} \text{(Standardization of positive indicators)}, \tag{3}$$

$$\acute{x}_{ij} = \frac{\max_i \{x_{ij}\} - x_{ij}}{\max_i \{x_{ij}\} - \min_i \{x_{ij}\}} \text{(Standardization of negative indicators)}, \tag{4}$$

$$\text{Economic importance assessment formula: } E_i^{'} = 0.5Q_i^{'} + 0.5PA_i^{'}. \tag{5}$$

In Equation 5, $E_i$’ is the standardized economic importance of the $i$th mineral. $Q_i$’ is the standardized market value, and $PA_i$’ represents standardized profitability.

### 3.1.2 Market prospect

Market prospect is the expectation of the future market development of the minerals, and it is also one of the important indicators to consider. If there is no market demand for minerals, even if the reserves and production are rich, their value cannot be realized. This study adopts the changes in the consumption growth rate of minerals to reflect the market development trend in China. The compound growth rate can better reflect the stable growth ability of the demand for a particular mineral over a period of time. The specific calculation is as follows:

$$M_i = (ME_i/MB_i)^{\frac{1}{13}} - 1. \tag{6}$$

In Equation 6, $ME_i$ is the forecasted demand for the $i$th mineral in 2035, and $MB_i$ is the demand for the $i$th mineral in 2022. $M_i$ is the market prospect for the $i$th mineral. The time interval is 13 years, calculated by subtracting the start year (2022) from the end year (2035).

### 3.1.3 Supply risk

When a country has to import mineral resources from abroad to sustain its own development, it will be exposed to supply risks. In addition, the more concentrated the producers of a certain mineral, the easier it is to form an oligopoly, making price manipulation and fluctuations more likely. Therefore, minerals with supply disruption risk and high import reliance will be considered crisis minerals. By taking into account both the concentration of producing countries and import reliance, the riskiness of a mineral can be assessed more accurately.

① Concentration of production countries: it is expressed by the Herfindahl–Hirschman index (HHI). A greater HHI indicates higher market concentration and monopolization. This study cites the calculation of the HHI for raw materials in the European Union (European Commission, 2023; Li et al., 2023); in other words, it uses the Worldwide Governance Indicators (WGIs) to revise the HHI in order to better reflect the degree of monopoly and geopolitical risk in the supply of a certain mineral (European Commission, 2023; Li J. et al., 2023). The formulas are provided in Equations 7–9.

$$CPC = \sum^{c} ((SC)^2 WGI_c), \tag{7}$$

$$WGI_c = \left(\prod_{k=1}^{6} WGI_k^{'}\right)^{\frac{1}{6}}, \tag{8}$$

$$WGI_k^{'} = 1 - \frac{WGI_k + 3.5}{7}, \tag{9}$$

where $k$ has a value of 1–6 and $WGI_k$ is the initial value of the $k$th indicator in WGIs. $WGI_k$’ represents the value after the standardization of $WGI_k$. $WGI_c$ is WGI for country $C$ after standardization, and $SC$ is the global proportion of the production of a certain mineral in country $C$. $CPC$ is the evaluation value for the concentration of production countries. The WGI scores for China are relatively low, which does not reflect the country’s actual situation (National Governance Index Construction Research Group et al., 2024; Lu and Zhang, 2017; You, 2017). According to a comprehensive evaluation by the Chinese People's Forum Evaluation Center, China and Australia are both major resource-rich countries, with their comprehensive scores being relatively close. This article refers to the practices of some scholars, and China's WGIs are corrected according to Australia's[3]. Since China is under one-party rule and the political risk is lower than that in other countries, China's political stability and absence of violence/terrorism index was adjusted to a maximum of 2.5.

② Import reliance: the index reflects the extent of China's reliance on mineral resources from other countries (Zhou et al., 2019). The calculation is provided in Equation 10.

$$IR = \frac{C - P - R}{C}, \tag{10}$$

where $C$ is domestic consumption, $P$ is primary resource production, $R$ is secondary recovery, and $IR$ is the evaluation value of import reliance.

In summary, the supply risk indicator assessment formula of the $i$th mineral is provided in Equation 11.

$$SR_i = CPC_i \times IR_i. \tag{11}$$

A mineral's importance is heightened by its higher economic value, improved market prospects, and elevated supply risks. Consequently, $M_i$ and $SR_i$ are all positive indicators and are standardized using Equation 3.

The comprehensive evaluation model is presented in Equation 12.

$$LD_i = 0.5E_i^{'} + 0.3M_i^{'} + 0.2SR_i^{'}. \tag{12}$$

In Equation 12, $LD_i$ is the comprehensive evaluation value of the $i$th long-term balanced developmental mineral, and $M_i'$ and $SR_i'$ are the values after normalization.

## 3.2 National strategic advantage mineral evaluation system

National strategic advantage minerals possess strong reserves and mining capabilities. Their import reliance is low, and they even have the potential to be exported. As an advantage mineral of a country, it is necessary to measure whether this mineral is critical to other countries and whether it has international strategic importance. Therefore, when assessing the relative importance of national strategic advantage minerals, evaluation indicators can be constructed from three dimensions, namely, economic importance, strategic importance, and mineral influence, as shown in Figure 4.

### 3.2.1 Importance

Importance includes both economic and strategic importance. The indicators of economic importance have the same definition and calculation method as mentioned above. Strategic importance primarily measures the criticality of a certain mineral to a major economy (Li et al., 2023; Hayes and Mccullough, 2018). The evaluation model is as follows:

$$S = \frac{QC}{QL}, \tag{13}$$

In Equation 13, $S$ is the evaluation value for strategic importance. $QC$ denotes the frequency of the mineral being listed as a critical mineral by major economies. $QL$ represents the total count of major economies[4].

### 3.2.2 Mineral influence

Mineral influence mainly measures the international status and control of minerals. If the mineral resource endowment is good and the export capacity is strong, its influence will be stronger. Reserves, production, and exports are the three main factors of influence (Li J. et al., 2023). The mineral influence (I) is evaluated in Equation 14:

$$I = \left(\frac{E_c}{E}\right)\sqrt{\left(\frac{P_c}{P}\right)\left(\frac{R_c}{R}\right)}, \tag{14}$$

where $E$, $P$, and $R$ denote global exports, production, and reserves, respectively. $E_c$, $P_c$, and $R_c$ denote China's exports, production, and reserves, respectively. If no reserve data are available for minerals, the calculation is instead based on the product of its export and production shares. That means, $I = (E_c/E)^*(P_c/P)$.

$S$ and $I$ are positive indicators; if a certain mineral not only has economic and strategic importance but also has excellent export capacity, then it is an important strategic advantage mineral. The comprehensive evaluation model is provided in Equation 15.

$$ND_i = 0.25E_i^{'} + 0.25S_i^{'} + 0.5I_i^{'}. \tag{15}$$

In the formula, $ND_i$ is the comprehensive evaluation value of the $i$th national strategic advantage mineral, and $S_i'$ and $I_i'$ are obtained through normalization using Equation 3.

## 3.3 National strategic scarce mineral evaluation system

As a critical mineral resource for national industrial transformation and upgrading, national strategic scarce minerals are heavily reliant on imports. The supply risk of these minerals is a key indicator in their evaluation. When mineral production or import sources are too concentrated, problems or disruptions in supply from the main producing or importing countries can severely threaten the industrial security of the buyers. Moreover, when the proportion of the associated minerals is high and their exploitation and utilization are challenging, these minerals also face supply risks (Shao and Lan, 2020). Accordingly, within the national strategic scarce mineral evaluation system, minerals are considered more important if they are both economically valuable and strategically significant but severely scarce. The detailed evaluation system is illustrated in Figure 5.

3 WGIs include voice and accountability, political stability and absence of violence/terrorism, government effectiveness, regulatory quality, rule of law, and control of corruption. In addition to the index of "political stability and absence of violence/terrorism," the Australian WGI was used in the place of the Chinese WGI.

4 In this study, the major economies are China, the United States, and the European Union.

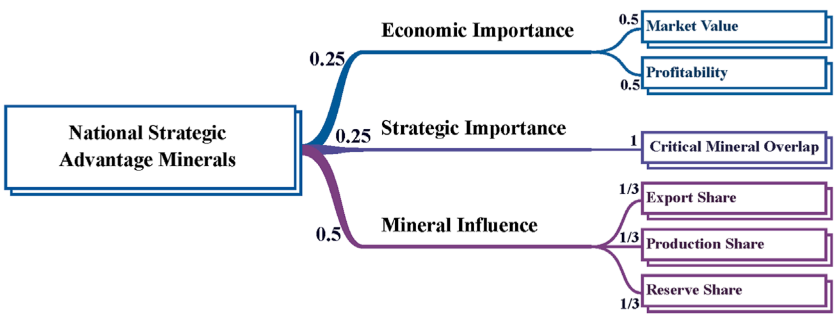


FIGURE 4
National strategic advantage mineral evaluation system.

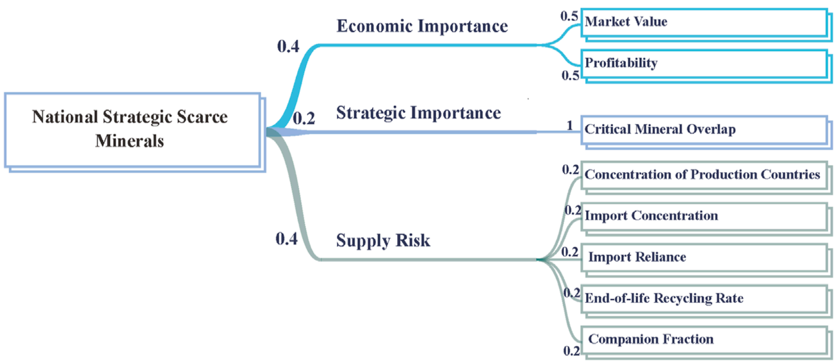


FIGURE 5
National strategic scarce mineral evaluation system.

(1) Economic and strategic importance: the definition and calculation of the indicators are the same as mentioned above.
(2) Supply risk

This study analyzes the sources of supply risk at each stage based on the whole life cycle of minerals (European Commission, 2023; Li J. et al., 2023). The supply risk of minerals is affected not only by the production concentration and the stability of the producing country but also by the import concentration, import reliance, resource recycling, and associated production. The higher the indicator score, the greater the mineral supply risk and the more prominent the shortage. *SR* is a positive indicator. The specific calculation formula is provided in Equation 16.

$$SR = CPC \times IC \times IR \times (1 - EOL_{RIR}) \times \mathrm{CF}', \tag{16}$$

where *CPC* and *IR* are calculated similarly to Equations 7, 10. *IC* is the import concentration, that is, the proportion of China's imports from major countries. $EOL_{RIR}$ is the end-of-life recycling rate, namely, the proportion of domestic secondary resources in the total supply. *CF* is the percentage of associated minerals. In terms of current production, the supply of associated minor metals is constrained by the production of the main mine, which is far from reaching its potential capacity (Fizaine, 2013; Frenzel et al., 2016; Frenzel et al., 2017; Shao and Lan, 2020). Therefore, a logarithmic standardization method is used to process the indicator and reduce the impact of the original data on the calculation results of supply risk. The standardization method is shown in Equation 17:

$$CF' = \frac{1}{1 + e^{(-CF)}}. \tag{17}$$

The comprehensive evaluation model of national strategic scarce minerals is provided in Equation 18.

$$NS_i = 0.4E_i' + 0.2S_i' + 0.4SR_i'. \tag{18}$$

In Equation 18, $NS_i$ is the comprehensive evaluation value of the *i*th minerals. $SR_i'$ is the value after standardization.

## 3.4 Data sources

Data on global mineral consumption, market prospects, import reliance, and end-of-life recycling rates in 2022 are sourced from the Chinese Academy of Geological Sciences. The production, reserves, and price data of each mineral in 2022 are sourced from the USGS. The average profit margin of each mineral from 2018 to 2022 is derived from the annual reports and financial statements of various enterprises. WGI data come from the World Bank. CF data are taken from Nassar et al. (2015). Trade data for each mineral in 2022 are obtained from China Customs and the UN Comtrade Database. Any missing data are supplemented with data from the last 3 years.

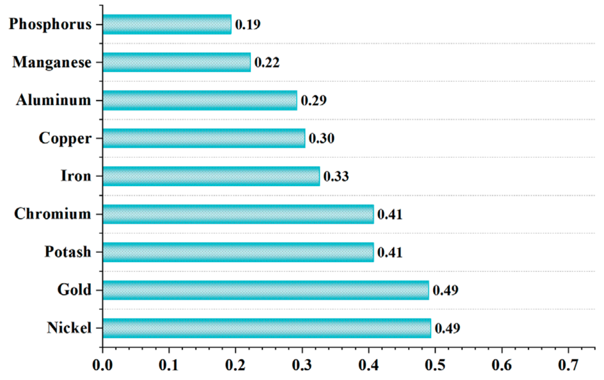


FIGURE 6
Evaluation ranking of long-term balanced developmental minerals.

# 4 Results and discussion

After data collection and standardization, the linear weighted sum method is used to evaluate the three types of minerals.

## 4.1 Long-term balanced developmental minerals

As shown in Figure 6, among the long-term balanced developmental minerals, nickel has the highest comprehensive score, indicating that it is a critical mineral deserving long-term attention. Next are gold, potash, chromium, iron, copper, aluminum, and manganese, with a comprehensive score of 0.193 for phosphorus, which ranks last. According to the scores in Table 2, the market prospects of nickel and gold have high scores of 0.829 and 1, respectively, indicating strong development potential. The supply risk scores of nickel and chromium are 1 and 0.841, respectively, classifying them as high-risk minerals. Iron and potash rank among the top two in economic importance, possessing high economic value.

As shown in Figure 7, nickel has high scores for economic importance, market prospects, and supply risk. Its demand is driven by the growing need for ternary cathode materials and power batteries in the field of new energy, giving it strong market potential (Wu X. et al., 2024), but its low profitability is mainly related to the low grade of nickel ore in China, which limits effective utlization. Therefore, nickel ore production is highly dependent on foreign resources, and imports from the Philippines, particularly, are highly concentrated in a single channel (Wu Q. et al., 2024). This high demand coupled with high-risk characteristics has increased the importance of nickel. Gold has the highest market prospects. Due to increased global economic uncertainty and risk, gold has become a means of investment and value preservation. According to statistics, global gold consumption reached 4,741 tons in 2022, the highest point in 11 years and an increase of 18% year-on-year (World Gold Council, 2023). High demand and increasing gold prices have attracted more investors to the gold mining market, and the market size continues to expand, making gold the second most important mineral after nickel. Potash and chromium have similar importance scores. As an important fertilizer raw material, potash is widely used in China. In addition, the profitability of potash enterprises is significantly higher than that of other minerals due to the significant increase in potash prices over the past 2 years, making potash second only to iron in economic importance. Chromium is mainly used in the metallurgical industry, and due to the impact of China's industrial transformation, the market prospects of the construction and metallurgical industries are weak. Nevertheless, chromium is an important mineral that supports the development of the new materials industry, and its market prospects is still rank among the highest of the nine minerals assessed. Due to the scarcity of chromium resources in China, there are many poor mines and very low production. If secondary recovery is not considered, chromium ore is extremely dependent on imports from South Africa, Turkey, Kazakhstan, and other import countries, which is the main reason for the high supply risk of chromium.

In the analysis of China and different provinces by Chen and Wang (2007), Lv and Wang (2014), and Chen and Zhang (2010), iron, copper, aluminum, and manganese are all considered important, which is consistent with the research conclusions of this paper. This is mainly because these minerals are the basic resources to ensure economic development and national defense security, with great demand, low domestic security, high import-source concentration, high import dependence, and coexistence of importance and supply risk. However, as China enters the later stages of industrialization, the consumption prospects of iron, copper, aluminum, and manganese are weak, and their overall importance is lower than that of nickel, gold, potash, and chromium. This ranking differs from the results of Chen and Wang (2007) and Wang et al. (2016), mainly due to differences in the evaluation objects and the weights of the evaluation indicators.

Phosphorus scored the lowest among the long-term balanced developmental minerals because China is rich in phosphorus resources, is generally self-sufficient, and has a certain export capacity. Compared with potash as a raw material for fertilizers, phosphorus has a lower supply risk, and its market value is small, so its economic importance and market prospects are not high (Figure 7).

## 4.2 National strategic advantage minerals

The national strategic advantage mineral scores, in descending order, are tungsten, arsenic, bismuth, fluorspar, graphite, antimony, germanium, magnesium, rare earth elements, vanadium, gallium, molybdenum, and barite (Figure 8). Table 3 shows that the comprehensive scores of tungsten, arsenic, and bismuth are all greater than 0.6, ranking them in the top three. The comprehensive scores of fluorspar, graphite, antimony, germanium, magnesium, rare earth elements, vanadium, and gallium range from 0.2 to 0.5. The comprehensive scores of molybdenum and barite are less than 0.2, ranking them in the bottom two. Judging from the scores of each indicator, the strategic importance indicators for tungsten, fluorspar, graphite, antimony, and rare earth elements score 1, while the influence indicators for tungsten, arsenic, and bismuth score between 0.7 and 1. The economic importance scores are higher for molybdenum and fluorspar, both of which are greater than 0.6.

TABLE 2 Indicator evaluation scores for long-term balanced developmental minerals.

| Mineral | Economic importance | Market prospect | Supply risk | Comprehensive score |
|---|---|---|---|---|
| Nickel | 0.089 | 0.829 | 1.000 | 0.493 |
| Gold | 0.347 | 1.000 | 0.082 | 0.490 |
| Potash | 0.521 | 0.324 | 0.249 | 0.407 |
| Chromium | 0.265 | 0.355 | 0.841 | 0.407 |
| Iron | 0.528 | 0.000 | 0.307 | 0.326 |
| Copper | 0.433 | 0.126 | 0.247 | 0.304 |
| Aluminum | 0.268 | 0.340 | 0.279 | 0.292 |
| Manganese | 0.043 | 0.101 | 0.851 | 0.222 |
| Phosphorus | 0.230 | 0.259 | 0.000 | 0.193 |

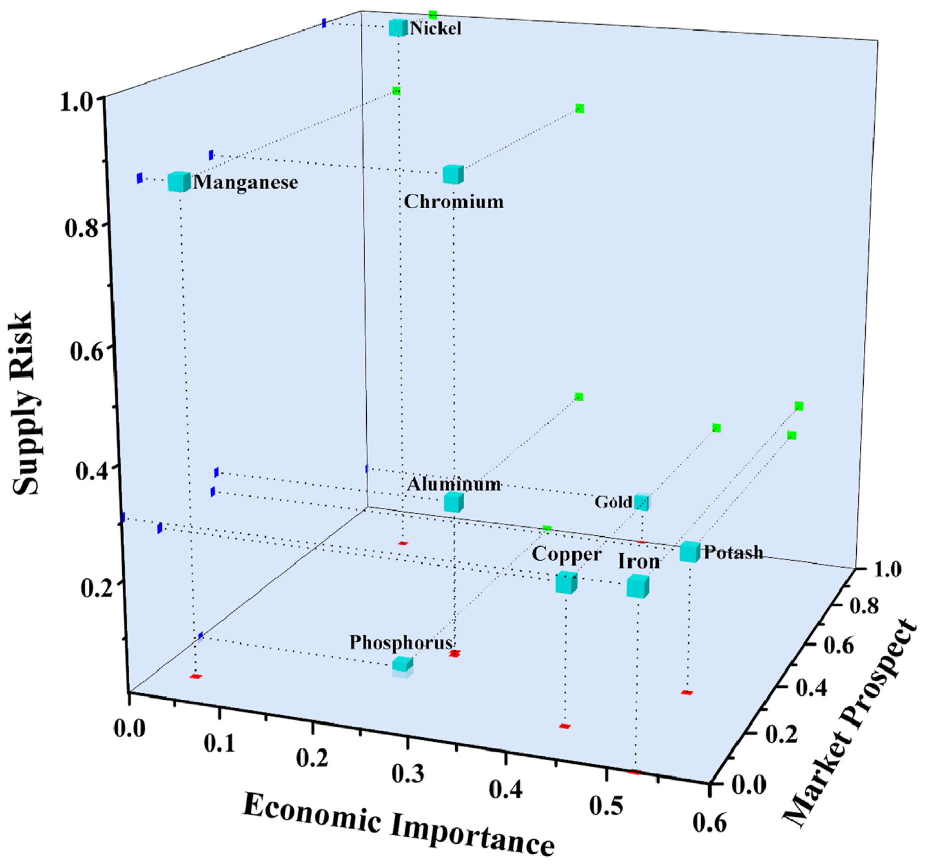


FIGURE 7
Evaluation indicator scores for long-term balanced developmental minerals.

According to the results of our assessment, China's tungsten, arsenic, and bismuth are important advantageous minerals with a strong influence. Not only are the resource reserves abundant, but China also holds a global export share of 50% or more, establishing it a major resource-producing power (Mei et al., 2024). From the perspective of product structure, because Chinese tungsten products are mainly concentrated in the low-to-mid-end, their profitability is not high, and the market value of arsenic and bismuth is relatively small, so the economic importance of tungsten, arsenic, and bismuth is relatively weak. Tungsten, because of its high melting

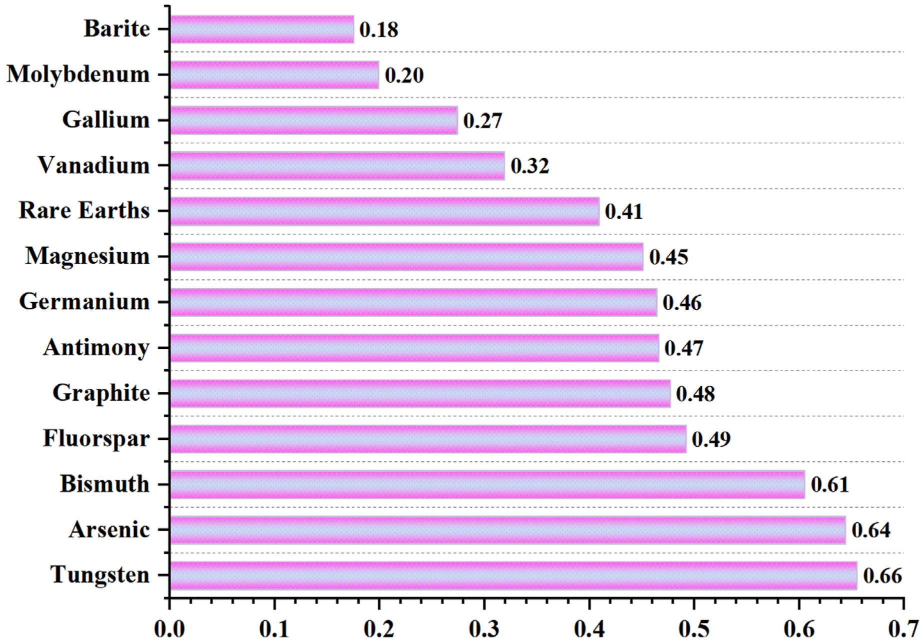


FIGURE 8
Evaluation ranking of national strategic advantage minerals.

TABLE 3 Indicator evaluation scores for national strategic advantage minerals.

| Mineral | Economic importance | Strategic importance | Mineral influence | Comprehensive score |
|---|---|---|---|---|
| Tungsten | 0.156 | 1.000 | 0.731 | 0.655 |
| Arsenic | 0.075 | 0.500 | 1.000 | 0.644 |
| Bismuth | 0.226 | 0.500 | 0.846 | 0.605 |
| Fluorspar | 0.629 | 1.000 | 0.169 | 0.492 |
| Graphite | 0.367 | 1.000 | 0.271 | 0.477 |
| Antimony | 0.271 | 1.000 | 0.297 | 0.466 |
| Germanium | 0.238 | 0.500 | 0.559 | 0.464 |
| Magnesium | 0.593 | 0.500 | 0.356 | 0.451 |
| Rare earth elements | 0.125 | 1.000 | 0.255 | 0.409 |
| Vanadium | 0.344 | 0.500 | 0.216 | 0.319 |
| Gallium | 0.055 | 0.500 | 0.271 | 0.274 |
| Molybdenum | 0.652 | 0.000 | 0.071 | 0.199 |
| Barite | 0.198 | 0.500 | 0.000 | 0.175 |

point, plays an important role in the national defense, energy, automotive, chemical, and medical fields. As a strategic national defense resource, it has been listed as a critical mineral by many countries (Mei et al., 2024). Arsenic and bismuth are also of strategic importance due to their growing demand in the fields of high technology and new energy. Therefore, the comprehensive score of tungsten, arsenic, and bismuth is high.

Based on the scores of each indicator in Table 3, fluorspar and graphite rank just below tungsten, arsenic, and bismuth in terms of importance. Graphite and fluorspar are important non-metallic resources and have strong demand, and their importance has been confirmed by Liu Y. et al. (2019). Through the analysis in this paper, it is found that Chinese fluorspar and graphite enterprises have relatively high economic importance due to their high average profit margins and good market value. In addition, fluorspar and graphite are widely used in new energy and new materials and have strong strategic importance (Chen J. et al., 2021). However, due to China's export controls on fluorspar and graphite, along with their relatively low global reserve proportions, their international influence remains limited. Antimony and rare earth elements are used as raw materials in the military industry, germanium is dispersed and has development potential in the high-tech field, and magnesium plays an important role in the metallurgical industry and transportation. Their strategic importance cannot be ignored. However, their performance in other indicators is average. Therefore, the importance of antimony, germanium, magnesium, and rare earth elements is average.

Although molybdenum has a relatively high score in economic importance, China's global share of molybdenum concentrates is only 6% in primary product exports, which is not as high as that of Chile, the United States, and Peru. In high-end product exports, the export volume of ferromolybdenum is less than that of South Korea, and its influence is limited. Moreover, molybdenum is not a critical mineral in many countries' lists and is not of high strategic importance, so its importance is relatively low. Barite is widely used in industries such as industry and energy and plays an important role in national economic security. The United States and the European Union have designated barite as a critical mineral, and the strategic importance of the mineral is relatively high. However, the market value of barite is relatively small, and its economic importance is not high. China's barite reserves account for only 9% of the global total (Liu et al., 2024), and exports account for only 13% of the global total, which is lower than India's 45% and Morocco's 21%. Consequently, when compared with other advantage minerals, barite's importance is relatively weak (Figure 9).

## 4.3 National strategic scarce minerals

From Table 4 and Figure 10, it can be observed that among the national strategic scarce minerals, the comprehensive evaluation score of lithium is 0.70, which is much higher than that of other minerals. The importance of other minerals is ranked as follows: zirconium, hafnium, cobalt, platinum group metals, titanium, tin, beryllium, niobium, and tantalum. From the scores of each indicator, we can observe that hafnium (1), zirconium (0.9), and lithium (0.7) have the highest supply risk scores and are high-risk minerals. In terms of strategic importance, lithium and cobalt have the highest scores, both of which are 1. In terms of economic importance, lithium, platinum group metals, and cobalt have higher scores, ranging from 0.45 to 0.5.

An analysis of the assessment results shows that the significance of lithium is reflected not only in its economic and strategic importance but also in its classification as a high-risk scarce mineral (Figure 11), which is consistent with the findings of Chen S (2023). This is mainly due to the rapid development of the new energy industry, the increasing demand for lithium, the larger market size, and enhanced profitability. However, lithium raw materials are highly dependent on foreign sources, mainly Australia, Chile, etc., and are subject to greater supply risks (Wen et al., 2024). Therefore, it ranks first in importance. Considering that the import reliance of zirconium and hafnium is greater than 90%, the importing countries are relatively concentrated, and it is difficult to recycle secondary resources; the proportion of associated mineral production is relatively high. So, zirconium and hafnium supply risks are higher.

Cobalt and platinum group metals are at the forefront of economic importance. Cobalt is a critical raw material for new energy batteries and is, therefore, becoming increasingly important in terms of market value and strategic position (Dong et al., 2023). Platinum group metals, as precious metals, have a much higher market value than other minerals. However, the supply risk of cobalt and platinum group metals is relatively low. Their high secondary resource recovery rate reduces scarcity. China, as the world's largest tin resource reserve and producer, is relatively rich in tin resources (Chen and Zhang, 2021). In addition, the proportion of associated mineral production is not high, and waste resources are available, which reduces the risk of supply. Beryllium has a small market scale, making it less important in terms of scarcity.

Tantalum and niobium are associated minerals with low economic importance, which reduces their score.

## 4.4 Comprehensive analysis

The analysis of evaluation results shows that the three evaluation systems are not completely parallel and independent but have certain connections. First, the relative importance of different minerals of the same type may change due to the influence of geological conditions, market demand, and environmental changes at different stages. Minerals of different types may also transform into one another. For example, advantage minerals will gradually lose their competitive edge when they are over-exploited, particularly in the case of limited reserve development and surging market demand; in some cases, they may even become scarce minerals, as observed with tin and manganese. Second, there is a complementary relationship between the long-term balanced developmental minerals and strategic small-quantity minerals in the development of a national economy. Long-term balanced developmental minerals are widely used and have high consumption rates. Strategic small-quantity minerals have important applications in high-tech, new energy, and other fields. The two are complementary and interdependent and support the stable development of the national economy together.

The ability to acquire and utilize critical minerals directly affects a country's competitiveness. The evaluation results of critical minerals can not only provide references for the security of different minerals, determine the development positioning of critical minerals, and provide support for strengthening resource

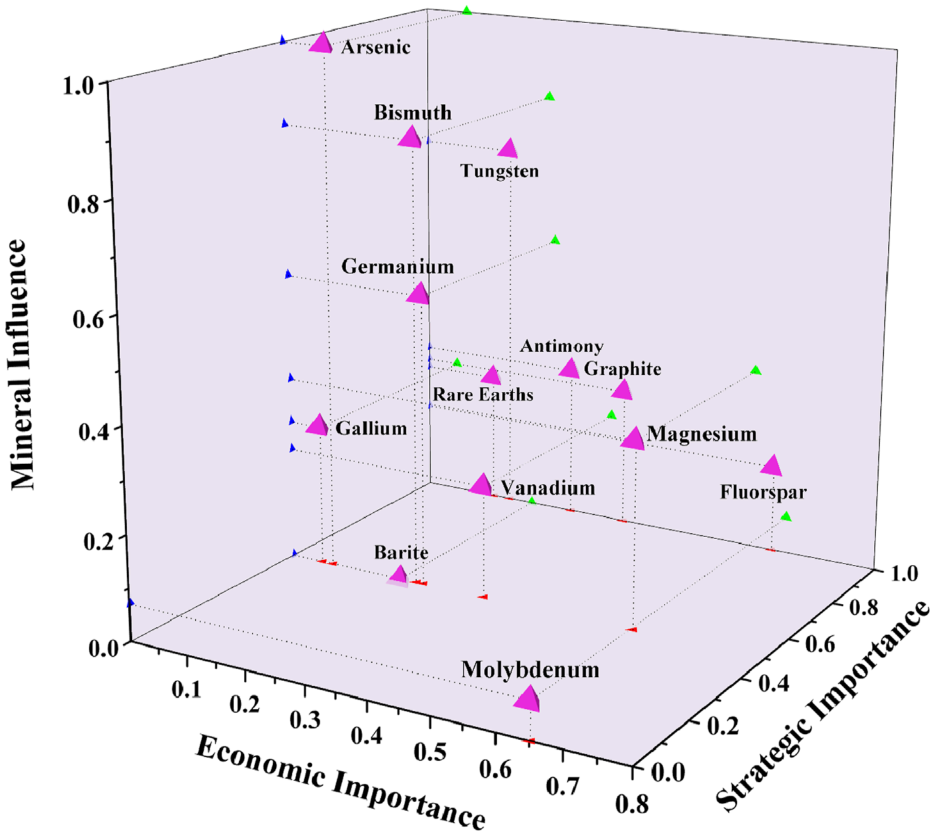


FIGURE 9
Evaluation indicator scores for national strategic advantage minerals.

**TABLE 4** Indicator evaluation scores for national strategic scarce minerals.

| Mineral | Economic importance | Strategic importance | Supply risk | Comprehensive score |
|---|---|---|---|---|
| Lithium | 0.509 | 1.000 | 0.740 | 0.700 |
| Zirconium | 0.276 | 0.000 | 0.910 | 0.474 |
| Hafnium | 0.128 | 0.000 | 1.000 | 0.451 |
| Cobalt | 0.453 | 1.000 | 0.002 | 0.382 |
| Platinum group metals | 0.500 | 0.000 | 0.008 | 0.203 |
| Titanium | 0.437 | 0.000 | 0.031 | 0.187 |
| Tin | 0.375 | 0.000 | 0.000 | 0.150 |
| Beryllium | 0.348 | 0.000 | 0.014 | 0.145 |
| Niobium | 0.254 | 0.000 | 0.075 | 0.132 |
| Tantalum | 0.225 | 0.000 | 0.022 | 0.099 |

protection and improving the regulatory system but also play a positive role in identifying the supply of critical minerals, promoting the development of related industries, and promoting the overall growth of the economy.

## 4.5 Approach limitation

A comprehensive and objective evaluation of critical minerals is a complex task. This paper selects key influencing factors

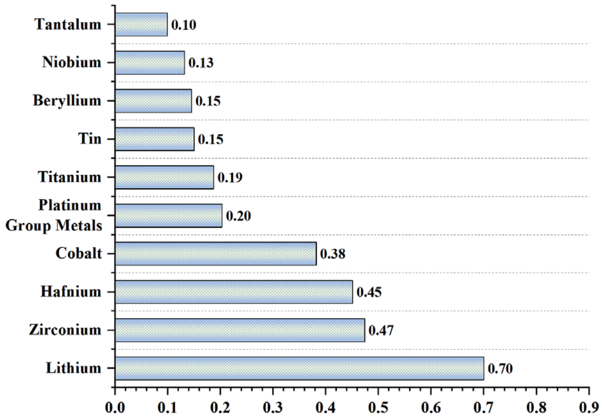


FIGURE 10
Evaluation ranking of national strategic scarce minerals.

based on the existing literature, but there are still some potential limitations that may affect the accuracy of the evaluation. For example, there is a mutual influence between different factors. Technological progress may have an impact on the economic value of minerals by influencing market demand, which is difficult to fully account for in the evaluation process. In determining the weights of influencing factors, expert evaluation involves a degree of subjectivity. In addition, some hard-to-quantify indicators have not been considered. With the deepening of low-carbon transformation, factors such as environmental impact and social responsibility fulfillment have gradually become important considerations. In our future work, we intend to stratify and set more comprehensive influencing factors and attempt to screen important factors with big data technology. We will determine weight based on the occurrence frequency of the influencing factors to improve the objectivity of the evaluation results.

# 5 Conclusion and suggestions

This study evaluates the relative importance of 32 minerals by setting up indicators according to the characteristics of different minerals and obtains the following conclusions.

(1) Nickel, gold, potash, and chromium are important long-term balanced developmental minerals, while phosphorus is relatively less important. Nickel has the highest comprehensive score due to its good market prospects and high supply risk. Gold, as a means of reserve and financial hedge, has good economic value and market prospect, and its relative importance is second only to nickel. Potash and chromium have gained high importance due to their high economic importance and high supply risk, respectively. However, phosphorus has a weak market prospect and economic importance, and the comprehensive ranking is low.
(2) Tungsten, arsenic, and bismuth are important national strategic advantage minerals with excellent export capacities and high strategic importance. Molybdenum and barite have relatively poor export capacity and lower importance. However, molybdenum is more important than barite due to its high economic importance.
(3) Lithium, zirconium, and hafnium are important national strategic scarce minerals, while niobium and tantalum are of relatively weak importance. Lithium ranked first in mineral importance due to its strong economy, high strategy, and high supply risk. Hafnium and zirconium, which are economically weak and highly risky, are second only to lithium in importance. The weak economics of niobium and tantalum reduce their importance scores.

The evaluation results reflect the relative importance of mineral resources. According to the relative positions of mineral resources with different categories and their scores across different indicators, the following suggestions are put forward.

(1) The focus should be on nickel and chromium, which are important and have high supply risks among long-term balanced developmental minerals. In terms of supply risk, the concentration of production countries and import reliance of nickel and chromium are high. Producers can explore alternative products and new mineral resources to reduce reliance. At the same time, they can strengthen cooperation with international mineral enterprises to diversify the risk of production country concentration. In terms of increasing the economic importance of the mineral, it is crucial to know recent trends; in recent years, nickel prices have declined due to oversupply in major producing countries, leading to a significant decrease in corporate profitability. Nickel enterprises can mitigate this impact by scaling back related operations. Chromium enterprises can explore new areas of application and enhance the market size of their resources as a way to improve the market value of their chromium products.
(2) The competitiveness of advantage resources should be improved. China's tungsten, arsenic, and bismuth have advantages in resource production and influence. On the one hand, in terms of economic importance, tungsten, arsenic, and bismuth enterprises can improve the scale of the mineral market value by integrating high-quality production resources and building a competitive industrial chain. In addition, high-end technology products can be developed to carry out technological innovation, reduce production costs, and enhance enterprise profitability. On the other hand, in terms of export, enterprises can optimize the export management chain, reduce transportation costs, establish stable export channels, enhance the brand influence of enterprises, and give full play to their resource advantages.
(3) The supply of importantly scarce minerals, such as lithium, zirconium, and hafnium, should be increased. Lithium ore holds significant economic and strategic value. Some countries have designated lithium as a reserve resource and tightened resource policies, heightening investment risks for enterprises. Lithium enterprises can reduce the supply risk by improving the recovery of waste resources. Chinese zirconium and hafnium production enterprises are limited, with poor profitability, making the supply dependent on imports. It is suggested that the production enterprises integrate relevant small enterprises, develop into large local mining companies,

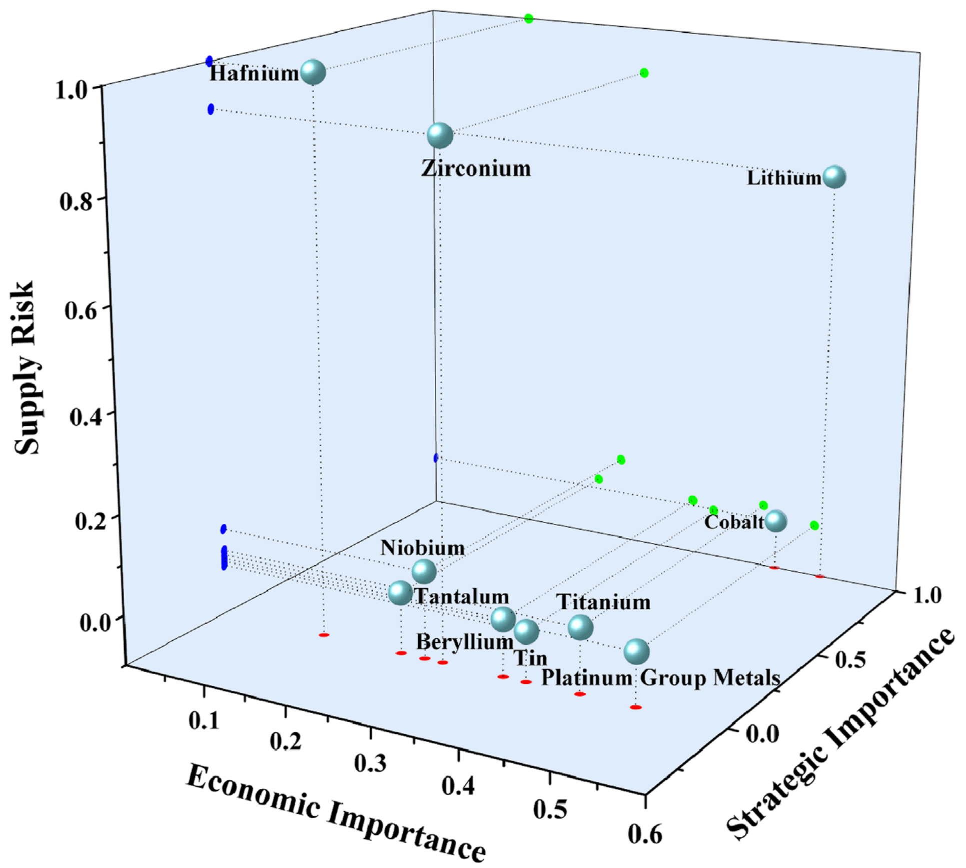


FIGURE 11
Evaluation indicator scores for national strategic scarce minerals.

improve the independent supply capacity of zirconium and hafnium resources, reduce import reliance, and enhance the risk resistance and stability of the zirconium and hafnium industrial chain. At the same time, enterprises should pay attention to the cultivation of relevant scientific research talents, build advanced experimental platforms, and accelerate the research and development process of more efficient mineral separation technology. This will weaken the constraints on the production capacity of high-associated minerals and improve mineral production.

(4) The efficiency of mineral resource development and utilization should be improved, and environmental protection should be strengthened to promote sustainable development. Environmental protection is a prerequisite for the development and utilization of mineral resources, and efficient resource development and utilization is a means of environmental protection. The process of developing and utilizing mineral resources often causes environmental pollution and ecological imbalance, and inefficient development aggravates the seriousness of these problems. Therefore, in order to ensure the sustainable development of mineral resources in terms of development and utilization, production enterprises can optimize and update mining technologies; adopt green environmental protection equipment; improve work efficiency; reduce the generation of waste gas, wastewater, and waste residue in the production process; and increase enterprise benefits. In terms of environmental protection, production enterprises can choose green development paths, formulate comprehensive environmental governance measures, and select appropriate restoration methods based on geological characteristics such as tailings ponds, subsidence areas, and closed pits to reduce adverse impacts on the environment.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material; further inquiries can be directed to the corresponding author.

## Author contributions

XR: formal analysis, writing–review and editing, data curation, visualization, and writing–original draft. FF: conceptualization, formal analysis, methodology, project administration, supervision, and writing–review and editing. QL: funding acquisition, investigation, and writing–review and editing. YL: writing–review and editing.

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## Conflict of interest

The 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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