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Structural evolution of global plastic life cycle trade: A multilayer network perspective

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ABSTRACT

International trade in plastics accounts for 5 % of total merchandise trade and involves all nations in modern society. To explore global plastic life cycle trade, a life cycle-based plastic trade multilayer network (LC-PTMN), including a raw materials layer, a semifinished products layer, a plastic products layer, and a plastic waste layer, is constructed. The structure of the global plastic trade is studied by analyzing each layer in the LC-PTMN from 1990 to 2019. The results reveal that the LC-PTMN has a prominent hierarchical structure and a small-world property, namely, a few countries occupy most trade channels and trade volume. The trade channels and trade volume in the plastic waste layer are the most concentrated. Countries with massive channels have a strong cooperative ability to prompt their trading partners to form close groups. Developing countries in Asia, such as Vietnam and Turkey, have outstanding performance in the LC-PTMN. The major trade flows have distinct geographical patterns, mainly occurring in intra-North American, intra-Asian and North American-Asian networks. Additionally, the community structures of the LC-PTMN have tended to stabilize. Dramatic changes are mainly caused by the merging of European countries with Asian and African countries and the split of North American countries from other countries. These findings will help policy makers encourage plastic sector transformation.

1. Introduction

Since mass production of plastics began in the 1950s, it has been widely used in the packaging, transportation, and electronics fields. Because of its outstanding properties, plastic has outstripped most other manmade materials and rose approximately 200-fold from 2 million tons in 1950 (Geyer et al., 2017) to 360 million tons in 2020 (Ferdous et al., 2021). Global plastic trade has expanded vastly over the past three decades, fueled by economic globalization and the rapidly increasing demand for plastic products (Wang et al., 2020b).

Due to the complexity and interdependence of global trade, examining the structural evolution of the international plastic trade calls for complex network analysis (van den Brink et al., 2020). For example, Ren et al. (2020) built an international plastic resin trade network and studied its spatiotemporal features at the worldwide, regional and country levels. Wang et al. (2020b) constructed a global plastic waste trade network and analyzed its spatiotemporal evolution. However, none of these studies analyzes trade relations across the global plastics industry and the life cycle of plastics.

To fill this research gap, this study builds a life cycle-based plastic trade multilayer network (LC-PTMN), which includes a raw materials layer, a semifinished products layer, a plastic products layer, and a plastic waste layer. The topological metrics in each layer are revealed, and the main trading countries and trade communities are identified. The main contribution of this study is to explore the heterogeneity and diversity of countries in the global plastic life cycle trade. The findings enable governments to identify the leading countries in the plastic life cycle trade and seek potential markets to prepare for and adapt to unexpected trade interruptions.

The remainder of this paper is organized as follows. Section 2 reviews the related works on the plastic trade. Section 3 presents the data and methods. The results and relevant discussion are presented in Section 4. Section 5 presents the conclusion.

2. Literature review

Plastic pollution has become a widely studied environmental issue in academia (Brooks et al., 2018), as reflected by the growing numbers

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Nomenclaturey
Year

M	Multilayer network
$G^{[y,M]}$	Family of directed graphs in year y
$C^{[y,M]}$	Set of interconnections between nodes belonging to different graphs in year y
$V_{\alpha}^{[y,M]}$	Number of countries in the α layer in year y
$E_{\alpha}^{[y,M]}$	Trade relations in the α layer in year y
$W_{\alpha}^{[y,M]}$	Trade volumes in the α layer in year y
$C_{\alpha\beta}^{[y,M]}$	Set of interconnections between the α layer and β layer in year y
$A^{[y,M[\alpha]]}$	Intralayer adjacency matrix in year y
$A^{[y,M[\alpha\beta]]}$	Cross-layer adjacency in year y

Abbreviations

LC-PTMN	Life cycle-based plastic trade multilayer network
GPWT	Global plastic waste trade
PE	Polyethylene
NMI	Normalized mutual information
ISO3	International Organization for Standardization 3166

of papers and reports in this area. A considerable amount of research is devoted to studying the global plastic waste trade (GPWT) by applying pure complex network theory. Wang et al. (2020b) established a GPWT network and found that the GPWT flow changed from China to Southeast Asian countries after China's “National Sword” policy. This result was confirmed by Zhao et al. (2021). In addition, Zhao et al. (2021) found that the GPWT was a sparse network. The relevant countries were less dependent and had fewer trade connections. Shi et al. (2021) analyzed the historical evolution of the GPWT, showing that China's import policies are the main driver of its expansion and contraction. Unlike previous scholars, Pacini et al. (2021) constructed a network analysis of the main polymers of plastic waste (ethylene, polyvinyl chloride, and styrene). They found that the European Union and North American countries played great roles in the GPWT, with strong links to a few Asian countries.

Meanwhile, several scholars have combined complex network theory with other techniques to explore the GPWT. Huang et al. (2020) combined it with a multiregional input–output model to model the global impact of China's ban on plastic waste imports. They found that China, the USA, the European Union (EU) and Germany were the main players in the GPWT network, and other large economies were unlikely to replace China's role in the short term. Xu et al. (2021) constructed an evolutionary game model of marine plastic waste treatment combining an evolutionary game with a complex network and explored the impact of economic factors, relational structure and game structure on the evolution of management cooperation in addressing marine plastic waste. Li et al. (2021) analyzed the impact of the collapse of the GPWT on the circular economy by using a cascading failure model and scenario analysis and proposed global mitigation strategies in response to trade fluctuations. Zhao et al. (2022) explored the impact of China's plastic waste ban on the GPWT's future development using link prediction and the quadratic assignment procedure method. Their findings suggested that in the future, plastic waste was likely to flow to countries in the Asia-Pacific, Middle East and Africa regions, while European countries would intensify their internal recycling and processing of plastic waste.

In addition to research on the global trade in plastic waste, scholars have extensively studied international trade in other plastic items. Ren et al. (2020) built an international plastic resin trade network and studied its spatiotemporal features at the worldwide, regional and country levels. Their results showed that the China-USA resin trade was mainly complementary and that a China-USA trade war would not benefit it. Xu et al. (2020) studied the global polyethylene (PE) waste trade from 1976 to 2017. They found that after the mid-1990s, PE waste essentially flowed from developed economies (mainly the EU and the USA) to developing economies such as China. Zappitelli et al. (2021) explored the global trade structure of primary plastic and reported estimates of specific impacts, including greenhouse gas emissions, cumulative fossil energy demand, and embedded carbon.

To shed light on the gaps in the related literature reviewed above, Table 1 summarizes the related studies in the global plastic trade area and categorizes them based on the plastic types/products, applied methodology, analysis period and regions/countries of analysis.

The studies referenced in Table 1 provide some insights into the topological features of the international plastic trade and the trade relationships among some core countries. However, previous studies have mainly focused on one or several plastic items, and none have tracked the plastic trade across its entire life cycle. This study aims to fill this gap and explore the structural evolution of global plastic life cycle trade.

Table 1
Related studies on the global plastic trade.

Publication	Plastic products	Methodology	Time	Findings
Huang et al. (2020)	Plastic waste	Complex network; Multiregional input–output model	2015	China's imports of plastic waste are mostly driven by domestic demand for material made from recycled plastics.
Ren et al. (2020)	Plastic resin	Complex network	1988–2017	The plastic resin trade between the USA and China was mostly complementary.
Wang et al. (2020b)	Plastic waste	Complex network	1988–2017	Plastic waste trade streams have been rerouted to Southeast Asian nations as a result of China's import prohibition.
Xu et al. (2020)	Polyethylene	Complex network	1976–2017	After the mid-1990s, PE waste basically flowed from developed economies, mainly the EU and the USA, to developing economies, such as China.
Pacini et al. (2021)	Plastic waste	Complex network	2018	In the worldwide plastic scrap trading network, the EU and North American countries play a significant role.
Shi et al. (2021)	Plastic waste	Complex network	1992–2018	From 1992 to 2012, the global plastic trade in plastic waste increased from 0.9 million tons to 16.4 million tons.
Zhao et al. (2021)	Plastic waste	Complex network	1990–2019	The center of gravity of the global trade network in plastic waste has changed, and the import center has gradually changed from China to Southeast Asia.
Li et al. (2021)	Plastic waste	Complex network; Cascading failure model; Scenario analysis	2009–2018	Most countries have been overloaded with plastic waste compared with their ordinary capacity since China's import ban in 2017.
Xu et al. (2021)	Plastic waste	Complex network	2018	The key to the current cooperative governance of marine plastic waste is to build a stable and long-term market mechanism and properly handle the influence of major powers.
Zappitelli et al. (2021)	Primary plastic	Complex network; Life cycle assessment	2018	In 2018, embodied greenhouse gas emissions of the global primary plastic trade network were comparable to annual carbon dioxide emissions of developed nations such as Italy and France.
Zhao et al. (2022)	Plastic waste	Complex network; Quadratic assignment procedure method	2010–2019	Plastic waste may continue to flow to countries in the Asia–Pacific, Middle East, and Africa regions, while European countries will strengthen their internal recycling and processing of plastic waste.

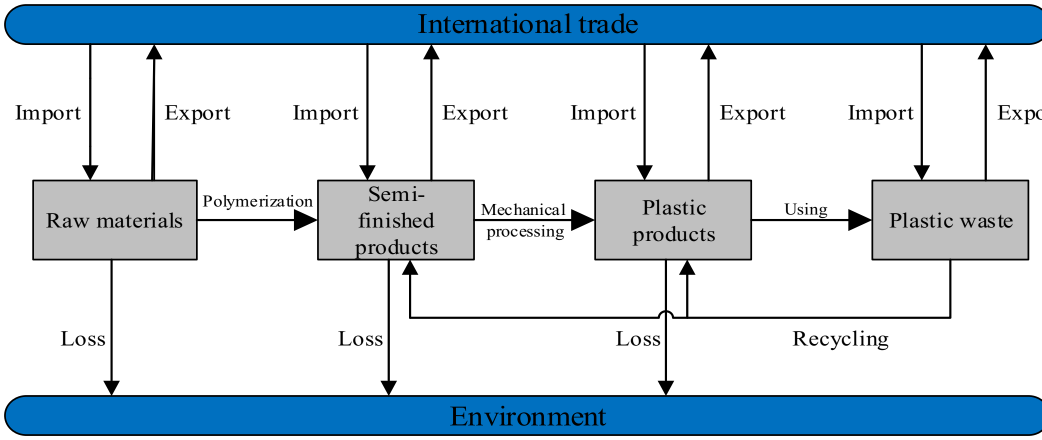

Fig. 1. Trade multilayer network based on the plastic life cycle.

3. Data and methods

3.1. Life cycle-based plastic trade multilayer network

Combining the plastic life cycle with a complex network, this study builds a life cycle-based plastic trade multilayer network (LC-PTMN), as shown in Fig. 1. The four stages of the plastic life cycle are production, manufacturing, consumption, and waste management, as shown in Fig. 2. The corresponding materials in each stage are plastic raw materials, plastic semifinished products, plastic products and plastic waste, respectively.

In the production stage, olefin polymers made from petroleum are included together with some raw materials, such as natural resins, cellulose, synthetic resins and ion exchangers. In the consumption stage, pure plastic products are included as well as products containing plastic components. The waste management stage contains the discarded parts of normal plastic products and the waste and scrap generated in the production and manufacturing stages.

3.2. Data

The plastic trade data for the four stages are extracted from the UN Comtrade Database, which includes trade data of countries and regions. Plastic trade data between countries were chosen for this study. Since each country voluntarily reports trade data, there are some inconsistencies in the extracted data. The specific data cleaning process is shown in Appendix A1. This study chooses plastic trade data containing plastic components, and the study period is from 1990 to 2019. The

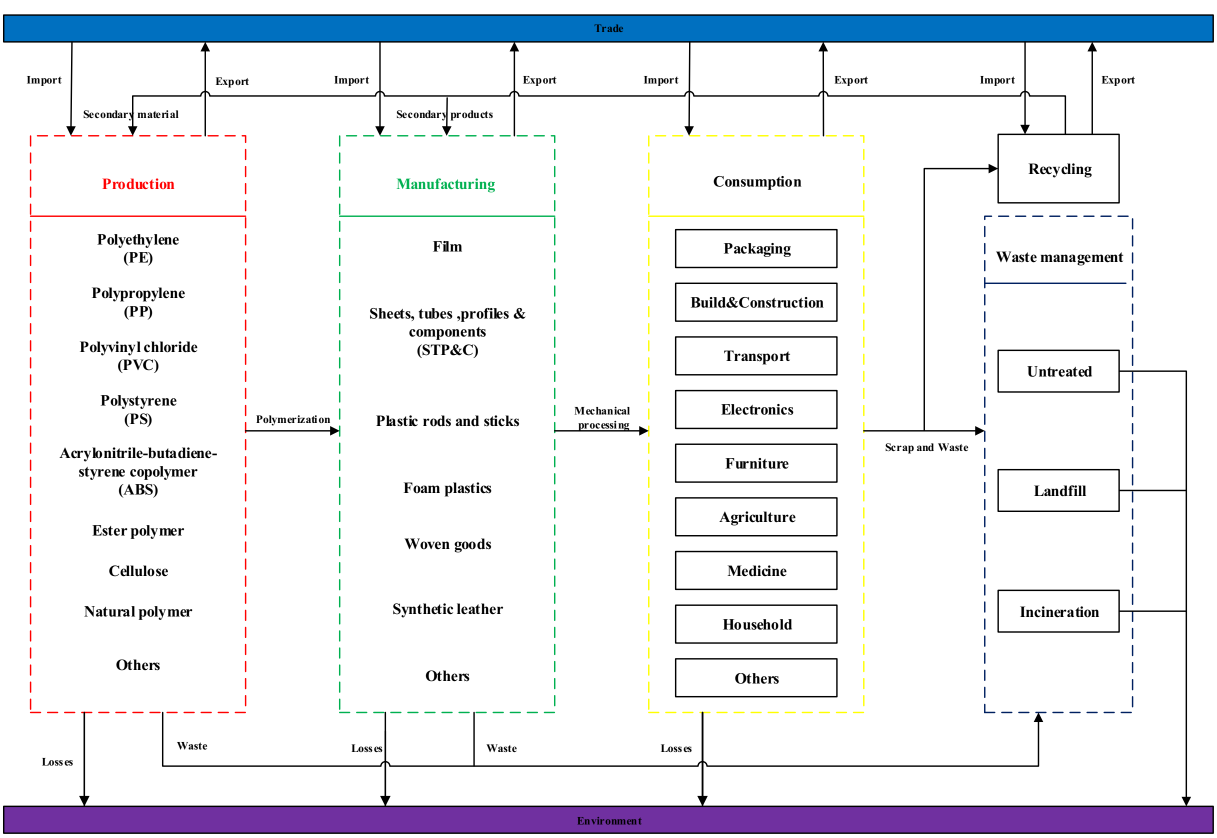

Fig. 2. Schematic diagram of plastic flows.

volume of trade is calculated in kg. Appendix A2 shows the precise plastic content coefficient and the HS code of the goods.

3.3. Trade network construction

An annual LC-PTMN was created for 1990 to 2019. The raw materials network, the semifinished products network, the plastic products network, and the plastic waste network are the four layers of the LC-PTMN, as depicted in Fig. 3. We define the LC-PTMN as a pair

$$M = \left(G^{[y]}, C^{[y]}\right) \tag{1}$$

where y represents a particular year in 1990 to 2019 and $G^{[y]} = \{G^{[y,\alpha]}; \alpha \in \{1,2,3,4\}\}$ is a family of directed and weighted graphs

$$G^{[y,\alpha]} = \left(V^{[y,\alpha]}, E^{[y,\alpha]}, W^{[y,\alpha]}\right) \tag{2}$$

associated with the four layers of the LC-PTMN in year y. $\alpha \in \{1,2,3,4\}$ denote the raw materials layer, the semifinished products layer, the plastic products layer, and the plastic waste layer, respectively. $V^{[y,\alpha]}$ denotes the set of nodes, namely, countries in the α layer of the LC-PTMN in year y, $E^{[y,\alpha]}$ represents the set of trade relations between countries in the α layer in year y, and $W^{[y,\alpha]}$ denotes the set of trade volumes between two countries in the $G^{[y,\alpha]}$. The weighted adjacency matrix for $G^{[y,\alpha]}$ is defined as $\mathbf{A}^{[y,\alpha]}$, and the element $a_{i,j}^{[y,\alpha]}$ is calculated as

$$a_{i,j}^{[y,\alpha]} = \begin{cases} w_{i,j}^{[y,\alpha]}, & \text{if } \left(v_i^{[y,\alpha]}, v_j^{[y,\alpha]}\right) \in E_{\alpha}^{[y,M]}, \\ 0, & \text{otherwise}, \end{cases} \tag{3}$$

where $v_i^{[y,\alpha]}$ denotes the country in $G^{[y,\alpha]}$, $v_i^{[y,\alpha]}$, $v_j^{[y,\alpha]} \in V^{[y,\alpha]}, i, j \in \{1,2,\ldots,N^{[y,\alpha]}\}$ and $N^{[y,\alpha]}$ is the total number of countries in $G^{[y,\alpha]}$. $w_{i,j}^{[y,\alpha]}$ is the trade volume between countries $v_i^{[y,\alpha]}$ and $v_j^{[y,\alpha]}$.

$C^{[y]}$ is the set of interconnections between the same nodes belonging to different graphs in the consecutive layers $G^{[y,\alpha]}$ and $G^{[y,\alpha+1]}$, $\alpha \in \{1,2,3\}$. Particularly, $C^{[y]}$ is a family of undirected graphs, which can be described by

$$C^{[y]} = \left\{C^{[y,\alpha,a+1]}, \alpha \in \{1,2,3\}\right\} \tag{4}$$

where $C^{[y,\alpha,\alpha+1]} = ((V^{[y,\alpha]}, V^{[y,\alpha+1]}), E^{[y,\alpha,a+1]}, \mathbf{A}^{[y,\alpha,\alpha+1]})$ and $E^{[y,\alpha,a+1]}$ is the set of edges between nodes in the consecutive layers α and $\alpha+1$. $E^{[y,\alpha,\alpha+1]} = \{(v_i^{[y,\alpha]}, v_i^{[y,\alpha+1]})\}$ and $(v_i^{[y,\alpha]}, v_i^{[y,\alpha+1]})$ indicate the connection between the same countries in layers α and $\alpha+1$. The element $a_{i,j}^{[y,\alpha,\alpha+1]}$ of the cross-layer adjacency matrix $\mathbf{A}^{[y,\alpha,\alpha+1]}$ is defined as

$$a_{i,j}^{[y,\alpha,\alpha+1]} = \begin{cases} 1, & v_i^{[y,\alpha]} = v_j^{[y,\alpha+1]}, \\ 0, & \text{otherwise}, \end{cases} \tag{5}$$

where $1 \le i \le N^{[y,\alpha]}$ and $1 \le j \le N^{[y,\alpha+1]}$. The countries are numbered based on the country code sorted in the same way. Therefore, a certain country in the different layers has the same number; namely, $v_i^{[y,\alpha]} = v_j^{[y,\alpha+1]}$ shows the same country in layers α and $\alpha+1$.

Given the notations mentioned above, the LC-PTMN in year y can be described by a superadjacency matrix $\mathbf{M}^{[y]}$ shown as

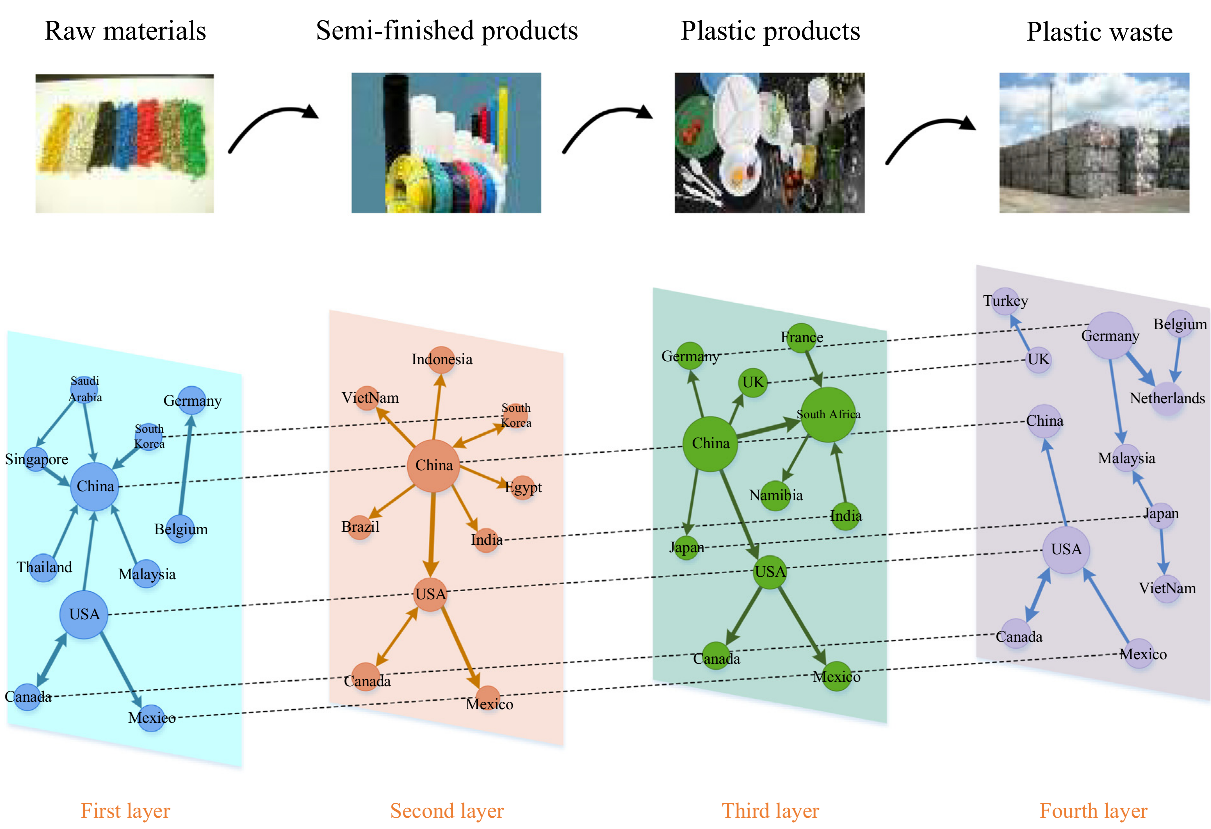

Fig. 3. Life cycle-based plastic trade multilayer network
Note: The first layer denotes the raw materials subnet, the second layer denotes the semifinished products subnet, the third layer denotes the plastic products subnet, and the fourth layer denotes the plastic waste subnet. Only the top 10 trade ties in 2019 ranked by trade volumes in each layer are given. The size of each node represents the trade volume, and dashed lines connect the nodes that are shared by both subnetworks.

$$\mathbf{M}^{[y]} = \begin{bmatrix} \mathbf{A}^{[y,1]} & \mathbf{A}^{[y,1,2]} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{A}^{[y,2]} & \mathbf{A}^{[y,2,3]} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{A}^{[y,3]} & \mathbf{A}^{[y,3,4]} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{A}^{[y,4]} \end{bmatrix} \tag{6}$$

3.4. Topological metrics

To understand how the LC-PTMN evolves under dynamic years, each layer is revealed by classic network topological metrics. In this study, the network intensity, node degree, node strength, modularity, normalized mutual information (NMI), clustering coefficient, and average path length are calculated. Since these statistics metrics have been widely used in previous studies (Hu et al., 2020; Wang et al., 2020a), the details introduced are provided in Appendix A3.

4. Results and discussion

4.1. Trade network intensity

The total numbers of trading countries and trade relationships demonstrate the network's size (An et al., 2014). The scale of the LC-PTMN is shown in Fig. 4, which notes an increasing trend. Particularly, the related industry witnessed a rapid increase in the number of involved countries, rapid expansion of the trade relationships established and increasing density before 2005. Then, the scale's development entered a stable period. American-led globalization started in 1990 with the end of the Cold War in 1991 (Bakich, 2021), and the world became more interconnected. Globalization increased the trade relationships among countries and made the global plastic life cycle trade denser. In addition to the similarities in the development of the four layers of the LC-PTMN, some differences are revealed by contrastive analysis. As shown in Fig. 4 (a), the number of countries in the raw materials, semifinished products and plastic products layers are similar but significantly greater than that in the plastic waste layer. However, there are obvious distinctions among the three layers in terms of the intensity of the same countries' involvement. These distinctions are reflected concretely by the variation in the numbers of trade relationships and the density in each layer shown in Fig. 4(b-c). Throughout the research period, in descending order, the layers with the largest number of trade relationships and the highest density are the plastic products layer, the semifinished products layer, the raw materials layer and the plastic waste layer. In addition, the plastic products layer has the highest network density, indicating that plastic products are widely used worldwide. The plastic waste layer has the lowest network density, which may be caused by the low global plastic recycling rate and low acceptance of contaminated, mixed or unrecyclable plastic waste from importing countries. It is worth noting that the increased network density of four layers in LC-PTMN is much lower than the world trade network with density value 0.81(Cepeda-López et al., 2019). This indicates that the global life cycle-based plastic trade still has ample space for globalization even after long-term development compared with the level of global trade. Appendix A4 provides details on the total number of countries and the trade relationships in each layer.

Fig. 5 depicts the average clustering coefficient and the average path length of the LC-PTMN. The average clustering coefficient index represents the network's overall connectedness. A higher value indicates that countries tend to form tight trade groups. Fig. 5(a) shows that the average clustering coefficients of the raw materials, semifinished products and plastic products layers remain above 0.7 and are significantly higher than that of the plastic waste layer, which reveals that the first three layers are more connected than the plastic waste layer. This indicates that there is ample room for development in the global plastic waste trade compared with the mature global trade market for raw materials, semifinished products and plastic products. This result is consistent with the findings shown in Fig. 4. Fig. 5(b) shows the average path length in the LC-PTMN. Over the last 30 years, the average path length shows a decreasing trend. Consistent with the increase in density in Fig. 5(b), this decreasing trend indicates that two countries in each layer can establish trade relations with fewer intermediate countries or even establish such relations directly. The decreasing trend of the average path length can be explained by the globalization of trade and the increase in bilateral and multilateral trade agreements (Xu et al., 2019). However, the plastic waste network has a longer average path length, and the decrement of this indicator is less than those of the other three layers. This indicates that the development of global trade cooperation in plastic waste falls behind that in the other three layers. This finding corroborates the conclusion shown in Fig. 5(a). In addition, the LC-PTMN has a high clustering coefficient and a short path length, which are both properties of a small-world network (Fagiolo et al., 2010).

4.2. Plastic trade concentration

The cumulative distribution of node degree and node strength are used to measure the concentration of trade relationships and trade volume in the trade network. Taking the LC-PTMN in 2019 as an example, countries are sorted by the node degree in descending order, and the cumulative degree distribution of each layer is calculated, as shown in Fig. 6(a). The plastic waste layer has the highest concentration of trade relationships, followed by the raw materials, semifinished products, and plastic products layers. In 2019, approximately 40 % of countries accounted for 80 % of plastic trade relationships. This shows that a few countries dominate most of the trade channels in the LC-PTMN.

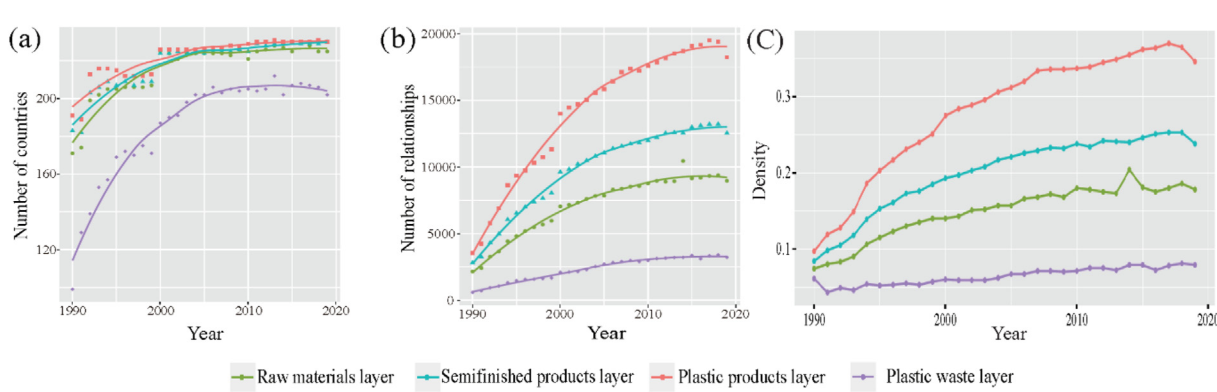

Fig. 4. Numbers of countries, trade relationships and network density.

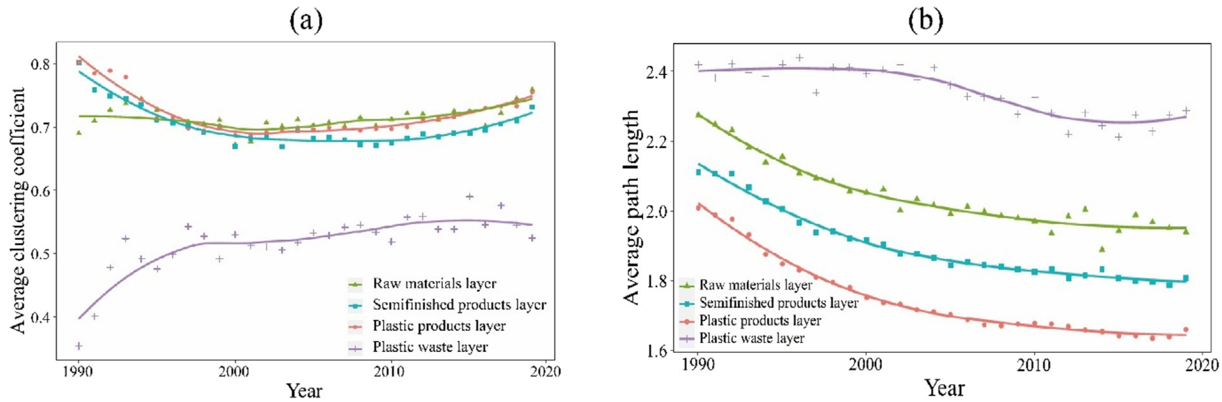

Fig. 5. Average clustering coefficient and the average path length.

Fig. 6(b) shows that the proportion of countries occupying over 80 % of the trade channels increased before 2000 and then remained relatively stable. The trends reflect that more countries have diversified their trading partners, and thus, the trade channel concentration has been relatively low and stable in the past ten years. Regarding the trade volume concentration in the LC-PTMN, the cumulative distribution of the four layers in 2019 is shown in Fig. 6(c). Comparing the trade channels, the trade volumes are more concentrated, with approximately 10 % of the countries owning 80 % of the plastic trade weight and even 8 % of the countries in the plastic products layer accounting for 80 % of the plastic trade volume. In addition, Fig. 6(d) shows that the proportion of countries owning 80 % of the plastic trade declined gradually from 1990 to 2004 and reached the highest concentration of trade volume in 2004. From 2004 to 2019, the percentage of countries increased gradually. The plastics trade was highly concentrated in 2004, with approximately 6.16 % of the countries owning 80 % of the global plastic trade volume in each layer. The highest concentration in 2004 was due to the dramatic increase in the trade volume between the USA and Mexico in the first three layers. For example, from 2003 to 2004, the proportion of trade volume flowing from the USA to Mexico increased sharply from 2.68 % to 7.95 % in the raw materials layer, from 1.78 % to 12.35 % in the semifinished products layer and from 3.28 % to 7.19 % in the plastic products layer. Similarly, the proportion of trade flows from Mexico to the USA grew dramatically from 2003 to 2004. The high dependence of trade in Mexico on the USA and Mexico's critical position in plastic-related products worked together and led to the highest concentration in 2004. To avoid or mitigate the risks of relying on a single market, Mexico sought to diversify its trade

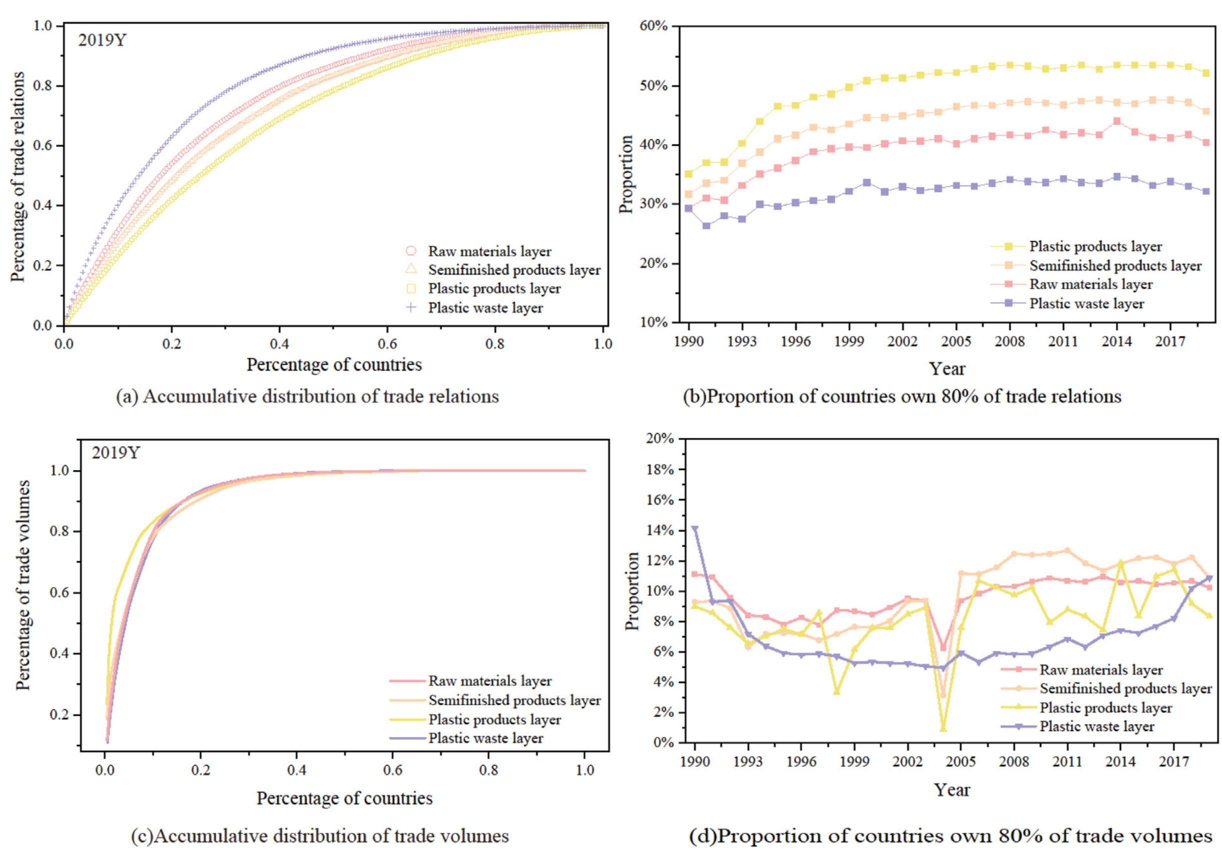

Fig. 6. Concentration of plastic trade relationships.

relationships and signed a bilateral free trade agreement with Japan in September 2004. This helped disperse the clustering of trade.

Comparing the concentrations of trade relationships and trade volume, there are some similarities and differences. Regarding the similarities, our findings show that the global plastic life cycle trade consists of a large number of countries with relatively few trade relations and a few countries with strong and intense relations. This reflects the prominent hierarchical structure of the LC-PTMN, namely, that a few countries dominate the trading channels and volume in the global markets of plastic-related products. In addition, the concentration of the trade channels and trade volume in the plastic waste layer is somewhat higher than those in the other layers despite the fluctuation of the trade volume concentration. This reflects that this layer's hierarchical structure is more prominent. In the plastic waste layer, the huge size of the consumer market and the effective implementation of garbage classification leads to the export concentration of plastic waste in developing countries. The extraordinary looseness of environmental protection policies and lower labor costs there result in the import concentration of plastic waste in developing countries. Regarding other aspects, our findings show that the concentration of trade relationships in the four layers is more stable than that of trade volume. Despite the plastic waste layer, the concentration of the trade relationships in the raw materials layer is the second highest, which is due to the uneven geographical distribution of raw materials. However, the distribution of trade volume in the plastic products layer is the second most concentrated, following the plastic waste layer.

In addition, the correlation between the node degree and the clustering coefficient of countries indicates the coordination and concentricity of countries occupying trade channels. Namely, a high correlation indicates that countries with rich trade channels tend to promote close ties among their trading partners. Therefore, for each layer in a given year, linear regression analysis between countries' degree and clustering coefficient is used to determine the relevance. The detailed results are shown in Appendix A5. Fig. 7 shows the R^2 of linear regression in the four layers of the LC-PTMN from 1990 to 2019. The degree and clustering coefficient of countries in the semifinished products and plastic products layers are found to be significantly positively correlated. The value of R^2 remains stable at a high level in these two layers during the twenty-year period and fluctuates between 0.8 and 0.95. This finding indicates that the trading partners of a country with diversified trading channels tend to form tight trade relationships. In this circumstance, the concentricity of the trade network in the semifinished products and plastic products layers based on a few critical countries will be reinforced. However, different trends appear in R^2 in the raw materials and plastic waste layers. The value of R^2 in the plastic waste layer

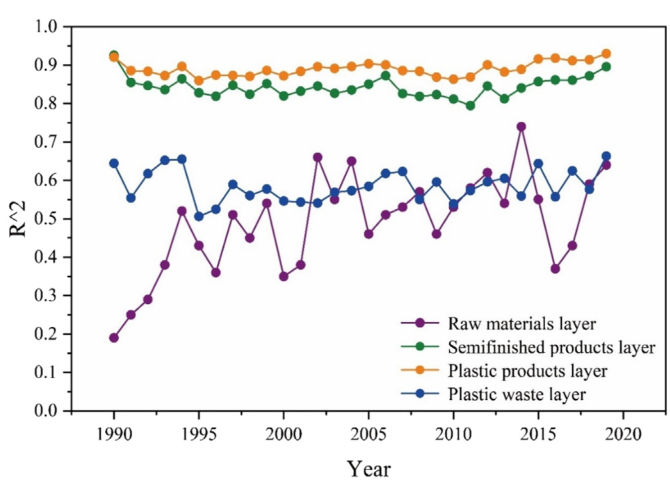

Fig. 7. R^2 of linear regression.

fluctuated around 0.6, which is less than those in the semifinished products and plastic products layers. These findings indicate that countries dominating the trade channels in the plastic waste layer have a weaker ability to coordinate with their trading partners than those in the semifinished products and plastic products layers. In addition, the value of R^2 in the raw materials layer fluctuates dramatically, indicating that countries with rich trade relationships have no stable ability to intensify their relationships with trading partners.

4.3. Core trading countries in the plastic trade

A bump chart in Fig. 8 presents the core countries in the plastic life cycle trade, showing the changes in the rankings of 2019's top 10 import and export countries from 1990 to 2019.

On the whole, critical import and export countries change frequently in the early period. With the development of the related industries, the rankings of the core countries gradually stabilized despite a sudden rise in the conditions of individual countries. In addition, the critical countries were mainly located in Asia and Europe. Specifically, in the raw materials layer, the USA and Germany occupied a stable core position in terms of both imports and exports. In contrast, China's export rankings rose rapidly despite the stable central position of imports. In addition, for importing countries, Turkey and Vietnam experienced extraordinary rises in their rankings. India's ranking showed a falling-rising trend, mainly because India reduced its import tariff on plastic raw materials in 2007 to stimulate economic growth and promote plastic raw material imports (Edmonds et al., 2010). Regarding exports in the raw materials layer, Asian countries showed outstanding performance. In particular, Saudi Arabia and Thailand experienced remarkable rises in their rankings. South Korea and Singapore occupied stable core positions among exporting countries.

In the plastic semifinished products layer, the USA, China and Germany occupied a stable core position in the import market. The rankings of Turkey and Vietnam sorted by imports have grown tremendously since 2005. For exports, highly industrialized countries, such as Germany, the USA, Korea, Italy and Belgium, play a critical role stably. India and Turkey experienced extraordinary rises in their rankings. Japan's core position among exporting countries showed a downward trend.

In the plastic products layer, the top import countries remained steadier compared with those in the other layers of the LC-PTMN, mainly consisting of the European and North American countries. Notably, South Africa has played a critical role in plastic product imports in recent years. Due to the advantages of their geographical location, South Africa's ports constitute the most significant maritime network on the African continent. South Africa's imports of plastic products will indirectly meet the rapidly increasing requirements of the other African countries. In contrast to the stable list of top countries in plastic product imports, the rankings of core countries have changed dramatically in the past 10 years. India, Vietnam and South Africa have sharply improved their standing. The large volume of imports and exports in South Africa indicates its critical position as a transit hub for African countries.

In the plastic waste layer, developing countries in Asia, including China, Malaysia, Indonesia, Vietnam, India and Turkey, have a central position in imports. In particular, Southeast Asian countries such as Malaysia, Vietnam and Indonesia experienced extraordinary rises in their rankings. In contrast, the top export countries are mainly distributed among the major developed economies. These findings reflect the trend in which the plastic waste trade flows from developed countries to developing countries. This is due to the looseness of environmental policies and dramatic growth in developing countries and the relatively mature garbage classification system in developed countries, which is in line with findings on plastic trade concentration noted in Section 4.2.

Fig. 8. Top 10 countries ranked by trade volume as of 2019.

A conceptual framework for global circulation was recently proposed in academia (Hu et al., 2021). In this framework, developing countries process raw materials into finished products and export them to developed countries. Then, developed countries send postconsumer waste to developing countries. However, the global plastic life cycle trade is more complicated than this conceptual framework. For example, Fig. 8 shows that the USA is the largest virgin plastic and plastic waste exporter, while intermediate and final plastic products are largely imported. Hence, this study enriches the understanding of the global circulation conceptual framework. In the global plastic circulation framework, virgin plastic polymers (raw materials) come from the petrochemical industry in industrialized economies. After semifinished products and plastic products are produced in leading manufacturing economies, such as China and Germany, plastic items are exported around the globe. Finally, the plastic waste is shipped from developed countries to newly industrialized countries and developing countries, such as China and Southeast Asian countries.

4.4. Major trading relationships in the plastic trade

To study the major trade relationships in the plastic life cycle trade, this study assesses the cumulative plastic trade volume between countries in each layer over 30 years, as shown in Appendix A6. The top 10 trading flows in the four layers of the LC-PTMN are depicted on the world map in Fig. 9. The line colors represent the different trade layers, and a wider line indicates a larger trade volume between countries. Notably, the top 10 trading flows in the raw materials layer, semifinished products layer, plastic products layer and plastic waste layer account for 28.9 %, 25 %, 47.4 % and 41.2 % of the total trade volume in the corresponding layer, respectively. These critical flows provide important clues on the geographical distribution of the trade volume in each layer. On the whole, the major plastic trade flows mainly occur in intra-North American, intra-Asian, and North American-Asian trade. The USA and China are the main drivers of plastic trade. The USA occupies 20.5 %, 18.4 %, 35.9 % and 49 % of the total volume in the raw materials, semifinished products, plastic products and plastic waste layers, respectively. China accounts for 21.8 %, 33.6 %, 45 % and 25.3 % of the total trade volume in these four layers, respectively. Intra-North American trade flows occur among the USA, Canada, and Mexico; intra-Asian trade flows occur in countries such as China, South Korea, Japan, and Thailand; and North American-Asian trade flows occur between China and the USA.

For the individual layers, the trade flows of the raw materials and semifinished products layers are mainly intracontinental, namely, within Asia and within North America. In particular, the trade volumes within Asia and within North America account for 42.5 % and 41.1 % of the total trade volume, respectively. This is mainly for geopolitical reasons; countries tend to trade plastics with their neighbors (Wang et al., 2020a). The concentration of North American trade flows may reflect the close trade relationships among the USA, Canada and Mexico under the North American Free Trade Agreement (NAFTA). Notably, some intercontinental trade flows occur among countries in the top 10 in the plastic products and plastic waste layers. In particular, the intercontinental trade in plastic products is mainly exported from China to North American and European countries, such as China-USA (12.6 %), China-UK (1.8 %), China-Germany (1.6 %) and China-Canada (1 %). These developed countries in North America and Europe have an enormous demand for plastic products, but their high labor costs and strict environmental policies lead them to import from countries with industrial production capacity and low production costs. In this context, China imports plastic raw materials and plastic semifinished products and exports plastic products to developed countries after processing and manufacturing. Different from the direction of the trade flows in plastic products, the major intercontinental trade flows of plastic waste occur from North American countries to Asian countries. For example, the trade flows from the USA to China, the USA to India and the USA to Indonesia account for 19.8 %, 3.1 % and 1.8 % of the total trade volume, respectively. Developing countries import plastic waste to reduce the manufacturing cost of plastic products and earn hard currency amid low labor costs and an extensive economic development pattern. Accordingly, developed countries relieve the pressure of waste disposal at low cost and avoid environmental pollution by exporting plastic waste.

4.5. Trade community evolution

The modularity coefficient of the LC-PTMN is presented in Fig. 10. It is between 0.36 and 0.43. The NMI can estimate the similarity between two communities in consecutive years. Fig. 10 shows the evolution of the NMI in the LC-PTMN. Growth in the NMI shows that the community's structure is becoming more stable, while a decrease indicates that the community is changing greatly. From 1990 to 2019, the NMI showed a fluctuating increasing trend, which indicates that the community structure is more stable; namely, the global plastic trade market is increasingly mature. There are changes in the community structure at specific points, shown as the turning points before descent in Fig. 10, including those in 1992–1993, 1999–2000, 2003–2004 and 2008–2009.

Fig. 11 depicts presents in detail the evolution of the network at these points. The community is named based on its hub countries. In the LC-PTMN, the changes in the trade community are mainly caused by countries in Asia, Europe and North America, including China, Korea, Japan, Germany, France, the UK, the USA, Canada and Mexico. In particular, the dramatic change in 1992 to 1993 indicates that the North American countries separated after being a single community. From 1999 to 2000, the European and South American countries further

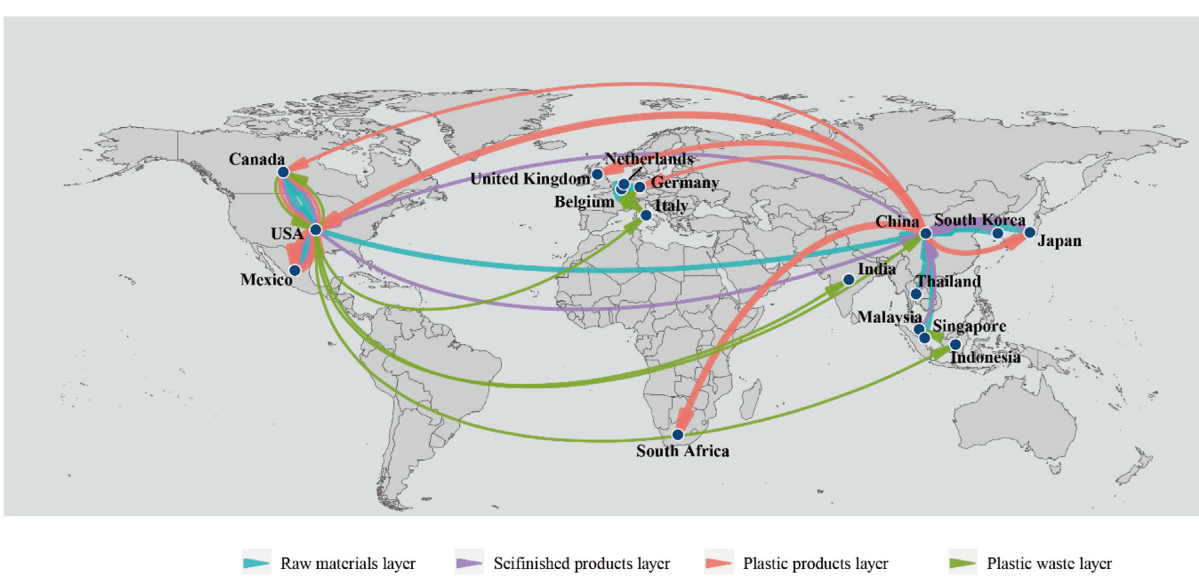

Fig. 9. Major trade relationships in the plastic life cycle trade.

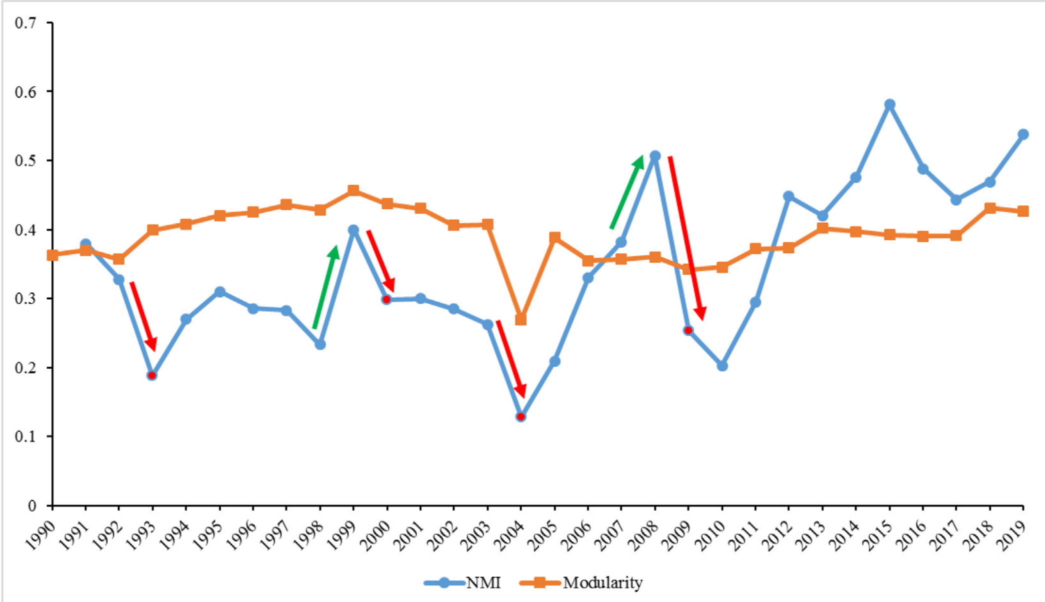

Fig. 10. Plastic NMI and plastic modularity in the LC-PTMN.

integrated with the African-Asian countries and African countries, respectively, and formed new communities. In 2003 to 2004, the merger of African, Asian and European countries is prominent, but the communities with hub countries in North America and South America were separated. At the turning point of 2008 to 2009, the European countries formed new communities with Asian and African countries. The above analyses above suggest that dramatic changes in community structure are embodied in the merging of European countries with Asian and African countries and the split of North American countries from a single community. This indicates that European countries tend to strengthen cooperation with other countries but that North American countries are inclined to independence in the global plastic trade.

5. Conclusions

This study builds a LC-PTMN to explore the global plastic life cycle trade. Using 1990–2019 trade data from the UN-Comtrade database, it analyzes the trade network intensity, plastic trade concentration, core trading countries and major trading relationships in the plastic trade, and trade community evolution. The main results are summarized as follows:

First, the global plastic life cycle trade has a high clustering coefficient and a short path length, which are both properties of a small-world network.

Second, the global plastic life cycle trade is a dense network that consists of a large number of countries with relatively weak trade relations and a few countries with strong and intense relations.

Third, the real-world global plastic life cycle trade enriches the understanding of the global circulation conceptual framework. In the plastic life cycle trade, virgin plastic polymers come from the petrochemical industry in industrialized economies. After semifinished products and plastic products are produced in the leading manufacturing economies, plastic items are exported worldwide. Finally, the plastic waste is shipped from developed countries to newly industrialized countries and developing countries.

Fourth, the major trading relationships in the plastic life cycle trade are mainly concentrated in intra-North American trade, intra-Asian trade, and North American-Asian trade. China dominates the import trade flow of the raw materials and semifinished products layers and the export trade flow of the plastic products layer. The USA dominates export trade flows of plastic waste.

Finally, the community structure in the global plastic life cycle trade is becoming more stable. The changes in the trade community are mainly caused by countries in Asia, Europe and North America, including China, Korea, Japan, Germany, France, the UK, the USA, Canada and Mexico.

Although a LC-PTMN has been built, the interlayer interdependencies are unexplored. In our future work, centrality and tightness, community structure, and topological correlation will be measured to investigate the interlayer structural characteristics of the plastic life cycle trade.

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.

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Appendix A. Supplementary data

The data processing for UN Comtrade records is briefly described in Appendix A1. Appendix A2 depicts the HS code in the LC-PTMN. Appendix A3 briefly explains the classic topological metrics in the LC-PTMN. Appendix A4 shows the total numbers of countries and trade relationships in the four layers. Appendix A5 presents the linear relation between the degree and clustering coefficient in the four layers. Appendix A6 tabulates the major trade relationships in the plastic life cycle trade. Appendix B presents the ISO3 code and the specific country names. In addition, the code and data used in this study can be accessed via the following link: https://github.com/WenjuSun95/Structural-evolution-of-global-plastic-lifecycle-trade-a-multilayer-

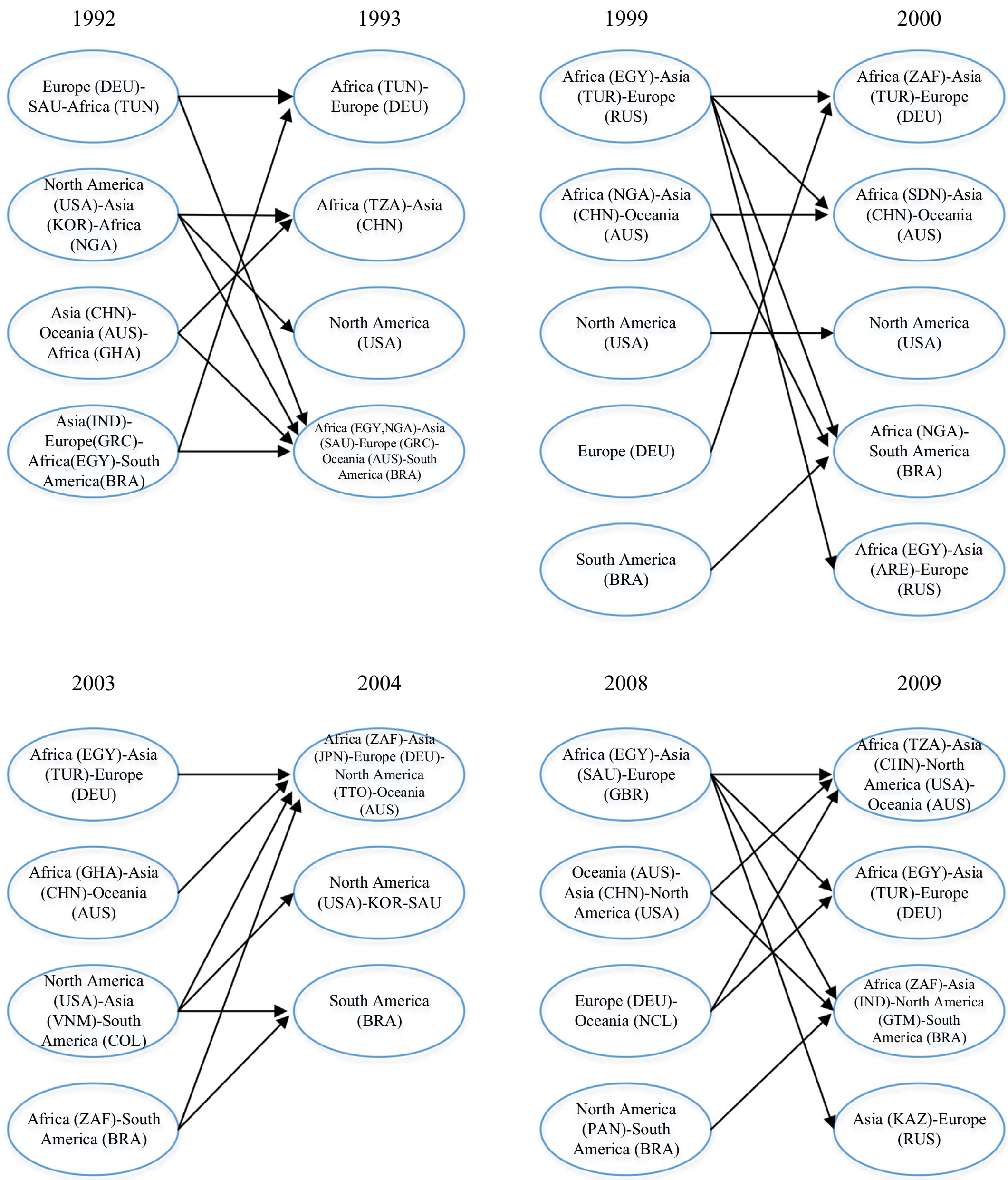

Fig. 11. The community experienced dramatic change in four representative years.
Note: The abbreviation in parentheses is the ISO3 code, indicating a representative country. See Appendix B for specific country names.

network-perspective. Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2022.08.027

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