Available online at www.sciencedirect.com
ScienceDirect
Trans. Nonferrous Met. Soc. China 35(2025) 1362−1380
Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Lithium material flow analysis in international trade: A life cycle perspective

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Received 10 May 2024; accepted 20 January 2025

Abstract: From a life cycle perspective, the material flow analysis is utilized to investigate the lithium material flows in international trade from 2000 to 2019. The results reveal that at the global level, the total volume of lithium trade grew rapidly, reaching 121116 t in 2019. Lithium trade was dominated by lithium minerals, lithium carbonate and lithium hydroxide rather than final lithium products, indicating an immaturity in global lithium industry. At the intercontinental level, Asia's import trade and Oceania's export trade led the world, accounting for 81.22% and 39.68%, respectively. At the national level, China, Japan and Korea became the main importers, while Chile and Australia were the main exporters. In addition, China's trade volume far exceeded that of the United States. China's exports were dominated by lithium-ion batteries, while the United States mainly imported lithium-ion batteries, proving that the development of China's lithium industry was relatively faster.

Key words: lithium; material flow analysis; international trade; life cycle

1 Introduction

Lithium, essential for the progression of strategic emerging industries, has diverse applications ranging from non-ferrous metallurgy and glass ceramics to batteries, electric vehicles, photovoltaic energy storage, nuclear fusion and aerospace [1−3]. Notably, the integration of lithium-ion batteries into the new energy vehicle sector signifies a pivotal shift in the trajectory of the automotive industry [4−6]. Data from the United States Geological Survey (USGS) indicate a significant surge in global lithium dynamics. Production saw a leap from 25300 t in 2010 to 180000 t in 2023. Concurrently, the consumption, measured in lithium content, rose from 13630 t in 2010 to an impressive 180000 t by 2023 [7,8]. Additionally, the global consumption proportion of lithium-ion batteries, which was 23% in 2010, surged to 87% in 2023, indicating that over half of the world's lithium consumption caters to battery demands. Its vast usage in the electric vehicle sector reinforces this trend. The International Energy Agency (IEA) forecasts that, owing to lithium's crucial significance in electric vehicles and energy storage, its demand is set to skyrocket, potentially seeing an over 40-fold increase by the year 2040. It can be expected that with the development of the lithium industry, the new energy automobile

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DOI: https://doi.org/10.1016/S1003-6326(24)66754-3

industry will rise rapidly, and the total production and consumption of global lithium resources will continue to increase. However, the surging demand for lithium introduces significant strain on its global supply, and the problem of insufficient supply is gradually emerging, further affecting the security of lithium resources and hindering the development of strategic emerging industries [9].

From the perspective of distribution, global lithium resources are mainly distributed in regions or countries such as South America, Australia and China, while the countries or regions with high demand for lithium resources are the United States, the European Union, China, Japan and Korea. Given the geographical disparities in resource distribution, there exists a distinct gap between where lithium is produced and where it is consumed [10]. This geographical separation of supply from demand triggers a global flow of lithium, manifested in the form of international trade [11,12]. Given the insufficient supply of lithium resources, countries compete around lithium, and trade competition between countries becomes intensified, resulting in an increasingly complex and volatile global lithium trade. Therefore, it becomes necessary to clarify the lithium flow in international trade. It is of great significance to improve lithium resource management, alleviate the shortage of lithium supply, safeguard the strategic security of resources and promote the further development of strategic emerging industries.

Given this context, researchers have employed material flow analysis (MFA) to investigate lithium flows from different perspectives and further studied lithium international trade. First, from the perspective of the lithium industry, many scholars have analyzed lithium flows at different life cycle stages [13−16]. ZIEMANN et al [17] constructed a static material flow model based on production, manufacturing and usage data, elucidating the global lithium flows. MELLINO et al [18] utilized life cycle assessment to compare electric bicycles powered by lithium-ion batteries with cars powered by hydrogen fuel cells, and identified a number of new environmental issues that arise during the production, operation and disposal stages. SONG et al [19] conducted a dynamic material flow analysis on lithium, nickel, cobalt and graphite related to lithium-ion batteries, determining the significance of material flows for different metals.

Secondly, some scholars have analyzed lithium material flows from a national perspective [20−22]. HAO et al [23] examined the flows of lithium products in China and found that while China's consumption of lithium carbonate was high, it was heavily reliant on imports. LIU et al [24] explored the evolution of lithium metabolism in China's lithium-ion battery system through a dynamic bottom-up material flow analysis. SHAFIQUE et al [25] estimated the future lithium-ion battery market in the United States and China, and their impacts on raw material demand, lithium-ion battery material end-of-life and secondary use based on three different scenarios. LI et al [26] explored the supply and demand characteristics of China's lithium trading market based on trade material flow and industrial material flow.

Thirdly, scholars have dissected lithium material flows at regional or global levels, focusing mainly on the lithium flows in international trade. SUN et al [1] developed a trade-related framework of material flow analysis to examine the life cycle of lithium products within nations and their international trade on a global scale. SUN et al [27] constructed a regional dynamic flow model of China's lithium product life cycle from 2000 to 2050, based on data of lithium production, consumption and international trade. YANG et al [11] analyzed the global trade of lithium for lithium-ion batteries and related chemicals based on the material flow analysis.

Fourthly, several scholars have analyzed lithium international trade based on a specific stage of the life cycle. After removing the impact of major exporters of lithium carbonate on the trade of other countries, ZHANG et al [28] investigated the lithium carbonate trade between importing countries and small-scale exporters. HU et al [29] explored the structural evolution of lithium-ion batteries trade in electric vehicles and analyzed the systemic risks in international electric vehicle trade. The results suggested that the center of lithium-ion batteries trade was shifting from Asia to Europe. ZHANG et al [30] studied the important minerals contained in the main elements of lithium-ion batteries and predicted the potential international trade relationships of these minerals. The results indicated that trading countries tended to establish long-term stable trade relations.

Many scholars have explored lithium material flow from different perspectives, yet there remains significant room for further research. Firstly, existing literatures have devoted more attention to the analysis of the first and second types of lithium material flows mentioned above, with relatively less study on the third type. Given that lithium material flows in international trade involve nearly all lithium-containing products, the challenge of acquiring relevant data has resulted in less scholarly investigation into lithium material flows within international trade. Secondly, based on the fourth type of research, the existing literatures have mainly examined lithium international trade at a specific stage of the life cycle, with fewer analyses of the lithium trade over the entire life cycle. Lastly, most existing studies have investigated lithium material flows from either a global, regional or national perspective, without integrating these three levels to provide a comprehensive depiction of lithium material flows in international trade.

To bridge this gap, we track lithium material flows in international trade, based on extensive and detailed trade data for all lithium-containing products. Moreover, from a life cycle perspective, we develop a framework for lithium material flow analysis that includes five stages: resource mining, chemical production, product manufacture, product use and waste management, thereby analyzing lithium international trade over the entire life cycle. Additionally, we provide a comprehensive depiction of lithium trade flows at global, intercontinental and national levels, including specific analysis of China and the United States, and then systematically examine lithium material flows in international trade.

2 Methods and data

2.1 System boundary

The system boundary features both spatial and temporal dimensions. For the spatial boundary, we select 246 countries or regions, with data indicating that these nations account for over 99% of the global lithium trade volume. For the temporal boundary, we choose the period from 2000 to 2019 as the target years, which adequately reflects the development and utilization of the contemporary lithium-related industries.

2.2 Framework for material flow analysis

The lithium throughout the entire life cycle is divided into five stages: resource mining, chemical production, product manufacture, product use and waste management. The material flow analysis framework within the life cycle for lithium is illustrated in Fig. 1.

2.2.1 Resource mining stage

Lithium mines in the resource mining stage primarily include lithium ores and lithium-bearing brines [31]. Compared to lithium ores, extraction of lithium-bearing brines is cost-effective, making it a major source of lithium extraction.

2.2.2 Chemical production stage

During the chemical production stage, lithium minerals are converted into a range of lithium chemical products, including lithium carbonate,

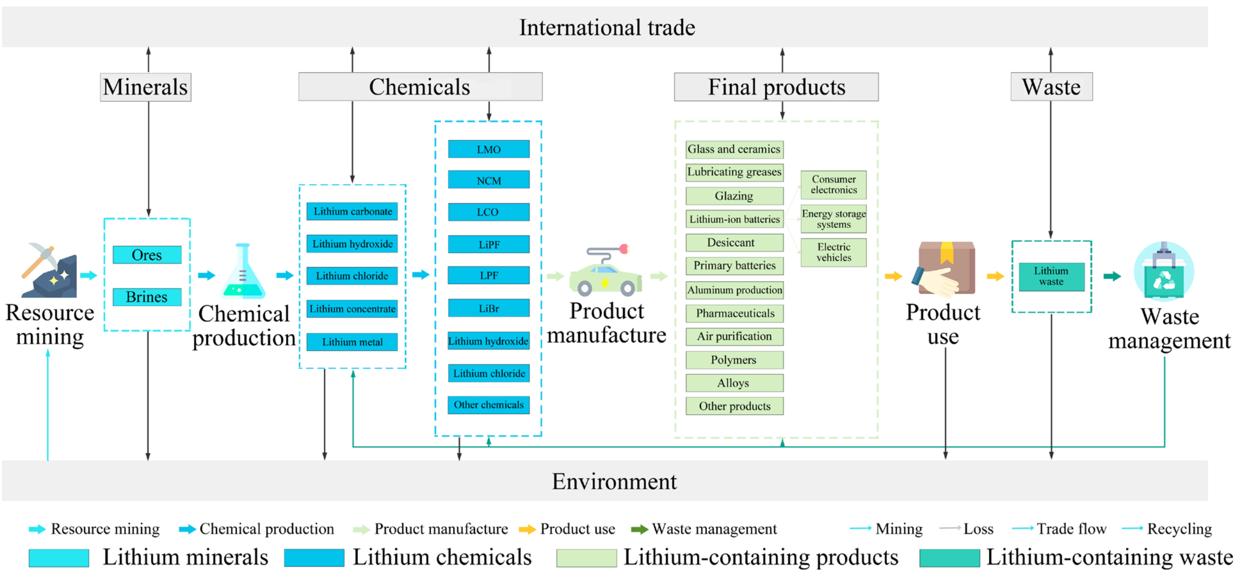

Fig. 1 Lithium material flow analysis framework within life cycle

lithium hydroxide, lithium chloride, lithium concentrate and more. These lithium chemical products are further used in the production of derivatives; for instance, after processing, lithium carbonate is mainly utilized to produce cathode materials for lithium-ion batteries [32].

2.2.3 Product manufacture stage

In the product manufacturing stage, lithium carbonate is applied in the production of cathode materials and ceramic glazing, while lithium hydroxide is a key raw material for lubricating greases. Lithium chloride is used in the production of brazing flux and desiccants. Lithium concentrate is utilized in the glass and ceramic industries. Notably, lithium-ion batteries produced from lithium carbonate can be used in consumer electronics, energy storage systems and new energy/ electric vehicles [33].

2.2.4 Product use stage

During the product use stage, lithium products are divided into dissipative lithium products and recyclable lithium products [17]. Dissipative lithium products, such as lubricating greases, are released into the natural environment during their use stage and cannot be recycled. Recyclable lithium products, such as lithium-ion batteries and glass-ceramic, can be recycled and further processed after they are disposal [34].

2.2.5 Waste management stage

There are currently three methods of dealing with lithium waste. The first is to return lithium waste to the manufacturing stage, the second is to divert lithium waste to other uses and reuse lithium-containing products, and the third is to release lithium waste into the natural environment [23,35].

In international trade, the lithium flows at different stages of the life cycle mainly refer to the flows of the element lithium (Li) in the form of products on a global scale. We categorize the lithium products in international trade into seven types. From the resource mining stage to the chemical production stage, the main products in the global lithium flows are lithium minerals. During the chemical production stage to the product manufacture stage, the products in the lithium flows include lithium carbonate, lithium hydroxide and other lithium chemicals. From the product manufacture stage to the product use stage, the lithium flows involve products such as lithium-ion batteries, glass and ceramics and other lithium products. Moreover, due to the low recycling rate of lithium, we exclude the flows of lithium products in the waste management stage.

2.3 Material flow accounting

After identifying lithium-containing products at each stage of the life cycle, the lithium content in each product is measured using conversion coefficients. For ease of calculation, the lithium content of all traded products is standardized using conversion coefficients and measured in unit of lithium metallic equivalents. Referring to the studies by HAO et al [23], SUN et al [1], SUN et al [36] and WANG et al [37], the products and conversion coefficients during resource mining, chemical production, product manufacture, product use and waste management stage are given in Table 1.

Table 1 Conversion coefficients of major lithium products

Lithium-containing product	Conversion coefficient
Brines	0.11 t(Li)/t
Ores	0.03 t(Li)/t
Lithium carbonate	0.19 t(Li)/t
Lithium hydroxide	0.17 t(Li)/t
Lithium chloride	0.16 t(Li)/t
Lithium concentrate	0.03 t(Li)/t
Lithium manganate	0.07 t(Li)/t
Lithium cobaltate	0.04 t(Li)/t
Lithium iron phosphate	0.07 t(Li)/t
Lithium nickel-cobalt manganese oxide	0.04 t(Li)/t
Lithium hexafluorophosphate	0.05 t(Li)/t
Lithium-ion battery	0.03 t(Li)/t
Ceramics and glasses	0.15 kg(Li)/item
Lubricating greases	0.15 kg(Li)/item
Battery electric passenger vehicle	2.80 kg(Li)/item
Battery electric bus	1.69 kg(Li)/item
Plug-in hybrid electric bus	9.34 kg(Li)/item
Plug-in hybrid electric passenger vehicle	2.40 kg(Li)/item
Electric bicycle	0.06 kg(Li)/item
Mobile phones	0.91 g(Li)/item
Portable computers	5.95 g(Li)/item
Cameras	2.05 g(Li)/item
Wearable Electronics	0.07 g(Li)/item
Energy storage systems	0.11 t(Li)/(W·h)

The lithium content in lithium minerals is measured based on the average unit content, while the lithium content in lithium chemical products is calculated based on the mass fraction of lithium in each chemical product. For products containing lithium-ion batteries, the conversion process involves calculating the lithium-ion battery capacity of each product to determine its lithium content. For the product use stage, data availability is limited, and there is no specific data on the stock of lithium products, making it challenging to accurately estimate the trade status of lithium product usage. Regarding the waste management stage, there is very limited data from the global recycling industry concerning lithium waste, making it difficult to quantify the trade of lithium waste between countries. Therefore, the product use stage and the waste management stage have not been included in the calculations.

Based on WEN et al [38], the mass of the traded product is multiplied by its corresponding conversion factor to obtain the lithium content as follows:

$$F_{i,t}^{\text{import}} = P_{i,t}^{\text{import}} \cdot C_i \tag{1}$$

$$F_{i,t}^{\text{export}} = P_{i,t}^{\text{export}} \cdot C_i \tag{2}$$

where $F_{i,t}^{\text{import}}$ and $F_{i,t}^{\text{export}}$ represent the lithium contents of the Product i that is imported and exported in Year t, respectively; $P_{i,t}^{\text{import}}$ and $P_{i,t}^{\text{export}}$ are the quantities of Product i imported and exported in Year t, respectively; C_i is the conversion coefficient corresponding to Product i.

Based on the mass and import/export quantity of a particular product, we can obtain the lithium content of that product in trade:

$$F_{i,t}^{\text{import}} = N_{i,t}^{\text{import}} \cdot M_i \cdot C_i \tag{3}$$

$$F_{i,t}^{\text{export}} = N_{i,t}^{\text{export}} \cdot M_i \cdot C_i \tag{4}$$

where $N_{i,t}^{\text{import}}$ represents the quantity of imported Product i, $N_{i,t}^{\text{export}}$ represents the quantity of exported Product i, and M_i is the mass of Product i.

The total volume of trade in lithium-containing products worldwide or for a specific country in a given year can be obtained by adding the import and export volumes for that year:

$$F_t^{\text{import}} = \sum_{i=1} F_{i,t}^{\text{import}} \tag{5}$$

$$F_t^{\text{export}} = \sum_{i=1} F_{i,t}^{\text{export}} \tag{6}$$

$$F_t^{\text{trade}} = \sum_{i=1} (F_{i,t}^{\text{import}} + F_{i,t}^{\text{export}}) \tag{7}$$

where F_t^{import} indicates the total volume of lithium-containing product imports, F_t^{export} represents the total volume of lithium-containing product exports, and F_t^{trade} indicates the total volume of lithium-containing product trade.

2.4 Data

To analyze the lithium flows in international trade, the relevant data mainly come from the United Nations Commodity Trade Database (UN Comtrade), the European Union Statistics Bureau Database (Eurostat), customs databases of various countries and other trade statistical agencies using specific commodity customs codes, namely Trade SNS, http://www.signumbox.com/ and https://www.zauba.com/. The data processing procedure refers to the studies of HAO et al [23], SUN et al [1] and SUN et al [36].

Based on extensive data collection efforts, we cover almost all trade data for lithium-containing products at different stages of the life cycle, but the relevant trade data still need to be further processed to fill data gaps. Our data processing is based on the following three premises. Firstly, when trade data for a lithium product are not available, sales data for the product can be used for estimation, and the available sales data are often very sufficient. For example, in the acquisition of trade data for electric vehicles, many countries do not have global trade data for imported brand electric vehicles, but the sales data of these brands in the trading countries are quite complete. Therefore, we use the sales of imported brand electric vehicles as the global trade data. Secondly, since the trade volume of certain lithium chemical products is particularly small and can almost be ignored, these types of products are overlooked during data collection. For example, lithium tritide is mainly used for military production in various countries. Over the years, the global trade volume of this chemical has been less than 10 kg, having almost no impact on the lithium international trade. Hence, the trade of this product is ignored. Lastly, global data on lithium waste are very limited, making it difficult to quantify the trade of lithium waste between countries. Therefore, the trade of lithium waste is not included in the analysis.

3 Results and analysis

3.1 Analysis of global lithium material flows in international trade

Figure 2 shows the changes in the global lithium material flows in international trade from 2000 to 2019. Over the past 20 years, the volume of lithium trade underwent significant changes, rising at an average annual rate of 11.7%, from 14722 t in 2000 to 121116 t in 2019. Specifically, the global lithium trade volume declined slightly from 2000, with a dip in trade volume in 2009, the year of the financial crisis. Overall, however, the global lithium trade volume grew steadily, increasing from 18885 t in 2004 to 28289 t in 2012, mainly due to the massive application of lithium-ion batteries in consumer electronics. After that, the global lithium trade volume entered a stable period until 2016. The transformation brought about by the electrification of vehicles once again sparked a new round of growth in global lithium trade, increasing from 48914 t in the same year to 121116 t in 2019.

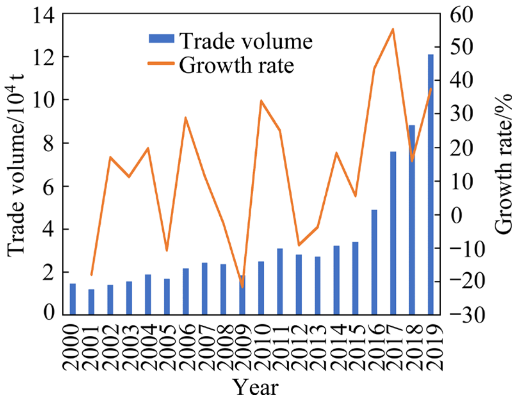

Fig. 2 Global lithium material flows in international trade

Figure 3 analyzes the changes in trade volumes of global lithium products at different life cycle stages. Figure 3(a) shows the evolution of the import and export volume of global lithium minerals from the resource mining stage to the chemical production stage. Overall, the global trade volume of lithium minerals showed a steady upward trend over the study period. From 2000 to 2015, the increase was relatively slow, with the volume rising from 8442 to 14438 t, an increase of only 1.5 times. After this period, there was a sharp increase in the global trade volume of lithium minerals. In 2019, the trade volume reached to 48022 t, which was 3.3 times the volume in 2015. Given the rapid rise of the new energy vehicle industry, the demand for lithium batteries in trading countries was increasing. USGS data showed that lithium batteries accounted for more than half of global lithium consumption share, even up to 65% in 2019 [8]. It can be seen that with the rapid development of the lithium-ion battery industry, trading countries have a huge demand for upstream raw materials.

During the stage from chemical production to product manufacture, lithium carbonate and lithium hydroxide are the main traded products, with their trade fluctuations shown in Figs. 3(b, c). The global trade volume of lithium carbonate showed a fluctuating upward trend, with significant decreases only in 2005, 2009 and 2018, and maintained an upward trend in the remaining years, culminating in a significant increase to 34318 t in 2019. The trade volume of lithium hydroxide increased significantly over 20 years, rising from 2673 t in 2000 to 26207 t in 2019, an increase of almost 10 times. Unlike the growth pattern of lithium carbonate, the trade volume of lithium hydroxide maintained a steady growth before 2016, slowly increasing from 2673 to 5401 t. After that, the trade volume surged to 26207 t in 2019, an increase of 385%. This was mainly due to the pursuit of long-range and high-performance targets for electric vehicle batteries. The mainstream method for increasing battery energy density at the current stage was the “high-nickel” treatment of the cathode material. High-nickel lithium-ion batteries used lithium hydroxide as the raw material. This industrial development trend led to a sharp increase in the global trade volume of lithium hydroxide.

As for other lithium chemical products from the chemical production stage to the product manufacture stage, such as lithium chloride, lithium cobalt oxide, and lithium manganate, due to the small trade volume, they are classified and aggregated for analysis, as shown in Fig. 3(d). The total trade volume of other lithium chemical products experienced significant fluctuations. In particular, before 2010, the trade volume showed great volatility and was relatively low. Afterwards, although the trade volume still fluctuated, it increased significantly, reaching a peak of 4597 t in 2017.

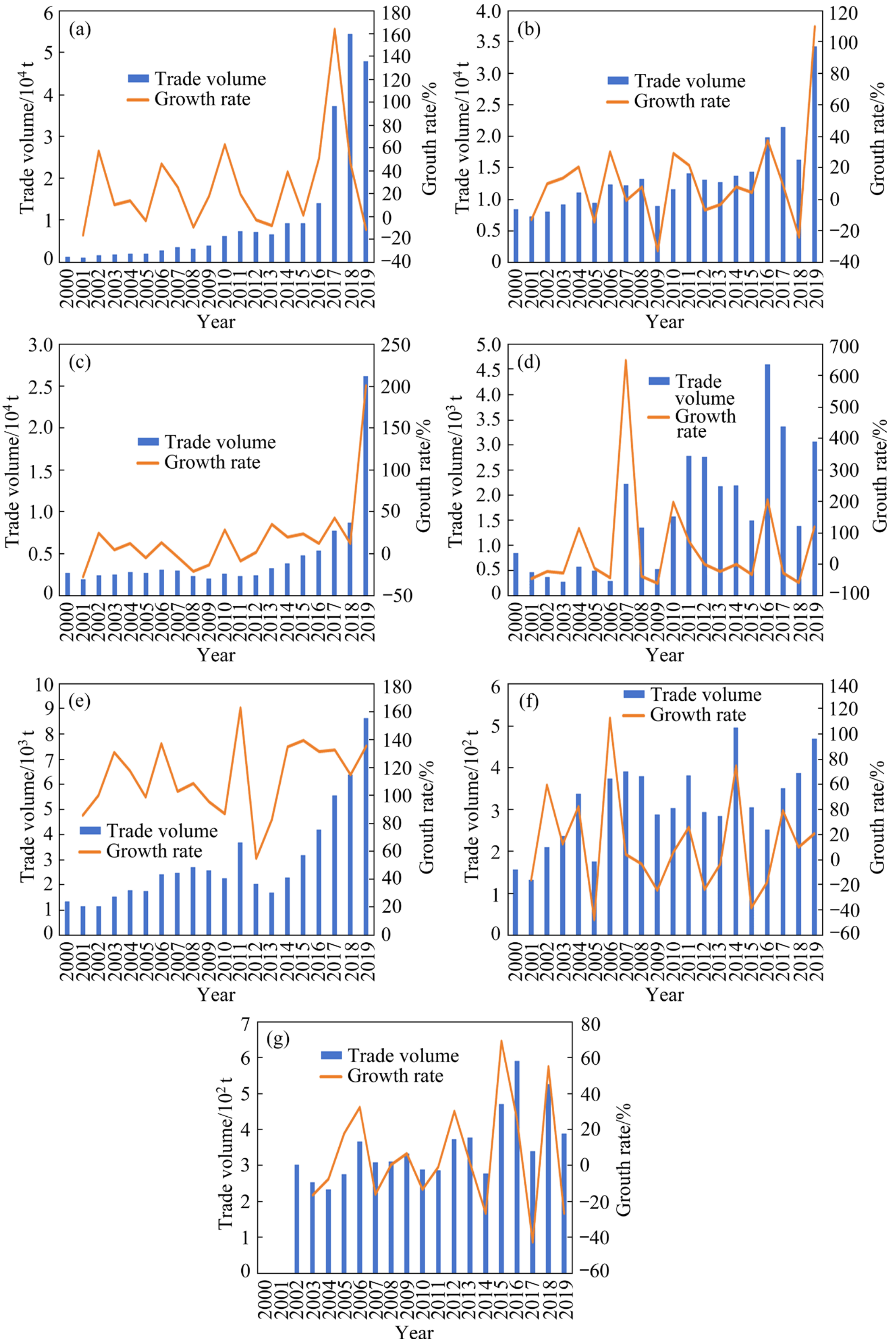

Fig. 3 Global lithium trade at different life cycle stages: (a) Lithium minerals; (b) Lithium carbonate; (c) Lithium hydroxide; (d) Other lithium chemicals; (e) Lithium-ion batteries; (f) Glass and ceramics; (g) Other lithium products

In the stage from product manufacture to product use, lithium-ion batteries and glass-ceramic are the most important traded products, and their trade changes are shown in Figs. 3(e, f). Lithium-ion batteries were the products with the largest trade volume in 2000—2019 and were widely used in consumer electronics, energy storage devices and new energy vehicles. Between 2000 and 2010, the trade volume of lithium-ion batteries increased steadily. After that, the growth entered a period of stagnation until 2015. With the rapid development of the battery industry, the trade volume of lithium-ion batteries also grew rapidly, reaching a peak of 8639 t in 2019. The trade volume in glass and ceramics remained relatively stable over the study period. There was a noticeable fluctuation in trade between 2000 and 2005. After that, the volume stabilized and, except for the years 2014 and 2019, remained consistently between 300 and 400 t.

In the stage from product manufacture to product use, the trade volume of other lithium products, such as polymers and pharmaceuticals, was relatively small in 2000—2019. Therefore, they were aggregated and analyzed as other lithium products, as shown in Fig. 3(g). The trade volume of these lithium products remained stable from 2000 to 2019, fluctuating around 300 t. However, the trade volume was relatively high in 2015, 2016 and 2018, reaching 471, 591 and 528 t, respectively.

In the global trade of lithium products at different life cycle stages, the trade volumes of lithium minerals, lithium carbonate and lithium hydroxide are larger, which are mainly concentrated in the stages of resource mining, chemical production and product manufacture, and are located in the middle and upper stream of the lithium industry chain. For trade in other products, lithium-ion batteries, glass and ceramics and other lithium products are located in the downstream of the industrial chain, belonging to the product manufacture and product use stages of life cycle, and their global trade volumes are relatively small. These results prove that most of the global lithium trade is dominated by midstream and upstream products, while trade in final products such as lithium batteries remains low. The development of the global lithium industry is not mature enough, and the overall manufacturing capacity needs to be further improved.

3.2 Analysis of intercontinental lithium material flows in international trade

The intercontinental lithium material flows in import and export trade are shown in Fig. 4. From 2000 to 2019, Asia was the largest importing continent, followed closely by Europe and North America. Prior to 2015, Asia's import volume grew steadily. Thereafter, Asia's lithium imports surged, increasing from 21297 t in 2015 to 98320 t in 2019. Europe and North America showed steady growth and remained the second and third largest importing continents. On the export side, Oceania, South America and Asia were the top three continents in terms of lithium export volumes. Oceania was second in terms of export volumes before 2016, but then jumped to first place, with a peak export volume of 54444 t in 2018. South America and Asia continued their steady growth in export volumes, ranking second and third, respectively.

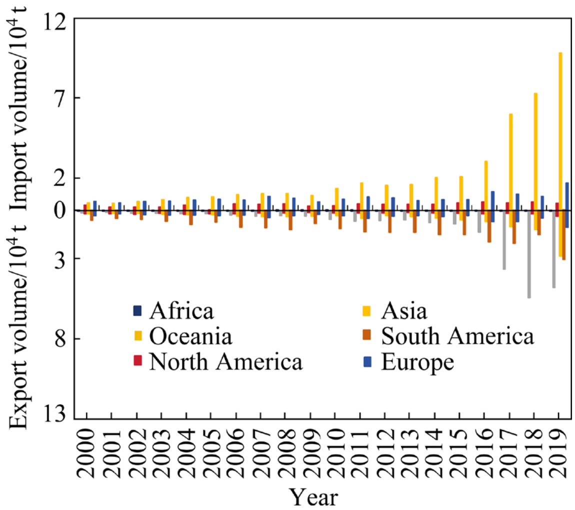

Fig. 4 Intercontinental lithium material flows in international trade

Figure 5 presents the share of intercontinental lithium material flows in import and export trade. For imports, as shown in Fig. 5(a), Asia accounted for the largest share of imports, and this share increased over time, from 33.3% in 2000 to 81.22% in 2019. Europe ranked second in terms of import volume share, but its share decreased significantly over the study period, from 39.4% in 2000 to 14.31% in 2019. The shares of other continents were smaller, all falling below 10% after 2016.

In terms of exports, as shown in Fig. 5(b), South America ranked the first in terms of export volume share. However, this share exhibited a downward trend and was overtaken by Oceania in 2017, falling from 41.5% in 2000 to 25.3% in 2019. Oceania, which ranked the second, showed an overall slow upward trend, increasing from 9.3% to 39.68% over the study period. Asia ranked the third in terms of export volume, with a relatively stable share of around 15%.

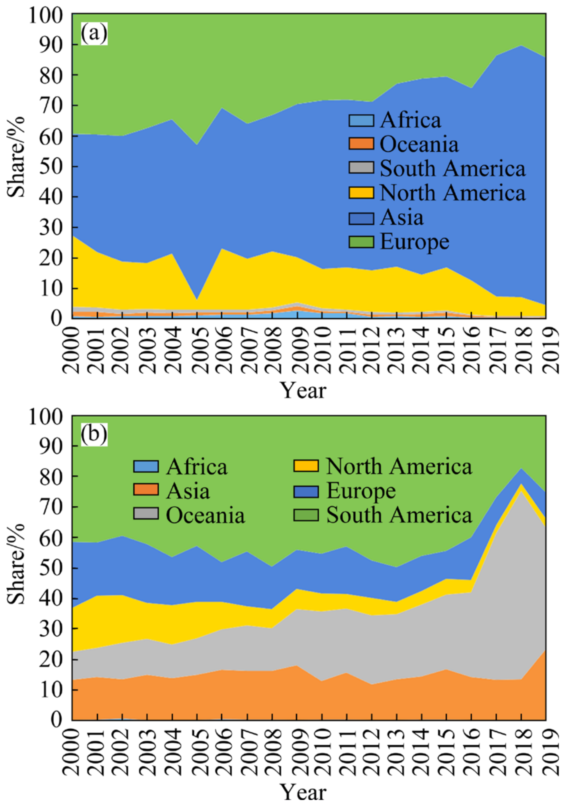

Fig. 5 Share of intercontinental lithium material flows in international trade: (a) Import; (b) Export

Further analysis in Fig. 6 examines the evolution in intercontinental trade volume of lithium products at different life cycle stages. Figure 6(a) shows the changes in intercontinental import and export volumes of lithium minerals from resource mining stage to chemical production stage between 2000 and 2019. Asia and Oceania dominated the import and export of lithium minerals, respectively, and experienced explosive growth after 2016.

During the stage from chemical production to product manufacture, the changes in inter-continental trade volume for lithium are shown in Figs. 6(b−d). For lithium carbonate trade, Asia and Europe were the continents with notable changes in trade volume. Starting in 2010, Asia overtook Europe as the continent with the largest import volume and then grew rapidly, significantly widening the gap with other continents. Regarding exports, South America became the continent with the largest export volume. In the trade of lithium hydroxide, Asia was far ahead in both imports and exports, while Europe was second in both imports and exports. Asia and Europe continued to lead in the trade of other lithium chemical products. Europe's trade volume experienced explosive growth from 2007, outpacing other continents. Meanwhile, Asia's trade volume of other lithium chemical products started to increase significantly in 2013 and even jumped to the first position in 2018.

Figure 6 shows the changes of intercontinental trade volume in lithium-ion batteries, glass-ceramics and other lithium products during the stage from product manufacture to product use. Asia was the leading region for lithium-ion batteries trade until 2015, when it was overtaken by Europe. North America's import volume increased steadily throughout the study period, consistently maintaining its third position. On the export side, Asia consistently maintained its status as the leading exporting continent, establishing a significant gap in export volume compared to other continents. Europe and North America ranked second and third, respectively. In terms of trade in glass-ceramics, Asia, Europe and North America were the main importers, with trade volume fluctuating. On the export side, Asia and Europe were more dominant and their trade volume fluctuated throughout the period. In the trade of other lithium products, Asia and Europe were in the lead on both the import and export side, with total trade volume fluctuating significantly from 2000 to 2019. In addition, North America's trade volume was relatively low, consistently ranking the third.

Figure 7 shows the changes in intercontinental lithium trade flows, dividing the years 2000—2019 into four periods: 2000—2004, 2005—2009, 2010—2014 and 2015—2019. Intercontinental lithium trade flows are compared and analyzed for these different time periods. Figure 7(a) presents the intercontinental lithium trade flows for the years 2000—2004. The main continents were Europe, Asia, South America and North America. Europe was the continent with the most active trade, with a volume of 42729 t. There was a significant amount of intracontinental lithium trade, with frequent trade between European countries. This was followed by import trade with South America. Asia ranked the second in terms of trade volume during this period with 41082 t. Asia's trade was mainly import based, with the largest volumes coming from South America, Oceania and North America, in that order. South America followed closely with trade volume

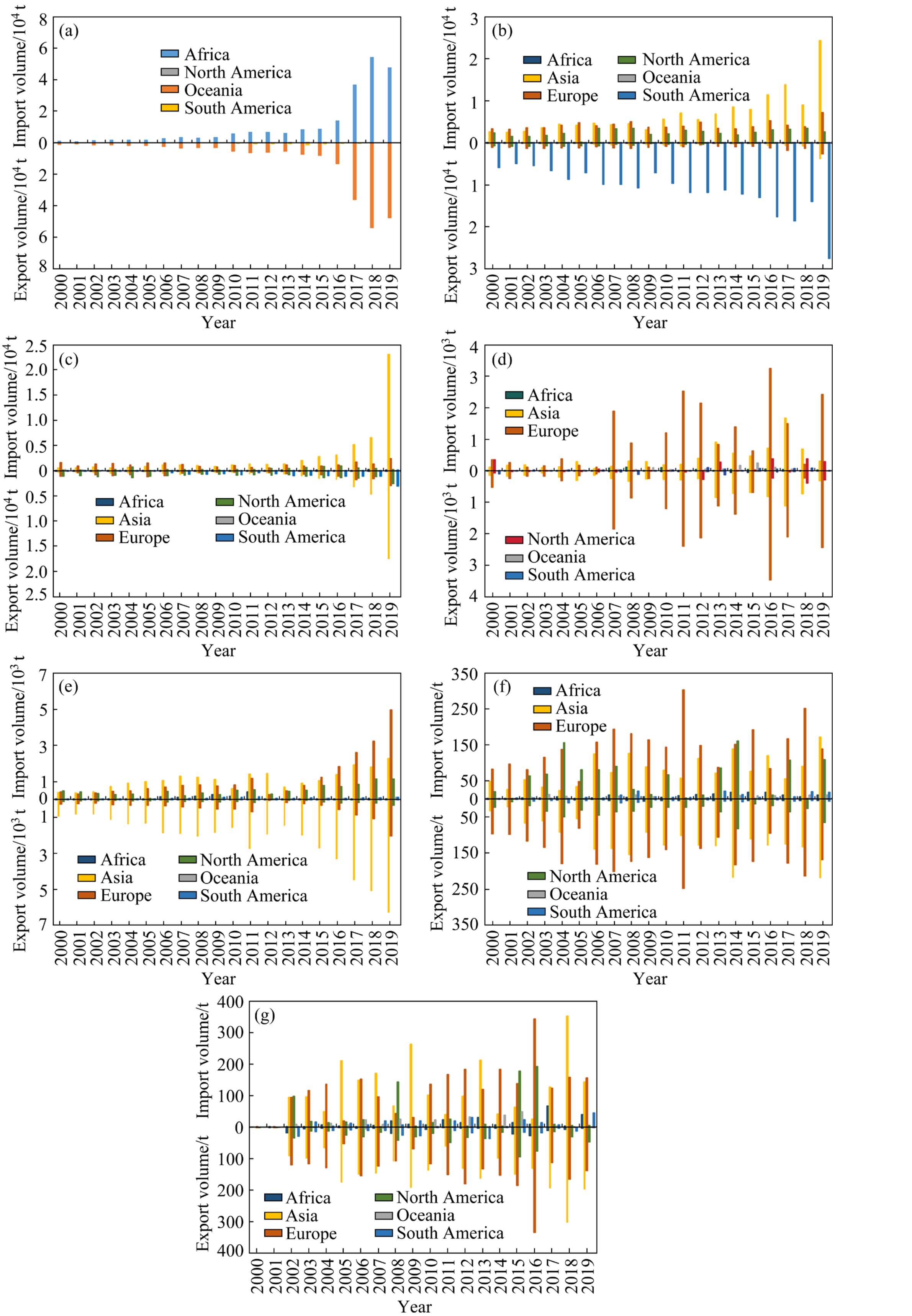

Fig. 6 Intercontinental lithium trade at different life cycle stages: (a) Lithium minerals; (b) Lithium carbonate; (c) Lithium hydroxide; (d) Other lithium chemicals; (e) Lithium-ion batteries; (f) Glass and ceramics; (g) Other lithium products

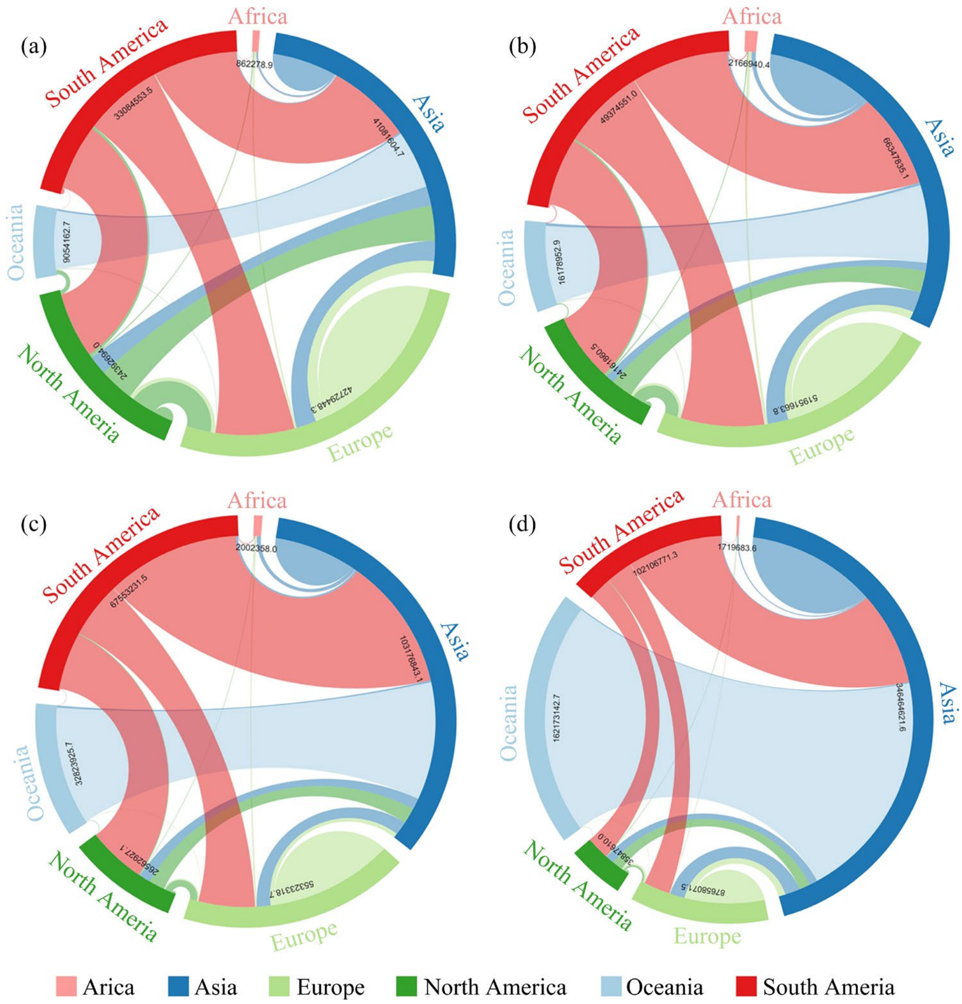

Fig. 7 Intercontinental lithium trade flows (Unit: t): (a) 2000—2004; (b) 2005—2009; (c) 2010—2014; (d) 2015—2019

of 33085 t, mainly focused on exports, with the main destinations being Asia, Europe and within South America itself. North America's lithium trade flows were more dispersed, with the main activity being import trade from South America, followed by export trade to Asia and Europe.

Figure 7(b) illustrates intercontinental lithium trade flows from 2005 to 2009. Asia, Europe and South America were the most active trading regions. During this period, Asia overtook Europe to become the continent with the highest trade volume, reaching 66348 t. Asia's trade was mainly based on imports from South America and Oceania, as well as intercontinental trade between its own countries. Europe ranked the second with a trade volume of 51952 t, mainly due to trade between countries within the continent, followed by imports from South America. South America ranked the third with a total trade volume of 49375 t during this period, continuing to focus on exports. The main export destinations were Asia, Europe and North America, in that order.

Figure 7(c) analyzes intercontinental lithium trade flows from 2010 to 2014. Asia, Europe and South America remained the most active continents in lithium trade. Asia maintained its top position with a trade volume of 103177 t, relying mainly on import trade from South America and Oceania. During this period, South America's trade volume surpassed that of Europe, climbing to the second place with 67553 t. Its main trade activities were exports to Asia, Europe and North America. Europe slipped to the third place during this period, and its trade activities focused on intra-continental trade and imports from South America.

Finally, Fig. 7(d) explores intercontinental lithium trade flows from 2015 to 2019. Asia, Oceania and South America emerged as the leading continents. During this period, Asia became the most dominant continent, not only maintaining its position as the top lithium trade volume, but also accounting for 47% of global trade volume, far ahead of other continents. Specifically, Asia's trade volume was 346465 t. Its main trade activities were imports from South America and Oceania, as well as intra-continental trade. Oceania ranked the second with a total trade volume of 162173 t, mainly driven by export trade to Asia. South America fell to the third place during this period with a trade volume of 102107 t, still mainly driven by exports to Asia, Europe and North America.

3.3 Analysis of lithium material flows among trading countries

The lithium material flows and shares among the major importing countries are presented in Fig. 8. China, Japan, United States, Korea, Germany, Belgium, France, Spain and Russia were the countries with the most active lithium imports. In particular, before 2013, the main countries importing lithium were China, the United States and Japan. These countries occupied the top three positions in terms of global lithium import volumes, accounting for around 50% of the global total. Subsequently, the United States' share of imports declined. Meanwhile, due to the rapid development of the domestic lithium-ion battery industry, the import volumes of China, Japan and Korea continued to grow at a high rate, forming a lithium import hub represented by these three countries. Notably, starting from 2017, the lithium imports of these three countries accounted for more than 70% of the global total, peaking at 79.4% in 2018. The global concentration of lithium imports became increasingly high over time, showing a continuous upward trend. These eventually led to a situation where a few countries dominated most of the global lithium import trade activity.

Figure 9 analyzes the lithium material flows and shares of the main exporting countries. Chile and Australia, with their resource advantages, became the world's major lithium exporters, accounting for more than 50% of the world's total lithium exports. During 2000—2019, these two countries became the world's largest suppliers of lithium. From 2000 to 2016, Chile led the world in lithium exports, and from 2016, Australia became the largest exporter of lithium. Notably, China consistently maintained its position as the world's third largest exporter, with a slowly increasing share of global trade, peaking at 20.9% in 2019. Other active exporters include Argentina, the United States, Germany, Belgium, Japan and Korea. From the above analysis, it is clear that global lithium exports were concentrated in a few major countries, which accounted for over 90% of total global exports, and that export volumes were increasingly concentrated in these major countries.

Figure 10 illustrates the lithium flows between the main countries at different stages of the life cycle from 2000 to 2019. The total trade volume of lithium minerals during 2000—2019 was 223153 t, with the main exporting countries being Chile and Australia. The main importing countries were China and the United States, with China importing more than the United States, mainly from Australia. The

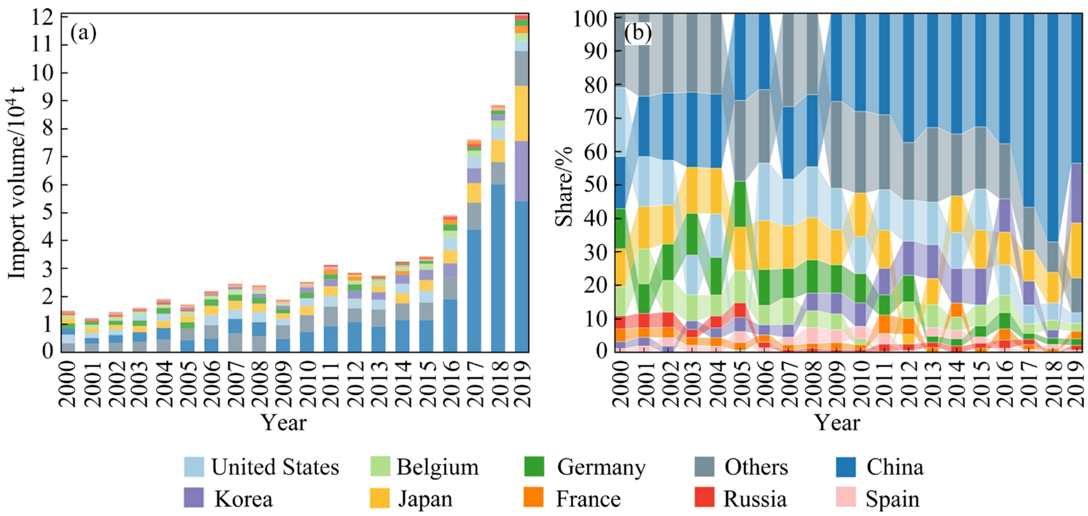

Fig. 8 Lithium material flows (a) and shares (b) in major importing countries

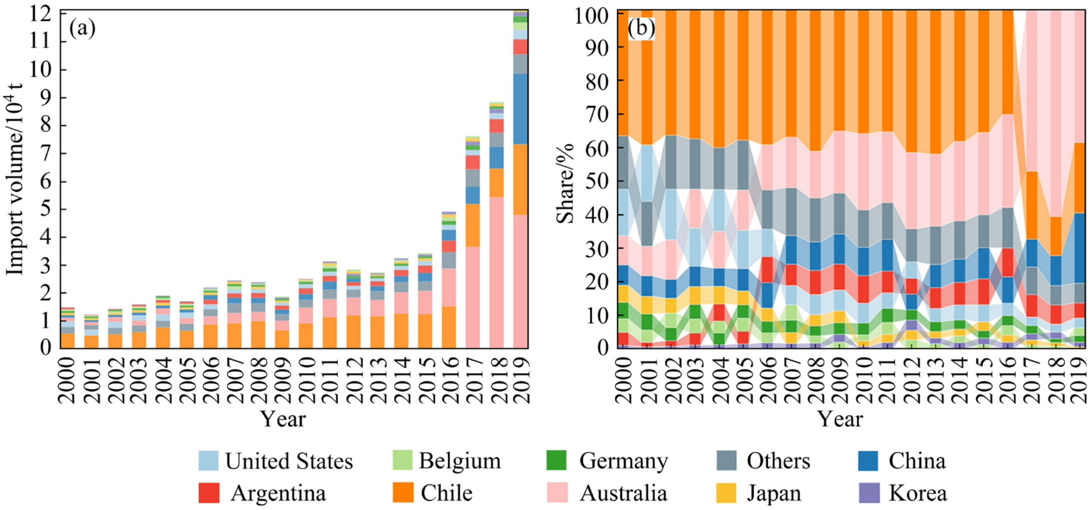

Fig. 9 Lithium material flows (a) and shares (b) in major exporting countries

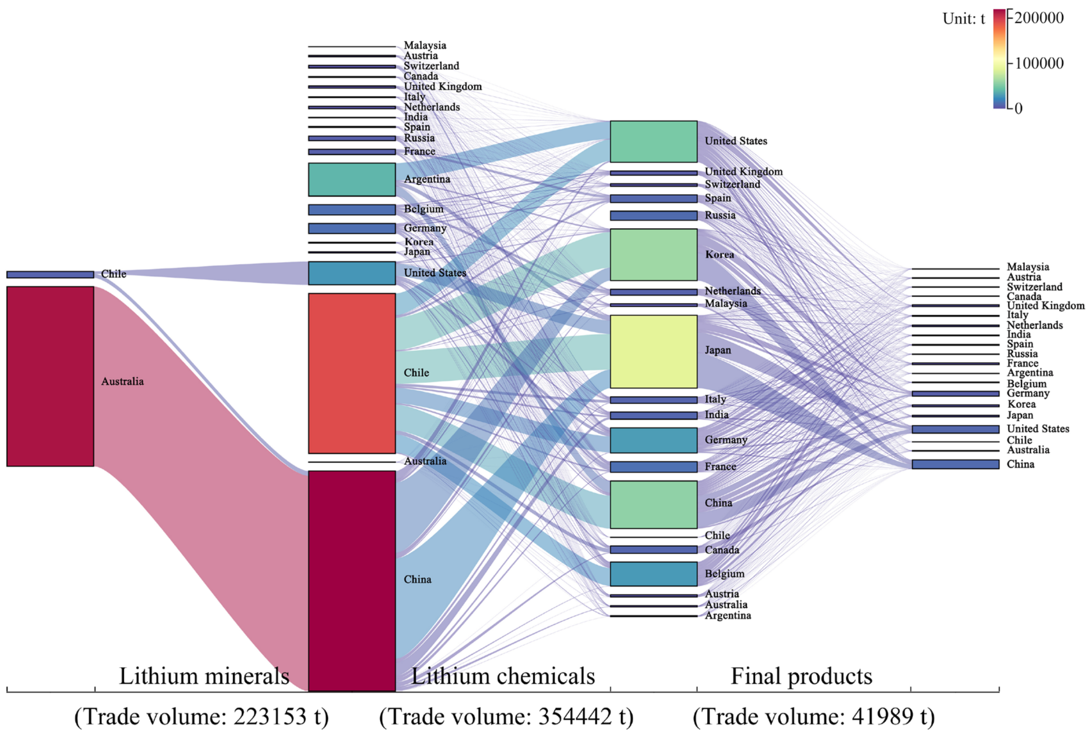

Fig. 10 Lithium trade flows across major countries at different life cycle stages

trade volume of lithium chemical products over the twenty years was 354442 t. The major exporting countries include Chile, China, Argentina and the United States, and the major importing countries include China, the United States, Japan, Korea, Belgium, Germany and others, with China leading in both imports and exports. The total trade volume of final products was 41989 t. The major exporting countries were China, the United States, Japan, Korea, Germany, etc. The major importing countries include China, the United States, Germany, the United Kingdom, France, etc. The volume of imports for these countries was lower than the exports of the main exporting countries, with China taking a leading position. At the final product stage, lithium trade flows were the largest between China, Japan and Korea. Among them, the trade volume from Japan to China was 5229 t, and the trade volume from Korea to China was 4085 t. For other major trading countries, Japan's trade to the United States was 3015 t, and Korea's trade to Germany was 1430 t.

3.4 Comparative analysis of lithium material flows between China and United States

As the global lithium trade evolves, the competition for this crucial resource has intensified among major countries. China and the United States, holding significant stakes in international trade, become particularly noteworthy due to recent trade conflicts. Given lithium's pivotal role in the strategic development of both countries, China and the United States serve as ideal subjects for a comparative analysis of lithium material flows in international trade.

3.4.1 Lithium material flows of China

The changes of China's lithium material flows in import and export trade from 2000 to 2019 are shown in Fig. 11. On the import side, China's lithium import trade volume grew steadily from 2272 to 11520 t between 2000 and 2015. With the rapid development of China's new energy vehicle industry, lithium demand surged, rising rapidly from 18998 t in 2016 to 54107 t in 2019. Compared to imports, China's lithium export volume was smaller. During the period, China's lithium export volume generally maintained a steady upward trend, but after 2016, it grew rapidly from 3806 t to 25262 t in 2019.

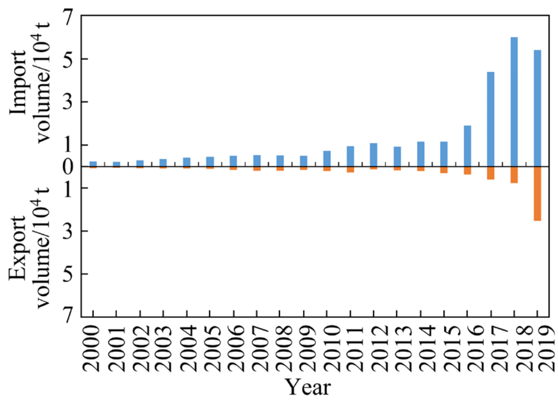

Fig. 11 China's lithium material flows in international trade

Figure 12 examines the changes in trade volumes of China's lithium products at different life cycle stages from 2000 to 2019. On the import side, the main product imported into China was lithium minerals. The volume of minerals increased steadily from 1248 t in 2000 to 47023 t in 2019. The second largest import was lithium carbonate, which showed a fluctuating upward trend in trade volume from 2000 to 2019. The trade volume of lithium carbonate maintained a steady increase from 2000 to 2005, then gradually decreased, reaching a low volume in 2009, followed by a fluctuating upward trend. In addition, the import volume of other lithium products, in comparison, remained relatively lower throughout this period.

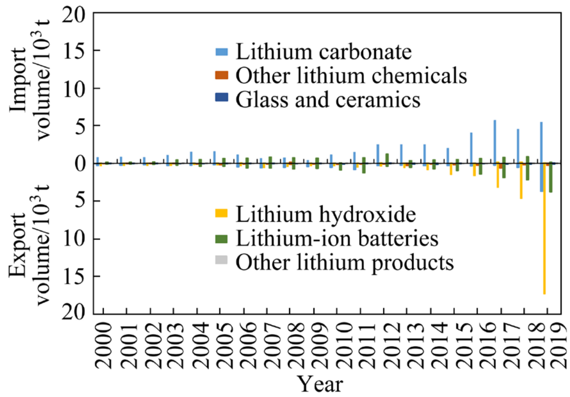

Fig. 12 China's lithium trade at different life cycle stages

In terms of exports, lithium hydroxide was China's main export product. Its export volume generally maintained a steady increase for most of the time, but showed a notable surge from 2017 to 2019, increasing from 3251 to 17397 t. The second major export product was lithium-ion batteries, with China's trade volume increasing from 120 t in 2000 to 3791 t in 2019. The third major export product was lithium carbonate, which experienced a steady increase from 2000 to 2018, followed by an explosive growth in 2019, reaching a trade volume of 3724 t. In contrast, the export volumes of other products were smaller. Given that China's exports in lithium minerals are zero, we do not include trade of lithium minerals in the figure.

Figure 13 presents an analysis of the trade volume shares of China's lithium products at different life cycle stages. As shown in Fig. 13(a), the main products in terms of import trade volume were lithium minerals, lithium carbonate and lithium-ion batteries. From 2000 to 2019, lithium minerals accounted for the largest share of import trade volume, increasing dramatically from 54.9% in 2000 to 88.8% in 2019. Lithium carbonate, which ranked the second in import trade volume share, experienced a significant decline, with its share falling from 36.9% in 2000 to just 10.2% in 2019. Lithium-ion batteries were close behind in the third place. Their share of import trade volume initially grew steadily from 2000 to 2009. However, this trend reversed in the following years, culminating in a minimal share of just 0.4% in 2019.

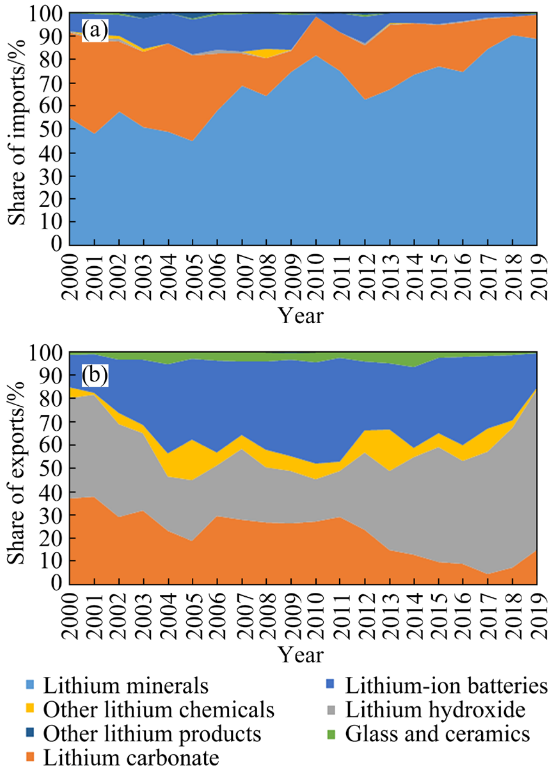

Fig. 13 Share of China's lithium trade at different life cycle stages: (a) Import; (b) Export

Figure 13(b) presents an analysis of the export trade volume shares of China. The results reveal that lithium carbonate, lithium-ion batteries and lithium hydroxide held significant shares in exports. Notably, lithium hydroxide emerged as the top product. Its export share initially decreased, dropping from 43.2% in 2000 to 18.4% in 2010, but then rebounded sharply, peaking at 68.9% in 2019. Lithium-ion batteries constituted the second largest export share. This category experienced a fluctuating trend, initially increasing from 13.8% in 2000 to as high as 44.9% in 2011, before declining to 15% by 2019. Lithium carbonate, holding the third in export share, showed a consistent decrease over the years, falling from 37.1% in 2000 to 14.7% in 2019.

3.4.2 Lithium material flows of the United States

Figure 14 provides a detailed examination of the United States' lithium material flows in import and export trade from 2000 to 2019. Regarding imports, the United States experienced a fluctuating but overall upward trend in lithium trade volume. The increase was moderate, starting from 2273 t in 2000 and reaching 54108 t by 2019. In contrast, the lithium export volume of the United States was initially lower than import volume. There was a steady decline in export volume from 2000 to 2009, dropping from 2023 to 1130 t. This trend was reversed in the following decade, with exports rising steadily to a volume of 3351 t in 2019.

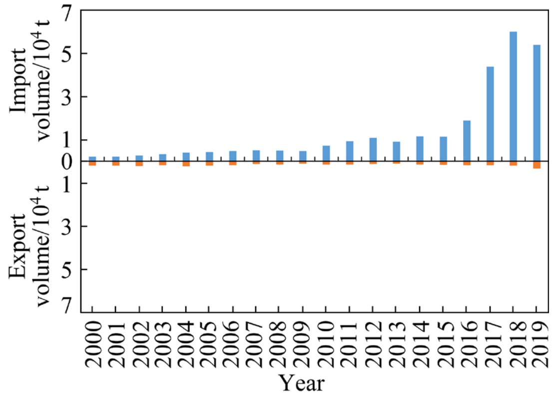

Fig. 14 United States' lithium material flows in international trade

Figure 15 examines the changes in trade volumes of the United States' lithium products at different life cycle stages from 2000 to 2019. The primary import for the United States during this period was lithium carbonate, which held a significant lead in trade volumes over other products. The trade volume of lithium carbonate showed fluctuating trends, with only a marginal increase from 2173 t in 2000 to 2387 t in 2019, despite peaking at 3239 t in 2018. Following lithium carbonate, lithium-ion batteries emerged as the second-largest import. The United States had a steady rise in the import of the batteries, with trade volume increasing from 418 t in 2000 to 1057 t in 2019.

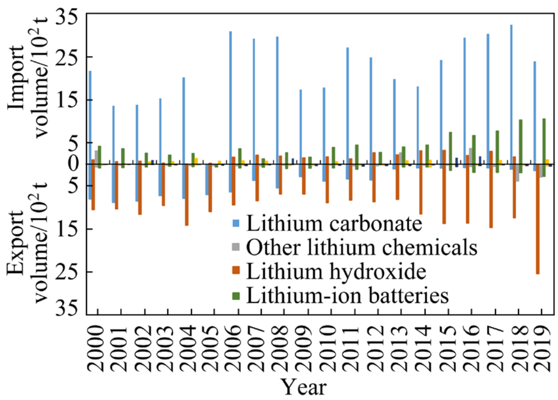

Fig. 15 United States' lithium trade at different life cycle stages

In terms of exports, lithium hydroxide stood out as the most important export product, showing a pattern of initial decline followed by a significant increase. Between 2000 and 2009, exports of lithium hydroxide gradually decreased from 1052 to 688 t. However, this trend reversed from 2010 onwards, with exports rising sharply from 897 t in 2010 to 2538 t in 2019. The second major export was lithium carbonate, which had a significant decline in its export volume from 807 t in 2000 to just 150 t in 2019. Meanwhile, lithium-ion batteries, although a smaller portion of the export market, displayed a slow but steady upward trend, increasing from 82 t in 2000 to 284 t in 2019. Given that there are zero exports of lithium minerals from the United States, we do not put lithium minerals trade into the figure.

Figure 16 provides an analysis of the trade volume share of the United States' lithium products at different life cycle stages from 2000 to 2019. As shown in Fig. 16(a), lithium carbonate had the largest share of imported trade volume. Its share initially increased from 72.1% in 2000 to 87.4% in 2007, before decreasing to 67.3% in 2019. Lithium-ion batteries had the second largest share of the imported trade volume. The share fluctuated over the years, generally remaining around 15% until 2018, when it exceeded 20% and peaked at 29.8% in 2019. Lithium hydroxide, which ranked the third in imports, had a relatively smaller share, fluctuating around 5% throughout the period.

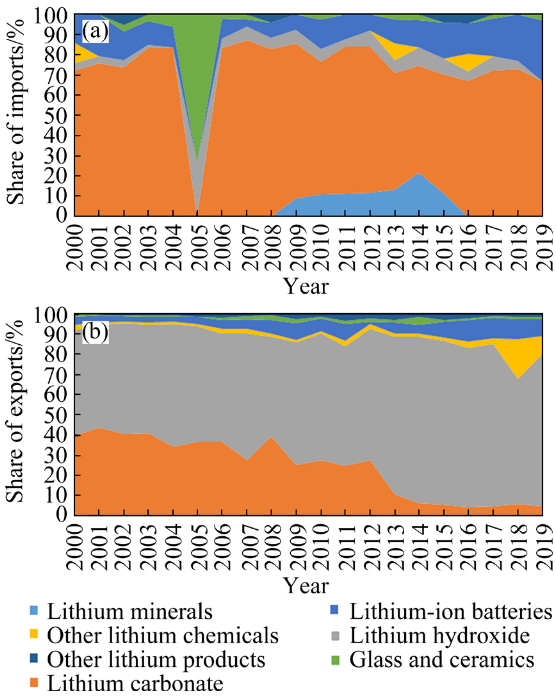

Fig. 16 Share of United States' lithium trade at different life cycle stages: (a) Import; (b) Export

In terms of exports, Fig. 16(b) shows that lithium hydroxide, with the largest export share, exhibited a steady growth from 52% in 2000 to 82.9% in 2014. However, this trend later shifted to a period of fluctuation, resulting in a decline to 75.7% in 2019. In contrast, lithium carbonate, the second ranked export product, experienced a significant downward trend. The share in export trade volume sharply decreased from 39.9% in 2000 to just 4.5% in 2019. Lithium-ion batteries, ranking the third, displayed a gradual upward trend in the export share, increasing from 4.1% in 2000 to 8.5% in 2019.

Based on the above analyses, the following suggestions are proposed. First, the management of lithium trade should be improved. With the annual increase in global lithium trade volume and the more frequent flows of lithium trade across continents and countries, the lithium international trade is rapidly evolving, and competition among nations is becoming fiercer. Therefore, government departments or policymakers in various countries need to further improve the management of lithium trade, standardize trade practices and coordinate the relationship with other trading countries to ensure the smooth development of import and export trade.

Second, international trade cooperation should be actively promoted. Government departments and policymakers need to strengthen ties with other trading countries to enhance international trade cooperation. In terms of lithium supply, there is a need to maintain relationships with supplier countries to form a diversified pattern of lithium resource supply. Meanwhile, it is necessary to enhance trade relations with countries in need of lithium products, and expand the international market for lithium products in the country, so as to gain a dominant position in the global market.

Third, the technological innovation capacity needs to be enhanced. With the exception of lithium minerals, lithium products trade at all other life cycle stages is dependent on the technological level of the national lithium industry. Accordingly, government departments should increase policy support and capital investment in lithium industry-related technologies, and industry stakeholders should enhance their own technological innovation capabilities. These can enhance the competitiveness of domestic lithium products in international trade, and thus promote the development of strategic emerging industries.

Our study still has some limitations, and further research is needed. Based on lithium trade data from 2000 to 2019, we analyze lithium material flows in international trade. Given the availability of data, the data in this work was only updated to 2019 and do not cover the latest trade data for lithium. Future research is required to further update trade data and explore the lithium material flows through international trade in recent years.

4 Conclusions

(1) At the global level, the total volume of lithium trade continued to rise, with a sharp increase from 2015, reaching 121116 t in 2019. This trade was focused on lithium minerals, lithium carbonate and lithium hydroxide rather than final lithium products.

(2) At the intercontinental level, Asia led in lithium imports, accounting for a substantial 81.22% share of global trade, while Oceania dominated lithium exports with 39.68% share. Throughout the entire life cycle, Asia is the most important continent for lithium trade.

(3) At the national level, China, Japan and Korea gradually became major importing countries, with their combined import share exceeding 70% globally after 2017. Meanwhile, Chile and Australia were the major exporting countries, with their export volumes accounting for more than 50% of the global share.

(4) In the comparative analysis between China and the United States, China's lithium trade volume witnessed a rapid increase after 2016, and the United States' lithium trade volume showed a fluctuating upward trend. China mainly exported lithium-ion batteries, lithium hydroxide and lithium carbonate, while the United States primarily imported lithium carbonate and lithium-ion batteries.

CRediT authorship contribution statement

Zi-tao ZHANG: Formal analysis, Conceptualization, Writing − Original draft; **Yun QIN:** Software, Methodology, Writing − Review & editing, Validation; **Xin SUN:** Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Nos. 71671187, 71874210, 71633006), the Natural Science Foundation of Hunan Province, China (No. 2024JJ6539), the National Social Science Fund of China (No. 22&ZD098), and the Social Sciences Fund of Hunan Province, China (No. 24YBQ138).

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国际贸易中的锂物质流分析：基于生命周期视角

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摘 要：基于生命周期视角，运用物质流分析方法探究 2000—2019 年国际贸易中的锂物质流。研究结果表明，全球层面下，锂贸易总量持续上升，2019 年高达 121116 t。锂贸易以含锂矿石、碳酸锂和氢氧化锂为主，而非最终锂产品，表明全球锂产业还不够成熟。洲际层面下，亚洲的进口贸易与大洋洲的出口贸易全球领先，占比分别为 81.22%和 39.68%。国家层面下，中、日、韩成为主要进口国，智利和澳大利亚则为主要出口国。此外，中国的贸易量远超美国，中国的出口以锂电池为主，而美国则主要进口锂电池，证明中国的锂产业发展相对更快。

关键词：锂；物质流分析；国际贸易；生命周期

(Edited by Bing YANG)