Mineral Economics
https://doi.org/10.1007/s13563-022-00340-4

ORIGINAL PAPER

The security of critical mineral supply chains

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Received: 18 June 2022 / Accepted: 16 August 2022

Abstract
Critical minerals are the cornerstone of the new round of the industrial revolution. The global division of labor established under the traditional technology, industry, and trade systems is facing a significant restructuring. Global economic and technological changes will lead to a long-term increase in demand for critical minerals. The critical minerals supply chain is rife with political interference and distorted trade practices compared to the robust resource demand. It faces several challenges that threaten the sustainability of the supply chain. We analyze the evolving security connotation of critical minerals supply chains. We also provide an overview of research on quantifying risks of critical minerals from two aspects: security evaluation mechanism and global value chain. The interdisciplinary research techniques and methods are more adapted to the new trends of international competition in critical minerals. The article reviews relevant security risk identification and response research in critical minerals supply chains. It analyzes how to address the risk challenges from national strategies. Finally, the article explores new trends under new technological revolution and industrial change.

Keywords Critical minerals · Supply chain · Supply security · Interdisciplinary

Introduction

Critical minerals are the key to guaranteeing national economic security, defense security, and resource security. Critical minerals are essential for strategic emerging industries (Ballinger et al. 2019). A recent report by the International Energy Agency (IEA) states that “the average amount of minerals required for a new power generation unit has increased by 50% since 2010 as the share of renewables in new investments has risen” (International Energy Agency 2021). Critical minerals are characterized by their non-substitutability in high-technology areas, the uneven global distribution of resource reserves, and the volatility of the international external environment, which exacerbates security risks in the supply chain of critical minerals (Day 2019; McNulty and Jowitt 2021).

The new technological revolution and industrial change are reshaping the global technological landscape and economic structure (Fortier et al. 2018). High-tech industries (i.e., clean energy, green transportation, and intelligent manufacturing) will profoundly change critical minerals’ existing supply and demand patterns (IEA 2021). In low carbon emission reduction alone, the World Bank estimates that about 3 billion tons of critical minerals will be required to decarbonize the global energy system by 2050 (Kirsten et al. 2020). In light of this, economies such as the EU, the USA, and Japan are stepping up their efforts to strengthen their critical minerals supply chain security through resource reserves, import-substituting country diversification, global mine acquisitions, and the establishment of international critical minerals alliances (USGS 2021). Western countries such as the USA and some members of the European Union have dominated the global critical minerals supply chain through national security layout at the “upstream end of resources” and technology and intellectual property control at the “downstream application end.” It poses a severe challenge to developing emerging countries and economies (Chang et al. 2017). Ensuring the security and control of critical mineral supply chains is a new challenge for major countries and economies in non-traditional national security.

The critical mineral supply chain has a fundamental role in the modernized industrial system (Grandell et al. 2016). Securing critical mineral supply chains is necessary for

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Published online: 25 August 2022

establishing a safe and efficient modernized industrial system. The concept and connotation of critical minerals supply chain security are rooted in global industrial changes and technological revolutions and are highly time-sensitive and political. The article analyzes the progress and trends of research on critical minerals supply chain security in the light of the current strategic layout of critical minerals and the theoretical frontier progress of major global powers. The article focuses on the following aspects: evaluating critical minerals supply chain security, critical minerals value chain accounting, risk identification of critical minerals supply chain, and national strategic layout.

The connotation of critical mineral supply chains security

The critical minerals are the basis of modern industrial development. With the development of the global economy, the evolution of the geopolitical situation, and the transformation and upgrading of the domestic economic structure, the connotation of security in the critical minerals supply chain is constantly adjusted to adapt to the changes in domestic and international forms. However, "security" has always been the core of critical minerals supply chain research (Gulley et al. 2018). A review of the academic and policy history of critical minerals supply chain security shows a trend of "national security—the global division of labor—autonomous control" (McCullough and Nassar 2017).

Western countries such as the USA and some members of the European Union have established management institutions for critical mineral reserves earlier (Schulz et al. 2017; Nassar et al. 2020). Early research on supply chains of critical minerals focused on responding to crises caused by resource supply shocks.

From the beginning of the twentieth century to 2015 was a period of "global allocation and division of labor" in the supply chains of critical minerals. Countries determined their roles and division of labor in the global value chains of critical minerals based on their resource endowments and comparative advantages (Lin 2011). For example, China has rapidly achieved coverage in the whole chain of critical minerals by taking advantage of its industrial and human capital.

From 2015 to the present, the period is the third critical minerals supply chain security stage. Taking the Trump administration's "List of Key Mineral Resources" as the node, the global division of labor in the supply chain of crucial minerals shifted from "comparative advantage" to "autonomous control." From the Trump Administration's Federal Strategy for Ensuring the Safe and Secure Supply of Critical Minerals to the Biden Administration's 100-Day Comprehensive Assessment of the Executive Order on Supply Chains and the E.U. 2050 Raw Materials Vision's roadmap for the development of the entire supply chain, countries have expanded their security strategies for critical minerals from upstream resource acquisition to the whole supply chain (Schulz et al. 2017). The EU, Japan, and the UK have adjusted or built their national supply chain strategies and established international supply chains to adapt to the new trend of global industrial competition in the post-epidemic era.

The USA has been working on the supply chain security of the critical minerals chain for a long time. Examples include the *Strategic and Critical Materials Stockpile Act* of 1979, *the Strategic and Critical Minerals Act* of 1990, and *the U.S. Minerals Security Act of 2015: the National Defense Stockpile Program (NDS)*. The Trump Administration released the *Federal Strategy for Ensuring the Security and Reliable Supply of Critical Minerals* and *Addressing the Threat to Domestic Supply Chains from Critical Minerals Dependent on Foreign Adversaries and Supporting Domestic Mining and Processing Industries*. Both documents focus on the concept of "critical minerals," i.e., mining, mineral processing, and related metal products or compounds, in the context of critical minerals security. The Biden Administration released the *100-Day Comprehensive Assessment of the Supply Chain Executive Order*. In this document, "Critical Minerals" was replaced by "Strategic and Critical Materials." "Strategic and Critical Materials" is broader in scope and includes downstream products and materials produced outside of mining activities (e.g., carbon fiber). The US government views Strategic and Critical Materials and its supply chain as the cornerstone of value-added manufacturing and the development, production, delivery, and sustainment of essential services fundamental to ensuring the future of US global economic, technological, and military leadership. Critical minerals supply chain security is not a single issue of diversifying and sustaining ore supplies but a comprehensive supply, technology, politics, and trade competition. We need to develop a "whole chain" mindset.

The reverse globalization brought about by the new crown epidemic has dealt a severe blow to the global division of the labor system based on trade liberalization (Vidya and Prabheesh 2020). Global supply chain reshaping has become a clear trend in developing the world economy (Butt and Shah 2020). Many countries and economies have formulated new industrial development plans or adjusted their existing programs to adapt to the latest global trade pattern. The EU and Germany adopted a draft Supply Chain Act in 2022 with a strong sense of "protective measures." In August 2020, Japan, India, and Australia launched the Supply Chain Resilience Initiative (SCRI), which explicitly identifies alternatives to reduce dependence on Chinese supply chains in key areas. Table 1 provides a selection of international key mineral alliances.

Table 1 International critical mineral alliances

Alliances	Time	Countries	Aim
European Raw Materials Alliance (ERMA)	2020	E.U	The Alliance addresses the challenge of securing access to sustainable raw materials, advanced materials, and industrial processing know-how
Supply Chain Resilience Initiative (SCRI)	2020	India, Japan, Australia	Counter China's dominance of the supply chain in the Indo-Pacific region
Five Eyes Critical Minerals Alliance (FVEY CMA)	Preparation	USA, UK, Canada, Australia, New Zealand	Strengthen cooperation in resource intelligence, mining finance, and technical expertise; develop integrated, secure, stable, sustainable, reliable, and resilient mineral supply chains critical to national and economic security; and reduce import dependence on China for these minerals
Energy Resource Governance Initiative (ERGI)	2019	Australia, Botswana, Canada, Peru, USA	Share and strengthen best mineral development practices, from mapping mineral resources to mine closure and reclamation
Critical Minerals Mapping Initiative	2020	USA, Australia, Canada	Build a diverse coalition of critical mineral supplies. Identify new sources of supply by mapping critical mineral potential by better understanding known mineral resources and determining the geological control of key mineral distribution by deposits producing byproducts

The discussion on the connotation of critical mineral supply chain security is still in the development stage, with blurred boundaries, unclear nodes, and poor logic. To scientifically define the purpose of strategic supply chain security, we need to accurately grasp the contemporary background of global industrial change and geopolitical evolution. Several key issues need attention: (1) the irreversibility of the new round of global industrial structural change and the fundamental role played by critical minerals in it; (2) the role played by countries in the global supply chain of critical minerals; (3) the challenges faced by the global division of labor allocation system of critical minerals under the global industrial change and technological revolution.

Critical minerals supply chain security assessment

Security risk evaluation object

There are a large number of institutions and scholars to assess critical minerals, such as the National Research Council (National Research Council 2005) and the European Union Communication (2011, 2017), Graedel et al. (2012), and Nassar (2017). However, the main focus is on the security of the supply of critical minerals. For example, the EU determines the critical minerals inventory based on the economic importance index, supply risk index, and environmental risk index (E.C. 2011). The US Geological Survey measures the country's critical minerals risk based on three indicators: indirect trade dependence, embedded trade dependence, and foreign ownership of mineral assets and operations (USGS 2020). However, relatively few studies have analyzed the security of critical minerals from a "chain-wide" perspective of the critical minerals supply chain. In particular, macro-level theoretical guidance is lacking (Helbig et al. 2016). The struggle over the security of critical mineral supply chains concerns the sustainability of primary resource supply and the whole life cycle of high-tech industries from birth to the cradle (The White House 2021). Take the lithium battery industry as an example. Although China lacks cobalt reserves, it has a total share in global purification and smelting technology (Chen et al. 2019). It still poses a security threat to its cobalt metal supply chain (Fig. 1).

We have reviewed the strategic layout of "critical minerals" and significant countries' supply chain policy guidance. Evaluating the critical minerals supply security has shifted from absolute resource acquisition at the upstream end to supply chain control at the downstream application end. The Trump Administration's "*Assessment and Strengthening of the U.S. Manufacturing and Defense Industrial Base and Supply Chain Resilience*" has extended the concept of critical minerals security to the whole supply chain of "exploration, mining, beneficiation, separation, metallurgy, and

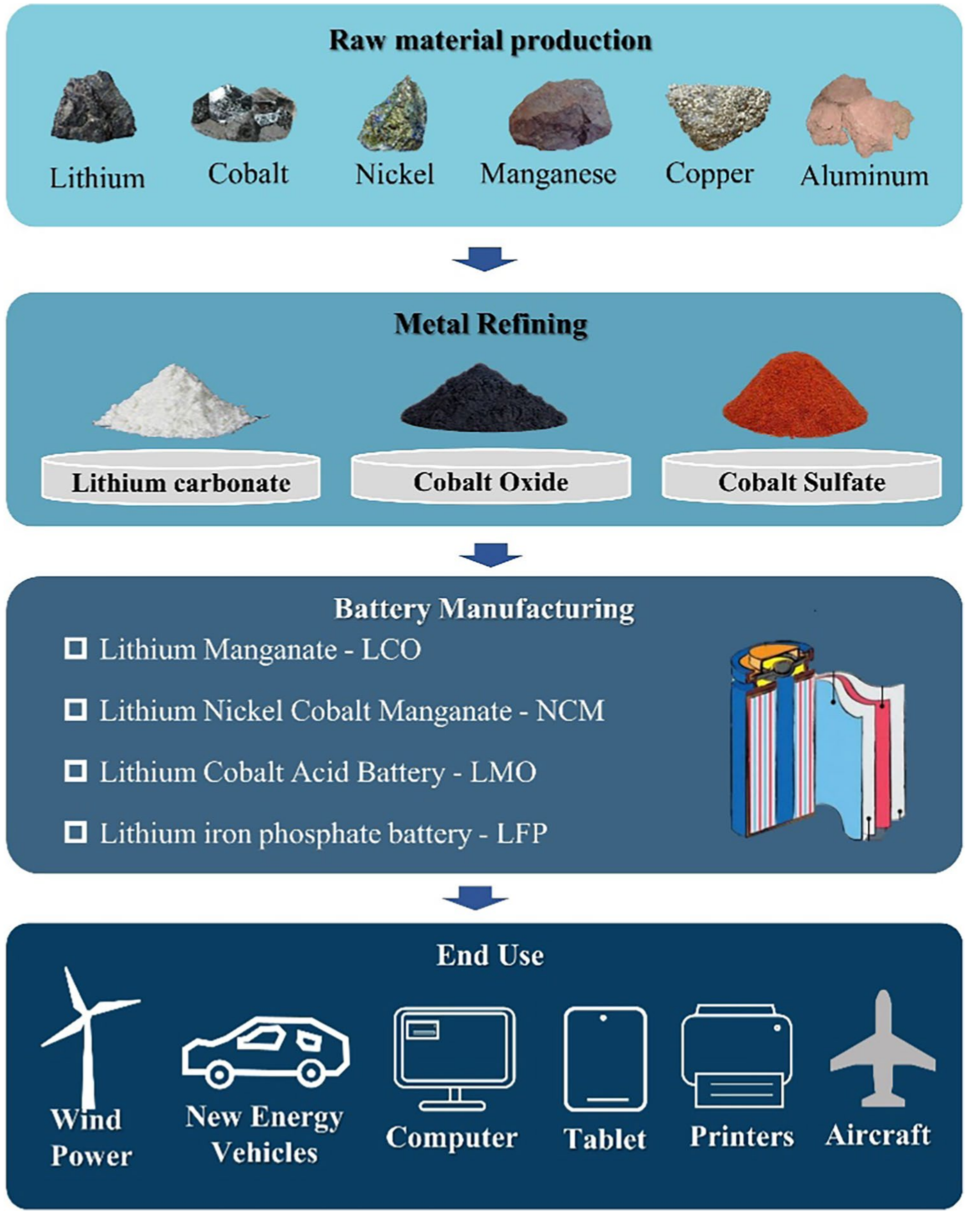

Fig. 1 Lithium battery-based supply chain (DOE Vehicle Technologies Office, VTO)

recovery," i.e., critical minerals security in a broad sense. There are several essential points of the evaluation of the security of the supply chain: (1) establishment of complete life cycle evaluation from extraction to recovery; (2) dual combination of hard security guarantee of resource acquisition and soft security guarantee of technological intellectual property downstream of resources; (3) evaluation principle from application-oriented perspective. We have to base on the global trend of industrial technology change and be oriented toward developing the high technology industry.

Security risk evaluation methods

The critical minerals are the cornerstone of modern technology industry development. The essential security of mineral supply chains is a mandatory area of contention for major powers. The traditional risk response model targeting mineral resource security only emphasizes the stability of mineral resource supply (Anderson 1988; Ray 1984). Under the global division of labor model, trade liberalization following the theory of comparative advantage has seriously challenged this security principle based on the concept of stability of mineral resource supply. Mineral resource supply risks are related to the availability of mineral resources supply and security in the production field. They are closely related to economic, social, environmental, and even political impacts (Hatayama and Tahara 2015). The separation of critical mineral minerals extraction, purification and processing, and back-end application links complicates the evaluation of supply chain security of key mineral chains.

At present, there are two main technical paths to evaluate the security risk of critical mineral supply chains. One is the "Mineral Commodity Net Import Reliance (NRI)" by the US Geological Survey, which visually demonstrates the dependence of the country's critical minerals on foreign countries, the fragmentation of supply sources, and the toughness of the supply chain (Galos et al. 2021). Compared with the evaluation index system that integrates multiple elements, objectives, and dimensions, the technical route of supply chain security evaluation represented by NRI avoids the interference of subjectivity in policy decisions to the greatest extent.

Secondly, use the system of indicators to assess critical mineral supply risks. With the development of technology and increased data availability, the evaluation system study has emerged as a multi-factor, multi-objective, and multi-dimensional feature (Galos et al. 2021; Achzet and Helbig 2013). The evaluation system can integrate indicators of multiple dimensions and combine geopolitical, economic structure, resource endowment, technology level, and other elements, which are more comprehensive to a certain extent than the NRI evaluation method. Zhou et al. (2020) sorted out the major domestic and foreign critical mineral security evaluation indicators. They summarized China's critical mineral security into three subgoals: global resource supply stability, domestic resource economic security, and optimal coexistence. Yu et al. (2021) assessed China's critical mineral security from four aspects: resource accessibility, economic relevance, technological capability, and import instability set the critical mineral security faced by China. From domestic and international research trends, the research on the supply chain security of critical minerals is still focused on mineral acquisition, mainly on the influence of economic, political, technological, and geological factors on the addition of critical minerals. There is a lack of research on the security of the whole supply chain of "exploration, mining, beneficiation, separation, metallurgy and recovery" and even the security issues posed by the technology property rights barriers attached. Take the patents of the whole rare earth industry as an example, China's patent advantage is concentrated in the middle-end of the chain, while Japan, the USA, Korea, and the EU hold the patent advantages in the upstream and downstream of the supply chain (Leng et al. 2021). However, the risks posed by such industry-wide technical barriers are not reflected in the traditional safety evaluation system for critical minerals.

Global value chain accounting for critical minerals

Global value chain accounting for mineral resources

The original concept of supply chain comes from the masterpiece of American management scientist Porter's "Competitive Advantage," in which supply chain and value chain are "two sides of the same coin" (Poirier and Reiter 1996). Under the model of global trade liberalization and regional comparative advantage division of labor, the supply chain of critical minerals is globally dispersed. Any strategy to seek the security of the supply chain of the country's critical minerals has to be based on a deep understanding of the global value chain of critical minerals. The US Geological Survey has accumulated many global geological intelligence data on critical minerals. It has produced some results in the primary mineral production of critical minerals. Arroyo (2020) assessed the position of countries within the Association of Southeast Asian Nations (ASEAN) and the Pacific Alliance (P.A.) in the global value chain of critical minerals. Mudd (2021) analyzed the application of associated critical minerals in new technologies globally. Werner et al. (2020) evaluated 1512 indium mine resources globally on a case-by-case basis. Swain et al. (2020) analyzed the role of rare earth and other metal resources in red mud in the global critical minerals value chain. Bam and Bruyne (2017) attempted to elaborate the rationality of the global locational layout of mineral value chains using global value chain (GVC) and global production network (GPN) analysis under the new economic geography (NEG) theory. Schlör et al. (2018) used the social life cycle assessment model (sLCA) based on the Social Hotspot Database (SHDB) to assess the position of Australia, the USA, and China in the global value chain of the rare earth industry and the respective social risk costs. Machacek and Fold (2014) depicted the global value chain of rare earth elements and described the strategies of three UK rare earth element deposit developers.

Analysis of critical mineral reserves, production, and import/export trade can obscure much information, such as critical mineral flows hidden in indirect and embedded business (Nassar et al. 2020). Smelting and purification will change the form of the mineral product and result in the mineral being classified under a different customs code. The source of the minerals mined will not be easily identified. Instead, some mineral commodities from different countries will be embedded in imported finished and semi-finished products. For example, neodymium and other rare metals are imported as permanent magnets. Few studies have examined the dependence on embedded trade. Johnson and Graedel (2008) examine "end-user net import dependence" for the USA, including ores, concentrates, refined forms, semi-finished products, and metals contained in five mineral commodities (chromium, copper, lead, silver, and zinc). Johnson and Graedel (2008) find that net margins for end users are higher than those for raw forms (ore, concentrate, and refined forms). Input–output models may be a possible way to address these issues. Xudong Sun et al. (2021) explored interregional supply chains for China's mineral resource demand in 2012 through multi-regional input–output and structural path analysis. Material flow analysis is another important technical tool in assessing critical minerals' global value chain assessment. JOGMEC (Japan Oil, Gas, and Metals National Corporation) conducted an annual material flow analysis survey of 40 minerals, including copper, lead, zinc, and gold in 2005. Jiali Song et al. (2019) used material flow analysis of strategic metals in China's lithium battery value chain. Koji Tokimatsu et al. (2017) developed a mineral resource balance model to simulate the supply and demand of critical minerals in different scenarios with a simplified material flow and inventory structure throughout the chain from mining, smelting, refining, and recycling. Rasmussen et al. (2019) developed a dynamic material flow analysis model that describes global platinum demand over the period 1975 to 2016. In summary, compared to traditional supply security evaluation studies, global value chain accounting for critical minerals requires the establishment of an objective, fully quantified, and predictable international division of labor network in the supply chain of critical minerals industry.

Critical minerals global value chain division of labor system

Traditional critical minerals security research has focused on primary mineral acquisition (Herrington 2013). The critical minerals supply chain concept includes prior minerals acquisition, immediate processing, purification and refining, and product application. The new connotation is more in line with the definition of "non-traditional security risks" under the national security concept (Dyatkin 2020). Compared with traditional resource supply risks, critical mineral supply chain security is characterized by three aspects: potential and suddenness, linkage and transmission, and global and developmental. The global economic general circulation model with Europe and the USA as the financial R&D and consumption centers, China as the production and manufacturing center, and some resource and energy powers as the resource goods export centers also basically fits the position of each economy in the global critical minerals division of labor system. In the case of high-density batteries, for example, the critical metals lithium, cobalt, and graphite supply chains are subject to regional concentration, geopolitical instability and risk, and competitive market growth (Alonso et al. 2012). China dominates the battery global value chain from refining to downstream battery manufacturing but is significantly inferior to Europe and the USA regarding technology and patent reserves on the application side (MINING.com 2020; Ballinger et al. 2019).

Reverse globalization has intensified critical mineral supply chains' localization, regionalization, and ideologization. The global comparative advantage division of labor system established under the free trade system has been seriously challenged. The global value chain pattern of critical minerals is facing reshaping. The Biden Administration's 100-day Comprehensive Assessment of the Supply Chain Executive Order clearly states that supply chain security partnerships within the Five Eyes Alliance (FVEY) are low risk. R&D funding support, policy subsidies, and international supply chain alliances are widely used. The return of manufacturing associated with critical minerals has accelerated. For example, India's P*roduction-Linked Incentives (PLI)*, Finland's "*National Battery Strategy 2021*," and the EU have set up special funds to support the development of the battery materials sector. Based on recent academic papers, newspaper commentaries, and national policies, there are several possible future changes in the division of labor in the global critical minerals value chain. (1) Inter-regional national key minerals alliances, such as the US-led Energy Resources Governance Initiative Alliance; (2) Technology alliances in key minerals value chains to create regional proprietary technology barriers (Dessemond et al. 2019); (3) "green trade barriers" and "labor human rights barriers" in key minerals value chains (Qurbani et al. 2021); and (4) " Re-shoring." The transfer of high-risk segments of the chain to home countries or allies (Bacchetta et al. 2021).

Critical mineral supply chain risk identification and response

Critical mineral supply chain risk identification

The new pneumonia epidemic is spreading around the world. Trade protectionism and counter-globalization have risen. The impact of uncertainty shocks on global supply chains has increased significantly. The pattern of the worldwide division of labor and collaboration in critical mineral supply chains is facing profound challenges. There is an urgent need to establish a risk assessment and monitoring system for critical mineral supply chains to identify the hidden dangers. Critical mineral supply chain risk assessment is mainly based on single-factor analysis, such as assessing the security of primary minerals supply, analyzing COVID-19 impact on the global industry chain, and assessing the supply of critical metals from national industrial and trade policies (Gavin 2015; Zhu et al. 2021). These studies can be summarized into two points: raw material supply risk and supply chain vulnerability (Graedel et al. 2012, 2015; Helbig et al. 2016).

However, there is still a lack of research to integrate the whole chain of "exploration, mining, beneficiation, separation, metallurgy, and recovery" of critical minerals and combine the production capacity of products and technical support capabilities. The global critical minerals industry and supply chain have developed into a complex network through the tough international division of labor and free trade. Each country has its weight and role as the global vital minerals production and supply network node. In the worldwide allocation of critical minerals, there is a fundamental principle for an optimal solution, either based on the priority of economic efficiency, based on the importance of national security or considering a group of countries (The White House 2021). The optimal solution for the global allocation of critical minerals changes dynamically under different circumstances. In summary, several key issues must be addressed in risk assessment and monitoring studies of critical mineral supply chains. (1) The target of assessment. Is it the security of supply of a single element or the continuity of the whole chain supply chain; (2) the purpose of the assessment? Is it to maximize economic benefits or ensure financial security; 3) the assessment scale? Is it a question of deterring the development of rivals or ensuring the country's position as a core node in the global strategic mineral supply chain network?

Another critical issue in the security of the critical minerals supply chain is the demand of other countries in the global allocation network of critical minerals. After the international financial crisis, developed countries have implemented the "re-industrialization" strategy to reshape new competitive advantages in manufacturing. This accelerates a new round of global trade and investment patterns. Some developing countries are also speeding up the planning and layout to actively participate in the global industrial redistribution of labor. By undertaking industrial and capital transfer, they will expand international market space. As a global production and manufacturing center, China has to ensure the stability of the supply of primary mineral products in the upstream resource section and climb up to high value-added products in the downstream application end. Countries like Australia, Brazil, and South Africa are building up their primary mineral processing capabilities to localize the "mining-separation-metallurgy" process as a resource export center. The global financial and technological powers, represented by Europe and the USA, are reducing the risk of single-source countries for critical minerals through a decentralization strategy on the one hand and securing their technological hegemony in high-tech fields through continuous capital investment on the other. Cooperation and competition coexist among various nodes in the global critical mineral allocation network. In the study of critical minerals supply chain risk identification, shifting the assessment perspective from a single country perspective to a global network perspective is conducive to improving the macro-control of the assessment. The trend of globalization is unstoppable, and the international division of labor system following comparative advantage is still the mainstream of development, regardless of whether the game of significant countries forms a new situation of global equilibrium or regional equilibrium.

Critical mineral supply chain resilience

The global critical minerals supply chain division of labor pattern faces structural changes. There is an urgent need to enhance the resilience of the critical minerals value chain by reshaping the global key minerals supply chain system. Factors affecting the strength of critical minerals supply chains include supply, geopolitical patterns, modernization of supply chains, and global governance (Jane 2021; Kalantzakos 2020).

The security of crucial minerals and primary minerals available is the basis of modern industrial development. Many critical minerals are distributed in politically unstable and economically underdeveloped countries, with an excellent supply security risk, such as cobalt, tantalum, and lithium. Both bulk minerals (e.g., copper, aluminum) and high-tech minerals (e.g., cobalt, lithium) are at risk of high concentration in supply countries (Zhang et al. 2021). Decentralizing critical mineral supply sources through a decentralization strategy is vital to addressing factor supply (Althaf and Babbitt 2021). By constructing a complex international tin ore trade network, Xia (2021) finds that global tin ore is highly homogeneous on both the supply and trade sides and vulnerable to external shocks. How to decentralize the supply of critical mineral elements is one of the difficulties in improving the resilience of essential chains of mineral and supply chains.

The geopolitical landscape has constantly threatened the security of strategic critical mineral resources. The impact of the three "oil crises" of the second half of the twentieth century on the global economic and political landscape and energy mix continues to influence international development today. In Africa, the volatile political situation limits investment in critical minerals and poses a significant threat to the fragile supply chain of critical minerals (Silva and Schaltegger 2019). With the establishment of global alliances in regional supply chains of critical minerals, the cost risk of the free flow of critical minerals in global trade networks has increased significantly. New theories and methodologies are needed to identify and assess the coercion of geopolitical risks to the resilience of critical minerals supply chains.

The level of modernization of supply chains affects the security of critical minerals. Taking China as an example, as a global manufacturing center, China dominates the middle-end of the critical minerals value chain, such as mineral purification, refining, and primary manufactured metal products. However, with high added value at the downstream application end, China's entire industrial system is still in a catch-up mode. China's critical minerals remain insecure from a chain-wide perspective of the industrial supply chain

(Gulley et al. 2019). In the global critical minerals network, China has an essential but unnecessary node position and faces the threat of "import substitution" and "technological barriers" from rival countries at any time.

The competition for, exploitation, utilization, and possession of key minerals has been a focal point in the world's political and economic development (Gulley et al. 2018). With the advent of new technological revolutionary changes, the exponential increase in demand for critical minerals is bound to stimulate global competition. There is an urgent need to establish a global-level governance system to maintain the global critical minerals network (Ali et al. 2017).

National strategy for critical mineral supply chain

Technological and industrial changes are accelerating the reshaping of the international industrial division of labor. Countries have adjusted their industrial structure and increased innovation efforts to seize the high-value-added links of the global manufacturing value chain. The critical minerals supply chain is essential to modern industrial infrastructure capability. It is a crucial link that restricts the national manufacturing industry's innovative development and quality improvement. The global competition for critical minerals presents new trends. (1) from primary mineral resources acquisition security, spread to the whole chain and supply chain; (2) from primary bulk minerals and energy competition to the development of high-tech minerals; (3) from national resources and energy acquisition to the group and regional inter-state organization evolution. Changes in the international economy and trade patterns have exacerbated the risk of national access to critical minerals.

Build the global mineral rights protection mechanism and risk warning system. Critical mineral acquisition faces serious overseas risks under the worldwide division of labor model of the critical mineral value chain. The main threats include resource foreign dependence, fundamental process dependence, and overseas mineral resource assets and business security (Xing et al. 2017; Oskarsson and Lahiri-Dutt 2019). COVID-19 shocks and global industrial restructuring have exacerbated the risks of overseas access to critical minerals. The supply of critical minerals faces the twin challenges of trade protectionism and resource nationalism (Marmolejo Cervantes and Garduño-Rivera 2021; Pryke 2017). Western power blocs control global mineral resources (i.e., appropriation, production, trade, prices, and consumption) through various means, including financial, technological, and industrial standards. This has seriously affected critical minerals' industrial, supply, value, and investment chains in emerging economies. There is an urgent need to establish a multi-factor, multi-objective, and multi-dimensional overseas interest protection and risk warning and prevention system (Wang et al. 2020).

Emerging economies should reduce technological dependence on developed economies by improving their innovation capabilities. Technology is fundamental in exploring, extracting, smelting, and applying critical minerals. Emerging economies must drive changes in the global critical minerals landscape from both the supply and demand sides (Krajnc and Glavič 2005). The porphyry theory of copper mineralization has significantly increased the global metallic copper resource reserves. The development and application of bioleaching technology have increased the mineral economic value of poor ores, tailings, and waste ores. The bio-oxidation process increased gold production in the USA by about 30% (Ibrahim and El-Sheikh 2011; Johnson 2014). Separation and extraction technology of rare earth elements from coal gangue and coal ash has eased the supply of critical minerals. The US Department of Energy (DOE) launched ten projects to extract rare earth elements from coal and its byproducts in 2016 (USGS 2020). Emerging economies must improve the technology in their critical mineral value chain links (Guerin 2020).

Global governance regulates the international order of critical mineral supply chains. Global bulk mineral resources are becoming increasingly "financialized." The pricing power of international bulk minerals is greatly influenced by futures trading. For example, the London Metal Exchange of the New York Mercantile Exchange sets the prices of crude oil, coal, aluminum, copper, lead, tin, and other energy resources (Wilson and Vencatachellum 2021). Global production capacity for highly technical minerals is monopolized by multinational mining giants, such as BHP Billiton, Rio Tinto, and Vale. Developed countries continue to strengthen their dominance in the supply chain through regional conglomerate alliances. Liberalization and fairness of critical trade-in minerals must be maintained by promoting global governance rules.

Research trends in critical minerals supply chain security

Connotation of critical mineral supply chain security

There is no clear and unified definition for critical mineral supply chain security. Combining the strategic trends of significant countries and existing studies, we believe that the purpose of critical mineral supply chain security needs to focus on several aspects. (1) The ultimate goal is to ensure national economic security, defense security, and strategic emerging industries' development needs. It includes traditional energy minerals such as oil and gas, critical metal, and non-metal resources needed for strategic industrial development, and rare earth and rare mineral resources necessary for developing high-tech industries. (2) It needs to cover the supply chain of "exploration, mining, beneficiation, separation, metallurgy, and recovery." The study is not limited to the acquisition of primary minerals. (3) Attention should be paid to the foreign dependence on primary minerals and indirect trade dependence, embedded trade dependence, and foreign ownership of overseas minerals. (4) The concept of crucial mineral supply chain security is not limited to the security of primary mineral supply in a narrow sense. It must include technology supply security, trade flow security, and environmental and human rights issues. (5) The issue of critical minerals security is a comprehensive competition among countries involving industrial structure, technology level, geopolitics, trade strategy, and global governance. We believe that critical minerals supply chain security can be understood as the extensive use of multi-dimensional means such as politics, economics, technology, and global governance in the global critical minerals value chain network. Integrate the domestic supply chain system. And actively promote the development of global governance rules for critical minerals to ensure the country's role in the critical minerals supply chain network.

Critical mineral chain and supply chain security evaluation

Critical minerals security is the security of the whole supply chain links. This security concept includes the security and control of primary mineral supply, the autonomy and control of process technology across the supply chain, and the climbing of the value chain of critical minerals. The expansion of the concept of supply security resulted from the global industrial revolution and economic structural changes. The traditional mineral security evaluation system can hardly meet the requirements of this multi-factor, multi-objective, and multi-dimensional national strategy (Glöser et al. 2015; Achzet and Helbig 2013).

The traditional mineral security evaluation system focuses on primary mineral supply security. It lacks consideration of the overall competition between countries and regionalization and localization of supply chains. Subject to the problems of regional heterogeneity and dynamics, the localization characteristics of the existing resource security evaluation mechanism are apparent. This evaluation mechanism is challenging to adapt to the standardization of global evaluation. The critical mineral supply chain emphasizes the comprehensiveness of competition. The purpose of security evaluation of strategic mineral supply chains is to serve national strategic decisions and layout. The existing security evaluation model is challenging to meet the requirements of the new development goals. There are many challenges to establishing a new mechanism that meets the global security rating of critical mineral supply chains. (1) It is difficult for a single indicator to address the multi-factor, multi-objective, and multi-dimensional challenges facing the security of critical mineral supply chains. (2) The indicator system lacks a global perspective. (3) The evaluation results are disconnected from the actual issues of international development.

National strategy of critical mineral supply chain security

The critical minerals chain and supply chain is a complex system combining economics, politics, technology, and trade. A quantitative assessment model based on four categories of criteria: affordability, availability, accessibility, and acceptability, is challenging to meet the new challenges of critical mineral security. We need to integrate resource, economic, political, environmental, and technological elements and explore the security strategy of the critical minerals supply chain from the perspective of the whole value chain. The current problems in the critical minerals supply chain are medium to long term. Many have not been experienced before, which requires deepening understanding and effective response from a strategic perspective. Formulating national strategies for critical minerals should go beyond the traditional thinking of security evaluation. Decision-makers need to consider primary mineral supply, process technology property rights, geopolitical landscape security, and environmental and human rights issues in an integrated manner. They need to identify the risk points in the supply chain network from the perspective of the complex system, and propose targeted solutions from a national strategic level.

Author contribution All authors contributed to the study conception and design.

Dou Shiquan: writing—original draft preparation, conceptualization.

Xu Deyi: article proofreading, discussion.

All authors read and approved the final manuscript.

Funding The research was supported by the Major project of the National Social Science Foundation of China (No. 21&ZD106).

Availability of data and materials All data generated or analyzed during this study are included in this published article (and its Supplementary information files).

Declarations

Ethical approval Not applicable.

Consent of the participant Not applicable.

Consent for publication All authors contributed to the research. They agreed to publish this research in Environmental Science and Pollution Research Journal.

Competing interests The authors declare no competing interests.

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