GOSPODARKA SUROWCAMI MINERALNYMI – MINERAL RESOURCES MANAGEMENT

2026 Volume 42 Issue 3 Pages 173–194

DOI: 10.24425/gsm.2026.6008

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Evolution analysis of the global lithium industrial chain trade network: based on the event-shock complex network method

Introduction

Lithium is the lightest metallic element. Owing to its physical and chemical properties such as low density, high hardness, high melting point, and strong reactivity, it is widely used as an industrial raw material in the production of greases, glass, ceramics, and other products (Rincón et al. 2025). Since 2000, however, the expanding market for lithium batteries in mobile information and communication technologies has brought lithium into greater prominence. After 2015, driven by the rapid development of electric vehicles and new-generation information technology, lithium has found increasingly extensive applications. Meanwhile, replacing fossil fuels with clean energy serves as a core approach to carbon emission reduction (Sun et al. 2025; Zheng et al. 2025). As a vital raw material for clean energy, lithium is known as the "green high-energy metal" and "white oil" of the 21st century, with its strategic importance continuously rising (Kong and Zhang 2022;

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Bai et al. 2024). Major global economies including the United States, the European Union, Japan and Australia have officially listed lithium as a critical mineral resource. Global lithium resources are unevenly distributed and highly concentrated in a small number of countries. Accordingly, the global lithium industrial chain is highly dependent on the political stability, economic policies, and natural conditions of these nations, and shocks from any major event may exert profound impacts on global lithium trade (Craig-Scheckman and Moore 2025). The lithium trade chain covers multiple links, ranging from ore mining, smelting and processing to finished product sales and transportation. Disruptions in any single link can trigger a chain reaction throughout the entire industrial chain trade system (Kong et al. 2024). Characterized by high globalization and structural complexity, the global lithium industrial chain exhibits prominent vulnerability when confronted with event shocks (Wang et al. 2025). Therefore, scientifically understanding the evolutionary pattern of the lithium industrial chain trade network and identifying the impacts of event shocks on network evolution are essential to enhancing the trade resilience of the lithium industrial chain.

A comprehensive analysis of the international trade characteristics of the lithium industrial chain requires consideration of the intricate trade relationships among countries, an issue that can be effectively addressed by applying complex network theory. Complex network theory abstracts complex real-world systems, reflects the topological connections between individual agents within a system (Wang et al. 2015), reveals the evolutionary laws of network structures (Hao et al. 2013; Man and Ren 2015; Dong et al. 2016), and enables a clearer and more comprehensive characterization of research objects. Groundbreaking progress was achieved in complex network theory at the end of the 20th century. Inspired by sociologist Granovetter (1985), Arthur et al. (1997) and other scholars argued that real economic systems possess the inherent attributes of social networks and can be investigated through social network analysis. In 1998, Watts (1998) proposed the small-world network model. In 1999, Barabási (1999) put forward the BA network model, namely the scale-free network, whose node degree follows a power-law distribution. Serrano et al. (2003) introduced the complex network analysis method into the research on global trade networks and verified that international trade networks feature small-world and scale-free properties. Since then, a growing number of scholars have adopted complex network theory to explore the evolution of trade patterns. Existing studies have investigated the trade network structural characteristics and evolutionary rules of agricultural products (Chen and Feng 2017), high-tech goods (Zhou et al. 2023), rare earths (Zhuang et al. 2022), fossil energy (Liu et al. 2020; Ye et al. 2022; Wang et al. 2023b) and other commodities, unanimously confirming that complex network theory is highly applicable to the analysis and optimization of product trade networks. Relevant research has also been conducted on mineral resource trade networks, with abundant literature focusing on iron (Hao et al. 2013; Yu et al. 2022), copper (Zhang et al. 2015; Hulianskyi 2025), chromium (Ling et al. 2024), rare earths (Yi et al. 2024), nickel (Wang et al. 2023a; Chen et al. 2025), cobalt (Yu and Ding 2021; Sun et al. 2022; Zhu et al. 2022; Hu et al. 2026) and other mineral commodities. In recent years, trade network analysis has gradually been introduced into research on lithium resources and lithium product trade. Nevertheless, most existing studies focus only on a single segment of the lithium industrial chain, while systematic research on the trade pattern evolution of the entire lithium industrial chain remains insufficient. For instance, Zhu et al. (2022) analyzed China's controlling power in the international trade network of lithium hydroxide; Shao et al. (2022) adopted scenario analysis to quantify the impacts of low-cobalt lithium battery technology on global cobalt and lithium trade networks; Chen et al. (2020) and Zhang et al. (2025) explored the evolutionary characteristics of trade communities for global lithium carbonate and lithium hydroxide; Yang et al. (2021) and Chen et al. (2025) focused on the optimization of lithium resource allocation in the lithium-ion battery industry. In this context, it is of great theoretical and practical significance to analyze the spatial-temporal patterns and evolutionary characteristics of the global trade network for core products across the whole lithium industrial chain. Currently, the world is in a period marked by frequent, sudden, and recurring risks. Various "black swan" events pose significant challenges to the global operational order. Sudden public health emergencies, regional conflicts, major-power competition, and extreme weather have directly or indirectly affected national resource trade (Wang et al. 2026). The impact of global major emergencies on international trade can be either passive and non-directional, or active and directional (Meng et al. 2025). However, such emergencies are often accompanied by structural shifts in global trade, exerting negative effects on trade stability. Therefore, the impact of event shocks must be taken into account when studying trade networks. Yet, no scholar has so far incorporated event shock factors into complex network models to quantify the impact of sudden events on trade network structure.

To fill the above research gaps, this study makes contributions in two major aspects. First, against the backdrop of the spatio-temporal evolution of trade networks, this paper comprehensively examines the global trade network characteristics of the full lithium industrial chain from multiple perspectives. By combining horizontal cross-country comparison and vertical comparison among industrial segments, it accurately captures the structural attributes, internal correlations, and overall features of the lithium trade network, thereby enriching and improving the theoretical framework for research on full lithium industrial chain trade networks. Second, this paper adopts the event-shock complex network method to explore the potential impacts of major events on upstream, midstream, and downstream trade of the global lithium industrial chain. Based on the intensity and direction of event shocks, it accurately captures changes in trade relationships. Integrating overall network features and individual node attributes, it summarizes the core characteristics and evolutionary laws of the lithium industrial chain trade network. The research findings provide valuable references for the formulation of global lithium trade policies, strategic industrial layout, industrial upgrading, and trade security governance.

1. Research data and methods

1.1. Data sources

This study mainly focuses on the product chain within the industrial chain. From the perspective of product production, it investigates the links of the industrial chain ranging from natural resources and intermediate products to final consumer goods (Tian et al. 2021; Shao et al. 2021). The lithium industrial chain forms a complete and systematic structure covering lithium resource extraction, processing, product manufacturing, and terminal consumption. Referring to the classification criteria proposed by Xing (2022) and Wang (2023b), the lithium industrial chain is divided into three segments: upstream, midstream, and downstream. The upstream refers to lithium resource extraction, covering primary lithium products extracted from lithium ores and salt lakes. The midstream mainly consists of processed lithium products, including industrial-grade lithium carbonate, battery-grade lithium carbonate, and deep-processed lithium carbonate derivatives. The downstream represents the application end of lithium products, covering terminal consumption fields such as consumer electronics, new energy vehicles, energy storage, glass and ceramics, and greases. To ensure data integrity, this study adopts the United Nations Commodity Trade Database as the data source for global trade data of lithium-containing products. After systematic sorting and screening, five commodity codes related to lithium products are selected. The upstream category covers lithium and other alkali and alkali; the midstream includes hydroxide and lithium carbonate; the downstream comprises cells and batteries and primary and lithium, as well as lithium-ion storage batteries. The product catalog and conversion coefficients for relevant units are presented in Table 1, with the conversion coefficients determined by the molar mass ratio of corresponding products (Sun et al. 2018; Chen et al. 2022). Discrepancies in data collection procedures and measurement standards lead to two major data problems: first, the trade value or volume between certain countries (regions) is recorded as zero; second, the import and export data between countries (regions)

Table 1. Conversion coefficients of products and relevant units in this study

Tabela 1. Współczynniki przeliczeniowe produktów i jednostek stosowanych w niniejszym badaniu

Industrial chain	HS Code	Product name	Conversion coefficient
Upstream	280519	Lithium, other alkali and alkali	–
Midstream	282520	Lithium oxide and hydroxide	0.165
	283691	Lithium carbonate	0.188
Downstream	850650	Cells and batteries; primary, lithium	1
	850760	Lithium-ion storage batteries	1

i and countries (regions) j are inconsistent in bilateral statistics. For the first issue, invalid bilateral trade records with zero values are eliminated. For the second discrepancy caused by differentiated statistical caliber across economies, the average value of the two sets of data is adopted for unified processing. After data cleaning, conversion, and standardization of import and export records, four cross-sectional years – 2010, 2015, 2020, and 2025 – are selected to depict the evolutionary process of the global lithium resource trade network.

1.2. Research methods

(1) Construction of trade network

Major global emergencies are often accompanied by changes in the global trade structure, which accelerate the withdrawal of certain trading countries, weaken trade linkages between economies, and lead to a continuous increase in trade barriers. Beck (2024) argued that factors influencing international trade fall into natural factors and human factors. Natural factors include variables with no significant short-term fluctuations, such as economic scale, geographical distance, and population size; human factors refer to variables highly susceptible to short-term policy adjustments, including bilateral relations, regulatory constraints, exchange rate fluctuations, and others. This study introduces the Event Impact Factor (EIF) to quantify the influence of unexpected events on the structural evolution of trade networks. The specific formula is as follows:

$$EIF_t = \sum_{i=1}^{n} w_i \frac{\left|X_{i,t} - X_{i,t-1}\right|}{X_{i,t-1}} \tag{1}$$

$$w_{i,t} = w_{i,t-1} \cdot \left(1 + EIF_t \cdot \frac{w_i}{w_{total,t}}\right) \tag{2}$$

↳ EIF_t – event impact factor in period t,

w_i – weight assigned to the i-th type of event based on the Analytic Hierarchy Process (AHP),

$X_{i,t}$ and $X_{i,t-1}$ – trade value related to the i-th type of event in period t and period t–1, respectively,

$w_{total,t}$ – total global lithium ore trade volume in period t.

Establishing a complex network model centered on event shocks can effectively characterize the actual features of trade patterns. Following the standard construction paradigm of complex networks, this paper takes countries (regions) as network nodes and constructs an $N \cdot N$ matrix for the global lithium product trade network:

$$W_{i,t,p,q} = \begin{bmatrix} w_{i,t,1,1} & w_{i,t,1,2} & \cdots & w_{i,t,1,n} \\ w_{i,t,2,1} & w_{i,t,2,2} & \cdots & w_{i,t,2,n} \\ \cdots & \cdots & \cdots & \cdots \\ w_{i,t,m,1} & w_{i,t,m,2} & \cdots & w_{i,t,m,n} \end{bmatrix} \tag{3}$$

$W_{i,t,p,q}$ – event-shock trade network of product i exported from country p to country q in period t,
$w_{i,t,p,q}$ – event-shock trade weight of product i exported from country p to country q in period t.

$$G_{i,t} = \langle V_{i,t}, E_{i,t} \rangle \tag{4}$$

$G_{i,t}$ – trade network graph of product i in period t,
$V_{i,t}$ – set of all participating countries (node set) in the trade network,
$E_{i,t}$ – set of relational connections (edge set) among trading economies for product i in period t.

(2) Construction of trade network indicators

This study adopts indicators including network density, average clustering coefficient, and average path length to describe the overall characteristics of the global trade network of the lithium industrial chain. These indicators help quantify the structural properties of the network, enabling further analysis of network tightness and transmission efficiency. Network centrality metrics can be used to measure whether each node occupies a central position within the network, further assessing the importance of nodes in the global trade network within trade chains and industrial chains, while also reflecting each node's capacity to access and control resources. This study selects betweenness centrality and eigenvector centrality as representative centrality indicators to characterize the country-level features of the global lithium industrial chain trade network.

Network density: Network density refers to the ratio of the actual number of edges in a network to the maximum possible number of edges. A higher network density indicates closer connections between nodes, and the network exerts a stronger influence on the attitudes and behaviors of participants (Kosztyán and Kosztyánné Mátrai 2025). This indicator reflects the trade closeness among all countries within the lithium industrial chain trade network. Its calculation formula is as follows:

$$D = \frac{m}{n(n-1)} \tag{5}$$

n – number of nodes,
m – actual number of edges contained in the network.

Average clustering coefficient: The average clustering coefficient is the average ratio of the actual edges between a node and its neighboring nodes to the maximum possible edges. It characterizes the agglomeration degree of network nodes. A value closer to 1 means a higher network agglomeration level and tighter node connections (Fehérvölgyi et al. 2024). This indicator reflects the trade intimacy between each country and its trading partners in the lithium trade network. The formula is expressed as:

$$C = \frac{1}{N}\sum_{i=1}^{n}\frac{E_i}{C_{K_i}^2} \tag{6}$$

E_i – actual number of edges between node i and its adjacent nodes,
K_i – number of neighboring nodes of node i,
$C_{K_i}^2$ – maximum possible number of edges,
N – total number of nodes.

Average path length: The average path length of a network is the average value of the shortest path lengths between any two nodes. It represents the transmission efficiency between nodes and the connectivity of the network (Watts and Strogatz 1998). A larger numerical value indicates lower transmission efficiency between nodes and poorer network connectivity. The calculation formula is:

$$L = \frac{1}{N(N-1)}\sum_{i,j} d(i,j) \tag{7}$$

N – total number of nodes,
$d(i,j)$ – shortest path distance between node i and node j.

Betweenness centrality: Betweenness centrality is a metric used to measure a node's coordination or control capacity within a network. It refers to the ratio of the number of shortest paths that pass through a particular node and connect two other nodes to the total number of shortest paths between those two nodes. A higher betweenness centrality indicates that the node plays a stronger bridging role in the network and has a greater potential to control other nodes (Freeman 1977). In a network with N nodes, the shortest paths between nodes p and q may pass through certain nodes. If node i is traversed by many of these shortest paths, it suggests that the node is highly important within the network. The formula for betweenness centrality is:

$$BC_i = \frac{1}{(n-1)(n-2)}\sum_{s,t\neq i}\frac{d_{st}(i)}{d_{st}} \tag{8}$$

d_{st} – total number of shortest paths between node s and node t,
$d_{st}(i)$ – number of shortest paths between node s and node t that pass through node i,
n – number of countries in the network.

Eigenvector centrality: Eigenvector centrality is used to measure the transmissive influence and connectivity between nodes, evaluating node importance based on the significance of its neighboring nodes. It holds that the importance of a node depends not only on the number of adjacent nodes but also on their respective centrality. Nodes with higher eigenvector centrality contribute more to the overall operation of the complex network (Freeman 1977). Its calculation formula is:

$$EC_i = x_i \frac{1}{\lambda} \sum_{j=1}^{n} a_{ij} x_j \tag{9}$$

x_i – importance measurement of node i,
x – centrality vector being the eigenvector of adjacency matrix A corresponding to eigenvalue λ,
λ – selected as the eigenvalue with the maximum absolute value of matrix A.

2. Result analysis

2.1 Evolution of the global lithium product trade network

In this study, Gephi 0.9.2 software is adopted to visualize the weighted directed trade networks of the upstream, midstream, and downstream segments of the lithium industrial chain in 2010, 2015, 2020 and 2025. In the trade network, countries are set as nodes, and bilateral trade connections between countries serve as edges. Larger and darker nodes indicate higher trade weights. Arrows denote trade directions, while thicker and darker lines represent more frequent trade between paired nodes.

The upstream trade network of the lithium industrial chain is shown in Figure 1. The results reveal obvious decentralization in upstream trade. The tripartite pattern dominated by the United States, Germany, and China in 2010 gradually evolved into a multipolar pattern involving the United States, Germany, China, India, the Netherlands, the United Kingdom, and South Africa by 2020. Breakthroughs in lithium extraction technologies such as salt lake lithium extraction and lepidolite lithium extraction have enabled more countries to participate in lithium resource development. Technological iteration has lowered industrial barriers and accelerated the exploitation of global lithium resources. Meanwhile, the rise of resource nationalism has driven various economies to pursue diversified import substitution

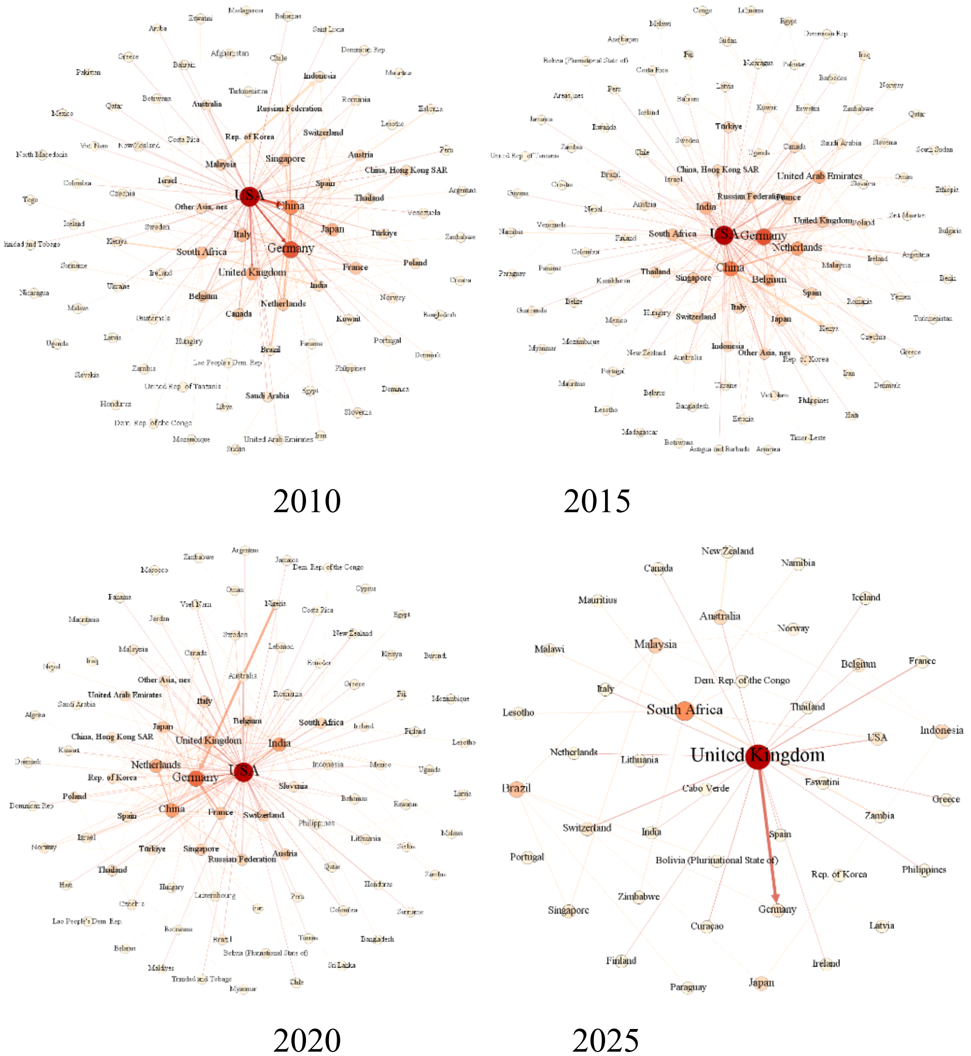

Fig. 1. Evolution of upstream trade network in lithium industrial chain

Rys. 1. Ewolucja sieci handlu na początkowych etapach łańcucha przemysłowego litowego

strategies, jointly leading to the decentralized characteristics of international trade in the upstream lithium industrial chain.

The midstream trade network of the lithium industrial chain is presented in Figure 2. The midstream sector shows a prominent trend of trade centralization. The tripartite competitive pattern of the United States, China, and Belgium in 2010 gradually centralized into a dual-core structure led by China and Germany, and eventually evolved into a dominant pattern with the United Kingdom as the core, making it a pivotal player in global midstream lithium trade. Benefiting from policy support and complete industrial chain advantages, China has grown into the world's largest new energy vehicle market. As Europe's largest economy, Germany boasts a sound chemical industrial foundation and mature trade networks, enabling both countries to become core production and processing hubs. Subsequently, relying on its superior trade hub status and strong market influence, the United Kingdom has secured a key position in the global midstream lithium trade.

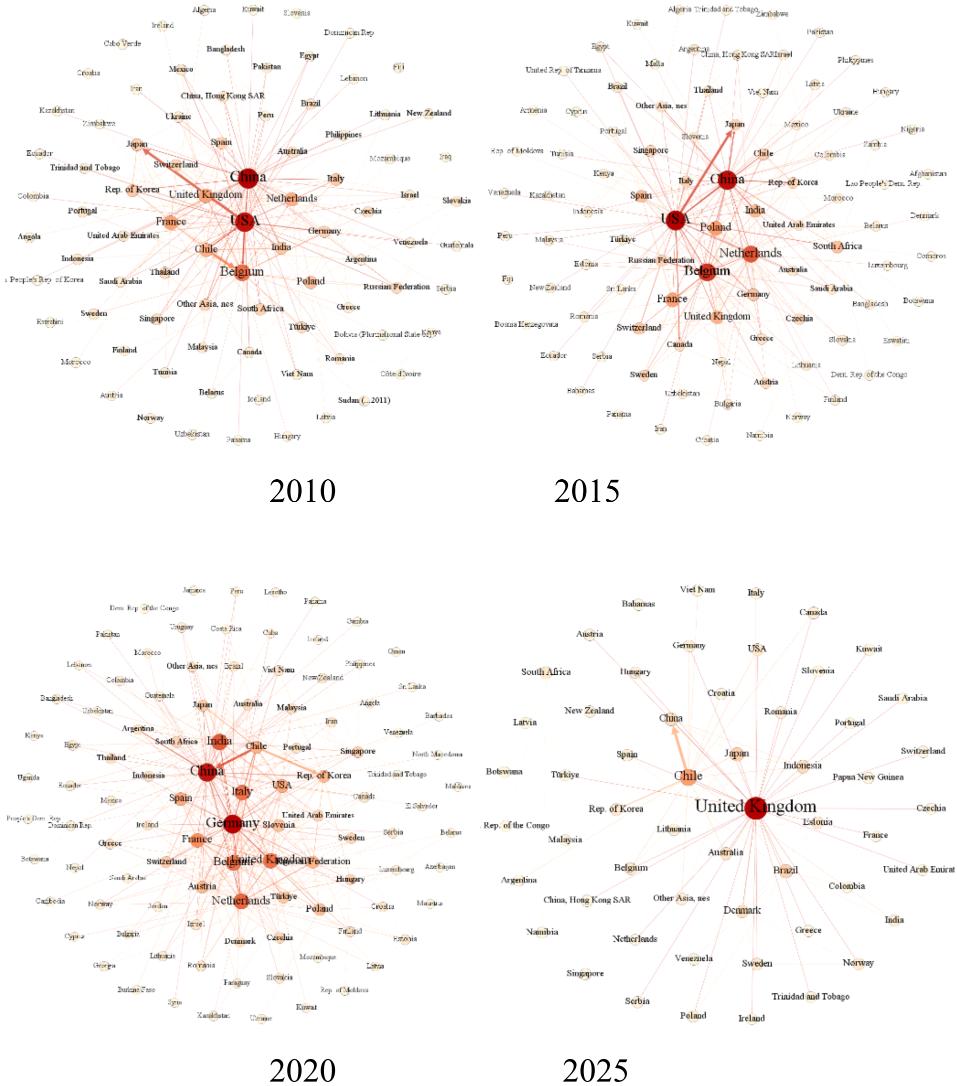

Fig. 2. Evolution of midstream trade network in lithium industrial chain

Rys. 2. Ewolucja sieci handlu pośredniego w łańcuchu przemysłowym litowym

The downstream trade network of the lithium industrial chain is illustrated in Figure 3, which reflects a noticeable polarization transfer. The original tripartite core pattern centered on Canada, China, and Belgium in 2010 has transformed into a new tripartite structure led by Denmark, Japan, and Indonesia. Driven by the rapid expansion of the new energy vehicle industry and intensified national strategic planning, Denmark and Japan have witnessed a sharp surge in demand for downstream lithium products. They can not only

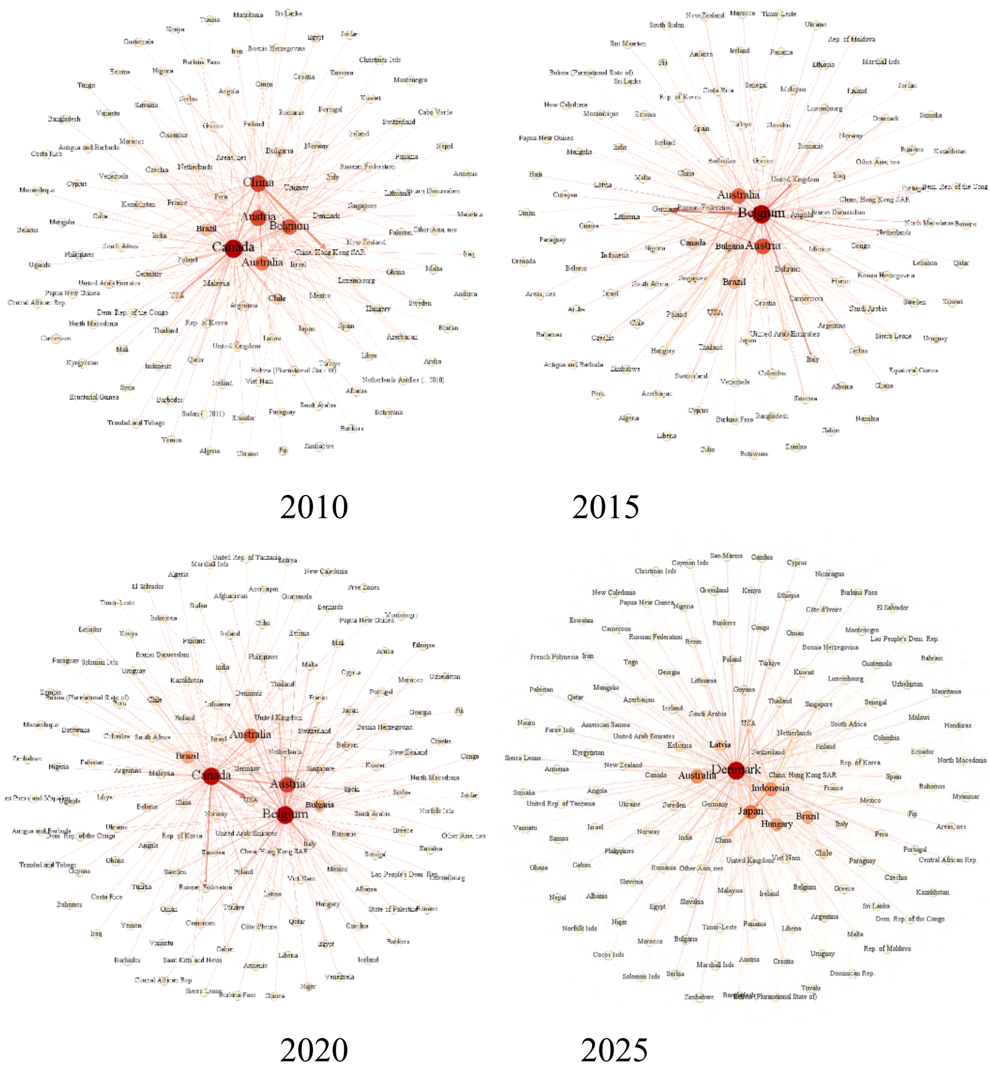

Fig. 3. Evolution of downstream trade network in lithium industrial chain

Rys. 3. Rozwój sieci handlu na dalszych etapach łańcucha przemysłowego litowego meet the needs of domestic electronic manufacturing through lithium-ion battery imports, but also export high-quality batteries to global markets to spread advanced technologies and products, thereby occupying a vital position in the downstream trade network and profoundly reshaping the global trade landscape of the lithium downstream sector. In addition, the Indonesian government has vigorously promoted its strategic goal of building a global electric vehicle manufacturing hub. In recent years, Indonesia has become a key layout destination for international lithium battery enterprises, gradually emerging as a core trading country in the downstream lithium industrial chain.

Overall, the trade scope, scale, and frequency of upstream and midstream lithium products are far lower than those of downstream products. The downstream trade network features a substantial increase in the number of nodes and edges, with wider participation of trading countries and rising network density year by year, indicating a higher level of trade globalization. In terms of node size, the gap among downstream nodes is narrower than that in the upstream and midstream, signifying more balanced and frequent bilateral trade among economies. Furthermore, regardless of whether it is the global trade network for upstream, midstream, or downstream lithium products, all exhibit a trend towards complexity, indicating that global lithium product trade has become increasingly interconnected.

2.2. Analysis of trade network indicators

From the perspective of the entire lithium product industrial chain, this section analyzes core trade network indicators and summarizes the basic network characteristics in 2010, 2015, 2020, and 2025.

Among the overall network indicators, network density reflects the closeness of trade ties between countries (regions); the average clustering coefficient represents trade cohesion; and the average path length measures trade efficiency. The calculated results are presented in Table 2. In terms of network density, the overall density of the full lithium industrial chain remains at a relatively low level with obvious fluctuations, yet shows a continuous upward trend. This indicates that trade linkages among economies have become increasingly closer, while being highly vulnerable to changes in the global economic situation. The average clustering coefficient exhibits fluctuating characteristics. Affected by the COVID-19 pandemic in 2020, the average clustering coefficient reached its peak, revealing a prominent trend of collectivization in global lithium product trade. It then declined to 0.713 in 2025, implying a gradual de-collectivization process. This change can be attributed to the rising strategic importance of lithium resources worldwide and the growing number of participants in lithium trade; nevertheless, the overall degree of network collectivization remains relatively high. The average path length shows a steady downward trend, which demonstrates continuous improvement in network connectivity and a notable increase in the overall efficiency of trade transmission.

Table 2. Overall network indicators of global lithium product trade

Tabela 2. Ogólne wskaźniki sieciowe dotyczące światowego handlu produktami litowymi

Year	Network density	Average clustering coefficient	Average path length
2010	0.032	0.535	2.658
2015	0.045	0.667	2.363
2020	0.061	0.782	2.159
2025	0.083	0.713	2.021

Nodes constitute the core components of the network topological structure, and their importance is generally quantified through centrality indicators. To further clarify the status and role of individual countries (regions) in the core trade network of the full lithium industrial chain, this study adopts betweenness centrality and eigenvector centrality to measure national centrality values.

Betweenness centrality in complex networks reflects the transit and coordination capacity of a country (region). Economies with high betweenness centrality often occupy "structural holes" in the network and gain advantages in accessing asymmetric information on resources and markets. Countries with prominent betweenness centrality control major information flows in international trade and possess strong capacity for cross-regional resource allocation. When affected by economic, political, and external shocks, these key economies may greatly hinder resource circulation within the lithium trade network and threaten the lithium trade security of other nations. As shown in Table 3, China, the United States and Germany consistently rank among the top three in betweenness centrality. These three countries lie on the key trade pathways of global lithium circulation and maintain strong resource control capability, with abundant lithium reserves and cutting-edge application technologies. In addition, developed economies including the United Kingdom, France and the Netherlands, as well as resource-endowed countries such as South Africa and Belgium, also maintain stable and high centrality rankings. Collectively, these economies exert powerful control over resource allocation and trade information, serving as critical bridge nodes in the global lithium trade network. Due to the impact of the pandemic in 2020, the betweenness centrality of most economies declined compared with the levels in 2015 and 2025.

Eigenvector centrality emphasizes both the quantity and quality of neighboring nodes. Countries with high eigenvector centrality not only maintain extensive trade partnerships but also connect with other high-centrality economies. This means that the trade groups centered on these nodes make substantial contributions to international lithium trade and exert long-term and stable influence. All eigenvector centrality values in this paper are normalized, and the top ten economies are listed in Table 4. Germany, the United States, and China stably rank within the top five, indicating that they maintain two-way trade with most regions and establish close cooperation with core trading nodes, whereas the rankings

Table 3. Betweenness centrality ranking of lithium product trade network

Tabela 3. Ranking centralności pośrednictwa w sieci handlu produktami litowymi

Ranking	2010		2015		2020		2025	
	Country (region)	Betweenness centrality	Country (region)	Betweenness centrality	Country (region)	Betweenness centrality	Country (region)	Betweenness centrality
1	USA	0.068	USA	0.075	China	0.073	USA	0.087
2	China	0.066	China	0.062	USA	0.053	China	0.073
3	Germany	0.042	Germany	0.060	Germany	0.022	Germany	0.043
4	Spain	0.033	Netherlands	0.032	Russian Federation	0.022	India	0.032
5	United Kingdom	0.026	United Kingdom	0.028	Netherlands	0.021	South Africa	0.023
6	South Africa	0.026	South Africa	0.021	New Zealand	0.019	United Kingdom	0.020
7	France	0.023	India	0.020	France	0.017	France	0.019
8	Italy	0.022	Poland	0.017	Belgium	0.016	Netherlands	0.018
9	Canada	0.025	Spain	0.015	Spain	0.013	New Zealand	0.015
10	New Zealand	0.011	Japan	0.013	India	0.011	Austria	0.012

Table 4. Eigenvector centrality ranking of lithium product trade network

Tabela 4. Ranking centralności wektorów własnych w sieci handlu produktami litowymi

Ranking	2010		2015		2020		2025	
	Country (region)	Eigenvector centrality	Country (region)	Eigenvector centrality	Country (region)	Eigenvector centrality	Country (region)	Eigenvector centrality
1	Germany	0.91	Germany	0.85	Germany	0.95	China	0.93
2	Italy	0.85	Korea	0.82	Russian Federation	0.88	Germany	0.90
3	China	0.81	Malaysia	0.74	USA	0.87	Korea	0.74
4	France	0.79	China	0.71	China	0.84	USA	0.52
5	USA	0.78	United Kingdom	0.69	Korea	0.68	Indonesia	0.51
6	Belgium	0.75	USA	0.69	Switzerland	0.68	Belgium	0.48
7	United Kingdom	0.72	India	0.68	Spain	0.63	Norway	0.48
8	Japan	0.72	Belgium	0.68	Belgium	0.62	Romania	0.48
9	India	0.65	France	0.67	India	0.62	Japan	0.26
10	Australia	0.64	Spain	0.65	Italy	0.59	Australia	0.26

of other countries fluctuate significantly. Germany has long occupied the first position, largely due to its superior geographical location and extensive partnerships with developed economies. China claimed the top ranking in 2025, driven by the vigorous development of the new energy vehicle industry, the advancement of the Belt and Road Initiative, and deepened economic cooperation under RCEP, together with remarkable geographical and neighboring advantages. Overall, the global lithium industrial chain is still predominantly dominated by developed economies in Europe and America, as well as China, the major developing country.

Conclusion

1. During the evolution of the global lithium product trade network, the international trade in the upstream, midstream, and downstream segments of the lithium industry chain has shown distinct characteristics of decentralization, centralization, and polarization transfer, respectively. Upstream trade of the lithium industry chain is mainly affected by industrial technological updates and geopolitics, while midstream and downstream trade is primarily driven by national strategic planning, industrial development, and geographical advantages.
2. A comparative analysis of the trade networks across the upstream, midstream, and downstream lithium industry chain reveals that the trade scope, scale, and frequency of upstream and midstream lithium products are far smaller than those of downstream products. Nevertheless, the trade networks at all three segments have demonstrated a growing trend of complexity, indicating increasingly close connections in global lithium product trade.
3. In terms of overall network indicators, the network density is generally low with drastic fluctuations but presents a continuous upward trend. This reflects that trade ties between countries in the network are steadily strengthening, yet highly vulnerable to economic conditions. The average clustering coefficient fluctuates periodically. As countries worldwide attach growing importance to lithium resources, de-bloc tendencies have emerged, though the network still maintains a high degree of bloc formation. The analysis of average path length shows that the connectivity of the entire lithium industry chain network has been continuously improved and optimized, leading to higher efficiency in trade circulation.
4. From the perspective of centrality analysis, countries with high and steadily ranked betweenness centrality and eigenvector centrality are Germany, the United States, and China. This indicates that these countries hold strong control over resources and information in the lithium trade, maintain close ties with key nodal economies, and serve as critical “bridges” within the trade network. It can be concluded that the global lithium industrial chain is still predominantly dominated by developed economies in Europe and America, as well as China, the major developing country.

4. Countermeasure suggestions

1) Improve global governance of the lithium industry chain trade network.

Countries worldwide should adopt multi-pronged measures to advance the sound development of the global lithium industry chain. First, efforts should be made to promote fairness and openness in the global lithium trade network. All nations need to collaborate to safeguard international trade order, facilitate the healthy development of the lithium industry chain, participate actively in global governance, and establish fair and transparent international trade rules to ensure equal rights and opportunities for all countries in lithium-related trade. Second, stronger supervision and guidance should be imposed on multinational corporations. As key participants in global lithium trade, their behaviors profoundly affect the stability and development of the lithium market. Governments need to regulate and guide multinational enterprises to ensure compliance with international norms and ethical standards in lithium trade, and standardize their commercial activities by formulating and improving relevant laws and regulations. Finally, transparency in global lithium trade information should be enhanced. Information transparency is an essential guarantee for maintaining orderly lithium trade. Countries shall establish information sharing mechanisms to release timely data on lithium resources, production, trade, and prices, improve market transparency and predictability, stabilize market expectations, and provide solid support for the sustainable development of global lithium trade.

2) Implement diversified trade strategies for the global lithium industry chain.

To address supply risks and enhance supply chain resilience across the global lithium industry chain, countries need to adopt comprehensive measures and optimize import and export channels. Current supply risks stem largely from excessive reliance of individual countries on single suppliers. For instance, China's lithium imports are highly dependent on Australia. Such an over-reliant trade structure is susceptible to geopolitical conflicts, market volatility, natural disasters, and other external shocks. Countries should actively explore diversified import and export channels, expand trade cooperation with diverse partners, reduce dependence on single supplier nations, and build stable trade partnerships with major lithium resource-rich economies to ensure alternative supply sources are readily available in case of supply disruptions. In addition, regional cooperation and trade liberalization should be advanced to improve the stability and efficiency of lithium trade. Active participation in regional economic organizations will help lower tariff and non-tariff barriers, boost the free flow of lithium products, and forge closer regional trade linkages.

3) Establish a global early warning and emergency response mechanism for lithium trade.

To cope with global lithium trade risks, all countries should jointly build a unified early warning and emergency response system, and strengthen real-time monitoring and risk forecasting. By developing integrated information sharing platforms, nations can timely monitor and analyze global lithium market supply and demand dynamics, price trends, and geopolitical changes, assess potential trade risks, and formulate targeted preventive measures. Moreover, lithium trade risks are typically cross-border and complex in nature, making it difficult for any single country to address them independently. It is imperative to strengthen international coordination and cooperation in trade management, risk early warning and emergency response. Through multilateral cooperation frameworks, countries can promote information sharing and coordinated actions to jointly mitigate trade risks. Furthermore, trade financial support should be optimized. As a core pillar for stable industrial chain operation, trade finance needs further development to provide targeted financial services for lithium enterprises, improve their capital turnover capacity, and reduce operational trade risks.

The Authors have no conflict of interest to declare.

REFERENCES

Arthur et al. 1997 – Arthur, B.W., Durlauf, S.N. and Lane, D.A. 1997. *The Economy as an Evolving Complex System II*. [In:] *Sfi Economics Program, Sfi Economics Program*.

Bai et al. 2024 – Bai, G.Y., Liang, M. and Qi, G.J. 2024. Dependency Risk and Countermeasures of China's Clean Energy Critical Minerals' Import. *Asia-Pacific Economic Review* 3, pp. 141–152, https://doi.org/10.16407/j.cnki.1000-6052.2024.03.011.

Barabasi, A.L. and Albert, R. 1999. Emergence of scaling in random networks. *Science* 286, pp. 509–512, https://doi.org/10.1126/science.286.5439.509.

Beck, K. and Jackson, K. 2024. International trade fluctuations: Global versus regional factors. *Canadian Journal of Economics* 57(1), pp. 331–358, https://doi.org/10.1111/caje.12702.

Chen et al. 2022 – Chen, C., Jiang, Z., Li, N., Wang, H., Wang, P., Zhang, Z., Chao Zhang, C., Ma, F., Huang, Y., Lu, X., Wei, J., Qi, J. and Chen, W.Q. 2022. Advancing UN Comtrade for Physical Trade Flow Analysis: Review of Data Quality Issues and Solutions. *Resources, Conservation and Recycling* 186, https://doi.org/10.1016/j.resconrec.2022.106526 (*in Chinese*).

Chen et al. 2020 – Chen, G., Kong, R. and Wang, Y. 2020. Research on the evolution of lithium trade communities based on the complex network. *Physica A: Statistical Mechanics and its Applications* 540(C), https://doi.org/10.1016/j.physa.2019.123002.

Chen et al. 2022 – Chen, W., Jiang, Y. and Liu, Z. 2025. Evolution and resilience of the global nickel resources trade network. *World Regional Studies* 34(1), https://doi.org/10.3969/j.issn.1004-9479.2025.01.20230643.

Chen, Z.H. and Feng, M. 2017. Spatial-temporal Variation Characteristics and Trade Pattern of the World Cotton Trade Network Based on the Dynamic Complex Network. I*nternational Economics and Trade Research*, pp. 36–50, https://doi.org/10.13687/j.cnki.gjjmts.2017.10.003 (*in Chinese*).

Craig-Scheckman, M. and Moore, S. 2025. Supply chain competitiveness index: Evaluating U.S. and China's lithium-ion battery industries. *Resources Policy* 107, https://doi.org/10.1016/j.resourpol.2025.105664.

Dong et al. 2016 – Dong, D., An, H., Hao, X. and Zhong, W. 2016. International copper ore trade pattern based on complex network. *Economic Geography* 36(10), pp. 93–101, https://doi.org/10.15957/j.cnki.jjdl.2016.10.013.

Fehérvölgyi et al. 2024 – Fehérvölgyi, B., Király, T. and Kosztyán, Z.T. 2024. Dynamic network analysis of trade networks (*Világkereskedelmi hálózatok idősoros vizsgálata*). *Statisztikai Szemle* 102, pp. 38–77, https://doi.org/10.20311/stat2024.01.hu0038 (*in Hungarian*).

Freeman, L.C. 1977. A Set of Measures of Centrality Based on Betweenness. *Sociometry* 40(1), pp. 35–41, https://doi.org/10.2307/3033543.

Granovetter, M. 1985. Economic Action and Social Structure: The Problem of Embeddedness. *American Journal of Sociology* 91(3), pp. 481–510.

Hao et al. 2013 – Hao X.Q., An, H.Z., Chen, Y.R. and Gao, X.Y. 2013. Research on Evolution of International Iron Ore Trade Based on Complex Network Theory. *Economic Geography* 1, pp. 92–97, https://doi.org/10.15957/j.cnki.jjdl.2013.01.027.

Hu et al. 2026 – Hu, Q.J., Hu, M.Y. and Li, J.H. 2026. Spatio-temporal evolution and driving mechanisms of the global petroleum trade dependency network. *Oil & Gas Storage and Transportation* 45(3), https://doi.org/10.6047/j.issn.1000-8241.2026.03.009.

Hulianskyi, O. 2025. The Evolution of Global Gold and Copper Trade Networks. *Northeast Journal of Complex Systems* 7(2), https://doi.org/10.63562/2577-8439.1112.

Kong et al. 2024 – Kong, W., Cheng, J. and Xiao, J. 2024. Market Risk of Lithium Industry Chain – Evidence from Listed Companies. *Energies* 17(23), https://doi.org/10.3390/en17236173.

Kong, X.Y. and Zhang, Y.S. 2022. Lithium Resources: The Driving Force of the New Energy Revolution. *Frontiers*, pp. 76–81, https://doi.org/10.16619/j.cnki.rmltxsqy.2022.13.008.

Kosztyán, Z.T. and Kosztyánné Mátrai, R. 2025. Dynamic analysis of multilayer trade networks. *Statisztikai Szemle* 103(9), pp. 811–852, https://doi.org/10.20311/stat2025.09.hu0811 (*in Hungarian*).

Ling et al. 2024 – Ling, J.Y., Zhou, N., Hu, P.Q., et al. 2024. Evolution of trade network pattern of chromium ore in global and analysis of competitiveness. *China Mining Magazine*, pp. 48–58 (*in Chinese*).

Liu et al. 2020 – Liu, S., Dong, Z., Ding, C., Wang, T. and Zhang, Y. 2020. Do you need cobalt ore? Estimating potential trade relations through link prediction. *Resources Policy* 66, https://doi.org/10.1016/j.resourpol.2020.101632.

Man, Y. and Ren, S.T. 2015. Detecting world trade patterns by complex networks. J*ournal of Beijing Normal University (Natural Science)* 51(2), pp. 140–143, https://doi.org/10.16360/j.cnki.jbnuns.2015.02.007 (*in Chinese*).

Meng et al. 2025 – Meng, Z., Sun, H., Daigo, I., Guan, J. and Shan, Y. 2025. Technological risks disrupting trade stability in the global lithium supply chain network. *iScience* 28(7), https://doi.org/10.1016/j.isci.2025.112939.

Rincón et al. 2025 – Rincón, J.M., Gómez, P.C. and Vidal, M.M.J. 2025. Lithium Minerals and their Applications in the "Glass Age". *Estudios Geologicos* 81(2), https://doi.org/10.3989/egeol.45713.1139.

Serrano, M.Á. and Boguñá, M. 2003. Topology of the world trade web. *Physical Review E* 68, https://doi.org/10.1103/PhysRevE.68.015101.

Shao et al. 2021 – Shao, L., Hu, J. and Zhang, H. 2021. Evolution of global lithium competition network pattern and its influence factors. *Resources Policy* 74, https://doi.org/10.1016/j.resourpol.2021.102353.

Shao et al. 2022 – Shao, L., Kou, W. and Zhang, H. 2022. The evolution of the global cobalt and lithium trade pattern and the impacts of the low-cobalt technology of lithium batteries based on multiplex network. *Resources Policy* 76, https://doi.org/10.1016/j.resourpol.2022.102550.

Sun et al. 2018 – Sun, X., Hao, H., Zhao, F. and Liu, Z. 2018. Global Lithium Flow 1994-2015: Implications for Improving Resource Efficiency and Security. *Environmental Science and Technology* 52(5), pp. 2827–2834, https://doi.org/10.1021/acs.est.7b06092.

Sun et al. 2021 – Sun, H., Chen, L., Cheng, J.H. and Zhou, W. 2025. Simulation of dynamic impact of technological innovation on the sustainable supply of key minerals: A case study of lithium. *Journal of Central South University Social Sciences* 4, pp. 113–127 (*in Chinese*).

Sun et al. 2022 – Sun, X., Shi, Q. and Hao, X. 2022. Supply crisis propagation in the global cobalt trade network. *Resources, Conservation & Recycling* 179, https://doi.org/10.1016/j.resconrec.2021.106035.

Tian et al. 2021. – Tian, X., Geng, Y., Sarkis, J., Gao, C., Sun, X., Micic, T., Hao, H. and Wang, X. 2021. Features of critical resource trade networks of lithium-ion batteries. *Resources Policy* 73, https://doi.org/10.1016/j.resourpol.2021.102177.

Wang et al. 2015 – Wang, J.L., Xu, L.B. and Pang, C.Y. 2015. Evolution model of online social networks based on complex networks. *CAAI Transactions on Intelligent Systems* 10(6), pp. 949–953, https://doi.org/10.11992/tis.201507042 (*in Chinese*).

Wang et al. 2023a – Wang, M., Guo, Y., Hu, H. and Ding, S. 2023a. Embodied carbon emission flow network analysis of the global nickel industry chain based on complex network. *Sustainable Production and Consumption* 42, pp. 380–391, https://doi.org/10.1016/j.spc.2023.09.023.

Wang et al. 2023b – Wang, X.Q., Qin, M., Moldovan, N.C. and Su, C.W. 2023b. Bubble behaviors in lithium price and the contagion effect: An industry chain perspective. *Resources Policy* 83, https://doi.org/10.1016/j.resourpol.2023.103725.

Wang et al. 2025 – Wang, J., Tan, X. and Liu, D. 2025. Critical risks in an industry chain-based global lithium supply networks: Static structure and dynamic propagation. *Process Safety and Environmental Protection* 198, https://doi.org/10.1016/j.psep.2025.107137.

Wang et al. 2026 – Wang, C., Tan, K., Hu, X., Sun, B. and Zhao, X. 2026. The determinants of global lithium-ion battery trade network based on temporal exponential random graph model. *Journal of Industrial Ecology* 30, https://doi.org/10.1007/s44498-026-00007-1.

Watts, D.J. and Strogatz, S.H. 1998. Collective dynamics of 'small-world' networks. *Nature* 393, pp. 440–442, https://doi.org/10.1038/30918.

Xing et al. 2022 – Xing, J., Chen, Q., Zhang, Y., Yu, W., Long, T., Zheng, G. and Wang, K. 2022. Development of Lithium and Its Downstream Power Battery Industry Chain in China. *Strategic Study of CAE* 24(3), pp. 10–19, https://www.engineering.org.cn/sscae/EN/10.15302/J-SSCAE-2022.03.002.

Yang et al. 2021 – Yang, P., Gao, X., Zhao, Y., Nanfei Jia, N. and Dong, X. 2021. Lithium resource allocation optimization of the lithium trading network based on material flow. *Resources Policy* 74, https://doi.org/10.1016/j.resourpol.2021.102356.

Ye et al. 2022 – Ye, H., Li, Z., Li, G. and Liu, G. 2022. Topology Analysis of Natural Gas Pipeline Networks Based on Complex Network Theory. *Energies* 15(11), https://doi.org/10.3390/en15113864.

Yi et al. 2024 – Yi, L., Li, Y.Y., Xie, L.Y., et al. 2024. Research on the evolution of trade pattern and export competitiveness of global rare earth industry chain. *China Mining Magazine*, pp. 53–62 (*in Chinese*).

Yu, H. and Ding, Y.H. 2021. Study on the spatial and temporal correlation of global cobalt intermediate products trade network. *China Mining Magazine*, pp. 40–47 (*in Chinese*).

Yu et al. 2022 – Yu, Y., Ma, D.P. and Wang, X.M. 2022. International trade network resilience for products in the whole industrial chain of iron ore resources. *Resources Science* 44, pp. 2006–2021, https://doi.org/10.18402/resci.2022.10.05 (*in Chinese*).

Zhang et al. 2015 – Zhang, L.J., Zhang, L.L., Hao, X.Q., Fang, W. and Wu Y.Y. 2015. Research into evolution of international copper ore trade based on complex network theory. *China Mining Magazine* 24(10), pp. 57–62 (*in Chinese*).

Zhang et al. 2025 – Zhang, Y., Wenbo, B., Yi, S. and Wu, C. 2025. Impact of geopolitical risks on resilience of lithium resource trade network: Based on complex network and panel regression analysis. *Resources Science* 47(7), pp. 1517–1532, https://doi.org/10.18402/resci.2025.07.10.

Zheng et al. 2025 – Zheng, L.C., Bao, W.Q., Chen, G. and Geng, A. 2025. Multi-scenario dynamic analysis of demand for critical minerals in China's new energy vehicles under "dual carbon" goals. *Resources Science* 47(7), pp. 1485–1504, https://doi.org/10.18402/resci.2025.07.08.

Zhou et al. 2023 – Zhou, R.B., Chen, Y.N. and Qin, Y. 2023. .Evolution and influencing factors of global high-tech products trade network. *World Regional Studies* 32(6), pp. 1–13, https://doi.org/10.3969/j.issn.1004-9479.2023.06.2021644 (*in Chinese*).

Zhu et al. 2025 – Zhu, X.H., Liu, J.R. and Zeng, A.Q. 2022. Analysis of China's embodied cobalt consumption structure characteristics and key paths based on industrial complex networks. *Journal of Central South University (Social Science)*, pp. 68–81 (*in Chinese*).

Zhuang et al. 2022 – Zhuang, D., Li, J., Chen, Z. and Liu, Y. 2022. The Dynamic Change of Global Rare Earth Trade Network and Its Impact Mechanism: From the Perspective of Industrial Chain. *Geographical Science* 42(11), pp. 1900–1911, https://doi.org/10.13249/j.cnki.sgs.2022.11.005 (*in Chinese*).

EVOLUTION ANALYSIS OF THE GLOBAL LITHIUM INDUSTRIAL CHAIN TRADE NETWORK: BASED ON THE EVENT-SHOCK COMPLEX NETWORK METHOD

Keywords

lithium product trade, full industrial chain, event-shock complex network, network evolution

Abstract

Lithium has become a driving force of the new energy revolution, a crucial option for the international community to jointly advance ecological civilization construction, and one of the fundamental resources for achieving carbon neutrality. Its industrial chain trade exerts a significant impact on the global economy. To further explore the patterns and characteristics of international trade in products across all stages of the lithium industrial chain, this paper adopts a full-industry-chain perspective. It applies the complex network method with Event Impact Factor to analyze the evolution of trade patterns in the upstream, midstream and downstream sectors, and constructs trade network indicators to examine the overall and individual nodal characteristics of the network. The research findings indicate that: The international trade of the lithium industrial chain presents distinct trends of decentralization, centralization and polarization transfer in the upstream, midstream and downstream respectively. Upstream trade is primarily affected by industrial technological upgrading and geopolitics, while midstream and downstream trade is mainly shaped by national strategic planning, industrial development and geographical advantages. Countries in the lithium trade network maintain close ties. While network connectivity and efficiency keep rising, blocization remains prominent. Finally, targeted policy recommendations are proposed to enhance the resilience of the entire lithium industrial chain, including improving global governance of the lithium trade network, promoting diversified trade strategies for the global lithium industrial chain, and establishing a global trade early warning and emergency response mechanism.

ANALIZA EWOLUCJI GLOBALNEJ SIECI HANDLOWEJ ŁAŃCUCHA PRZEMYSŁOWEGO LITOWEGO W OPARCIU O METODĘ SIECI ZŁOŻONYCH OPARTYCH NA ZDARZENIACH I WSTRZĄSACH

Słowa kluczowe

handel produktami litowymi, pełny łańcuch przemysłowy,
złożona sieć podlegająca wpływom zdarzeń i wstrząsów, ewolucja sieci

Streszczenie

Lit stał się siłą napędową rewolucji w dziedzinie nowych źródeł energii, kluczowym rozwiązaniem dla społeczności międzynarodowej w zakresie wspólnego budowania cywilizacji ekologicznej oraz jednym z podstawowych zasobów niezbędnych do osiągnięcia neutralności węglowej. Handel w ramach łańcucha przemysłowego litu wywiera znaczący wpływ na gospodarkę światową.

Aby dokładniej zbadać wzorce i cechy charakterystyczne handlu międzynarodowego produktami na wszystkich etapach łańcucha przemysłowego litu, w niniejszym artykule przyjęto perspektywę obejmującą cały łańcuch przemysłowy. Wykorzystano metodę sieci złożonych z uwzględnieniem wskaźnika wpływu zdarzeń (Event Impact Factor) do analizy ewolucji wzorców handlu w sektorach górnym, środkowym i dolnym łańcucha przemysłowego oraz skonstruowano wskaźniki sieci handlowej w celu zbadania ogólnych i indywidualnych cech węzłów sieci. Wyniki badań wskazują, że: międzynarodowy handel w łańcuchu przemysłowym litu wykazuje wyraźne tendencje do decentralizacji, centralizacji i przenoszenia polaryzacji odpowiednio w sektorach *upstream*, *midstream* i *downstream*. Na handel w sektorze *upstream* wpływają przede wszystkim modernizacja technologiczna przemysłu oraz uwarunkowania geopolityczne, natomiast handel w sektorach *midstream* i *downstream* kształtowany jest głównie przez krajowe planowanie strategiczne, rozwój przemysłowy oraz przewagi geograficzne. Kraje w sieci handlu litem utrzymują bliskie powiązania. Chociaż łączność i efektywność sieci stale rosną, nadal wyraźnie widoczne jest tworzenie się bloków. Na koniec przedstawiono konkretne zalecenia dotyczące polityki, mające na celu zwiększenie odporności całego łańcucha przemysłowego litowego, w tym poprawę globalnego zarządzania siecią handlu litem, promowanie zróżnicowanych strategii handlowych dla globalnego łańcucha przemysłowego litowego oraz ustanowienie globalnego mechanizmu wczesnego ostrzegania i reagowania kryzysowego w handlu.