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Global sunflower oil trade under COVID-19 and the Russia–Ukraine conflict: a complex network analysis of food system resilience and sustainable finance dynamics

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This study investigates how recent global crises have reshaped the sunflower oil trade network and what these shifts mean for the environmental sustainability and financial resilience of agri-food systems. Focusing on the COVID-19 pandemic and the Russia–Ukraine conflict, we analyze export flows from 2019 to 2022 using complex network techniques to identify changes in structural connectivity, core–periphery patterns and country-level influence. The findings show that Ukraine and India remained the most central actors in the network throughout the period, while 2022 marked a significant reorganization: Türkiye and Russia rose in prominence following the Grain Corridor initiative, signaling the emergence of alternative regional trade pathways. Despite these geopolitical shocks, the network preserved a dense and highly interconnected structure, revealing persistent interdependence among major producers and import-dependent economies. However, several key trade relationships weakened or shifted, illustrating the sensitivity of global edible-oil supply chains to geopolitical disruptions. These dynamics are closely linked to climate-sensitive agricultural systems, with implications for land-use pressures, food security risks, and the vulnerability of environmentally exposed importing countries. The study further highlights how sustainable finance mechanisms—including risk-responsive investment strategies and resilience-oriented funding models—can support the stability of edible-oil supply chains by addressing the concentration, dependency and reconfiguration patterns identified in the trade network under rising climate and geopolitical uncertainty. Network results were validated through cross-year structural consistency checks, ensuring methodological robustness. Overall, the analysis provides timely evidence on the reconfiguration of sunflower oil trade and offers insights relevant to SDG2 (Zero Hunger) and SDG13 (Climate Action), contributing to efforts to build more resilient and environmentally sustainable food systems.

KEYWORDS
agri-food system resilience, complex network analysis, COVID-19 pandemic, environmental sustainability, geopolitical shocks, Russia–Ukraine conflict, sunflower oil trade, sustainable finance

1 Introduction

Oilseed crops have long served as essential food sources for human consumption and as vital raw materials for various agro-industrial processes. Among these, sunflower oil stands out for its high nutritional value and widespread use in global food systems (Alzamel et al., 2022). Because sunflower cultivation depends on specific climatic conditions, many countries cannot produce sufficient quantities domestically and therefore rely heavily on imports. This dependence underscores the strategic importance of exports from major producing regions.

According to FAO data for 2024, global production of sunflower seeds reached nearly 54 million tons in 2022, accompanied by roughly 8 million tons of imports and a similar volume of exports. In 2021, worldwide sunflower oil production was approximately 18 million tons, with 13.6 million tons imported and 13.8 million tons exported. In 2022, the leading producers of sunflower seeds were Russia (around 16 million tons), Ukraine (11 million tons), Argentina (4 million tons), and China (3 million tons), while Türkiye, Romania, and Bulgaria each produced close to 2 million tons. Ukraine and Romania were the main exporters of sunflower seeds, whereas Bulgaria, Türkiye, and Romania were among the largest importers.

In sunflower oil production for 2022, Russia ranked first with around 5.2 million tons, followed by Ukraine with 4.9 million tons and Argentina with 1.3 million tons. During the same period, Ukraine exported nearly 5 million tons of sunflower oil, and Russia exported about 2.4 million tons. India was the largest importer, purchasing approximately 1.8 million tons, followed by China with 1.3 million tons and Türkiye with 909,000 tons. These figures highlight the central role of sunflower oil as a key export commodity for countries such as Türkiye, Russia, and Ukraine, reflecting its importance in global edible-oil markets and its contribution to the stability of agri-food supply chains.

Together, Russia and Ukraine accounted for over 50% of global sunflower production on average from 2016/17 to 2020/21. In these countries, the majority of this production is processed domestically into sunflower oil and meal, with sunflower oil also being exported to international markets. Ukraine and Russia represent approximately 50% and 25% of global sunflower oil exports, respectively (OECD, 2022). Adverse conditions such as natural disasters, seasonal fluctuations, economic crises, trade sanctions, and armed conflicts can create Geopolitical Trade Effects (GTE) for various commercial products, potentially affecting foreign trade. Recent examples of such circumstances occurred during the COVID-19 pandemic in 2019 and the onset of the Russia-Ukraine war in 2022.

Lohosha (2023) found that the Russian Federation's invasion of Ukraine resulted in adverse changes in the operations of businesses within the agricultural sector. Agricultural enterprises encountered significant challenges in selling their products and procuring essential production tools. In light of the current situation in the country, it has been determined that it is crucial for these enterprises to enhance their operations, particularly in the area of marketing, to improve the competitive characteristics of their goods and services. Despite the ongoing conflict and extensive destruction, it is noteworthy that agriculture is expected to maintain its status as one of the leading sectors of the Ukrainian economy.

According to the OECD's 2022 report, the war in Ukraine caused significant disruptions in the production, processing, and trade of sunflower seeds (OECD, 2022). Despite these challenges, Ukraine maintained its position as the leading exporter of sunflower oil during the 2022/23 period, with an export volume of approximately 5.7 million tons (Statista, 2024).

In the literature, several studies utilizing network analysis related to sunflower oil have been identified. Among these, Shi et al. (2023) focus on the period of the COVID-19 pandemic. However, no current study analyzes the impacts of the Russia-Ukraine war. This indicates that the existing literature has not yet evaluated how two consecutive global shocks have reshaped the geopolitical structure of sunflower oil trade.

Given that these two countries are vital in global production and exports, it is essential to assess how trade has been influenced by recent adverse conditions. This study aims to identify how the trade networks of selected countries, namely Türkiye, China, Argentina, the United States (United States), Russia, Germany, France, Italy, South Korea, Japan, Australia, Indonesia, the United Kingdom (United Kingdom), the Netherlands, Bulgaria, Spain, Romania, India, and Hungary, have been affected by the COVID-19 pandemic in 2019 and the Russia-Ukraine war in 2022. These countries were selected based on their high relevance in the global sunflower oil market. Specifically, these countries collectively account for a predominant share of global sunflower oil activity in terms of production and international trade volumes, as documented in FAOSTAT and summarized in Table 3. Accordingly, the inclusion criteria of these countries were based on countries' strategic prominence as major producers and trading hubs within the sunflower oil value chain, ensuring that the resulting network captures the core structure and dynamics of global trade flows and their exposure to systemic shocks.

Complex network analysis is particularly suitable for this purpose, as it captures shifts in centrality, dependency, and connectivity that traditional trade indicators may overlook.

Accordingly, production and foreign trade statistics on sunflower oil were initially compiled, and the countries prominent in its trade were identified. A social network analysis was conducted using sunflower oil export data from 2019, 2020, 2021, and 2022 to map the export network of the product, and the statistical findings were presented. The statistical values revealed through the network analysis method were interpreted, and the leading countries within core and peripheral groups were elucidated.

By combining crisis periods and multi-country network interactions, this study provides one of the first comparative network structures for the post-COVID and wartime periods. The findings help clarify not only which countries dominate the system but also how geopolitical shocks alter network resilience. From a financial perspective, identifying such structural reconfigurations is critical, as shifts in centrality, dependency, and core–periphery positions directly shape exposure to trade finance risks, liquidity constraints, and the need for resilience-oriented financing mechanisms in agri-food supply chains.

In light of these results, this study is regarded as a significant research endeavor that identifies the most recent developments in sunflower oil trade and contributes to the existing literature.

Moreover, the results offer new insights that align closely with current discussions on agri-food trade disruptions and resilience,

TABLE 1 Global sunflower oil production and foreign trade statistics (2010–2022).

Year	Production	Import	Export
2010	12,541,074	5,828,130	5,618,058
2011	13,253,901	6,489,699	6,928,288
2012	14,933,111	8,672,040	9,069,975
2013	14,167,093	8,201,609	8,479,694
2014	16,149,936	9,733,192	10,082,293
2015	15,293,119	8,954,034	9,383,285
2016	16,053,489	9,832,871	11,131,877
2017	18,178,984	12,377,040	13,073,993
2018	18,410,731	11,911,077	12,655,996
2019	20,054,680	13,624,198	13,843,525
2020	20,577,022	15,101,974	15,606,548
2021	18,495,059	13,437,004	12,624,771
2022	-	13,887,639	13,463,146

Source: (FAO, 2024b).

making the study relevant for the Special Issue on "International Trade in the Agri-Food Sector."

Some of the research questions are as follows:

RQ1: How have trade networks for sunflower oil been affected by the COVID-19 pandemic and the Russia-Ukraine conflict?
RQ2: Which countries have been most affected by disruptions in sunflower oil production and trade during these crises?
RQ3: What patterns emerge from the social network analysis of sunflower oil exports between 2019 and 2022?

2 Literature review

2.1 Global production structure and trade dynamics in the sunflower industry

This section presents global and country-level findings from previous studies and major data sources to provide a comprehensive background for understanding the structure of sunflower seed and sunflower oil production and trade.

Historically, sunflowers are believed to have originated in North America, with domestication likely occurring around 1000 BC. Spanish explorers introduced the plant to Europe in the early 15th century. By the 1860s, Russian farmers had significantly advanced sunflower cultivation, establishing themselves as the world's largest producer of sunflower seeds at that time. In the 21st century, sunflowers have regained prominence in Eastern Europe, where they have become the primary oil crop. As Argentina shifted its focus to soybeans and corn, countries such as Ukraine and Russia emerged as key producers. Eastern European sunflower producers include Russia, Ukraine, Türkiye, Bulgaria, Romania, and Moldova. Despite accounting for only 14% of the world's arable land, Eastern European countries rank among the top 10 globally for sunflower production. Türkiye is the largest importer in Eastern Europe, holding approximately 30% of the global sunflower trade market share (Kaya et al., 2015).

TABLE 2 Production and foreign trade statistics of sunflower oil in selected countries for 2021 (tons).

Countries	Production	Import	Export
Russia	5,248,935	1,173	2,412,384
Ukraine	4,928,742	19	5,161,205
Argentina	1,340,009	6	208,138
Türkiye	940,200	909,973	623,072
Bulgaria	619,000	25,154	559,455
France	528,700	262,789	368,856
Romania	459,700	33,928	189,847
Spain	455,900	574,700	223,687
China	269,000	1,306,584	2,374
The United States	189,000	136,378	54,870
The Netherlands	163,200	773,943	674,712
Italy	144,500	567,632	52,505
India	63,900	1,848,534	1,273
Germany	55,300	473,155	192,829
Australia	11,400	60,255	600
Indonesia	3,284	7,482	1
Japan	-	11,538	63
South Korea	-	43,369	51
The United Kingdom	-	296,308	7,858

Source: (FAO, 2024d).

Supplementary Table S1 presents the global sunflower seed production and foreign trade statistics from 2010 to 2022. Global sunflower seed production exhibits a long-term increasing trend, with notable fluctuations in recent years. Detailed production and trade figures are provided in Supplementary Table S1 (FAO, 2024a).

Table 1 presents global sunflower oil production and foreign trade statistics from 2010 to 2022.

The data indicate a general upward trend in sunflower oil production; however, declines were observed in 2013, 2015, and 2021 compared to the preceding years. In terms of foreign trade, both imports and exports exhibited a consistent upward trajectory until 2021. Export and import figures, which were approximately 6 million tons in 2010, reached nearly 15 million tons by 2020. Notably, despite the challenges presented by the pandemic in 2020, both sunflower oil production and foreign trade figures experienced an increase.

At the country level, global sunflower seed production and trade are highly concentrated, underscoring the vulnerability of supply to disruptions in a limited number of exporting countries. Detailed country-level data are provided in Supplementary Table S2 (FAO, 2024c).

Table 2 presents the sunflower oil production and foreign trade statistics of selected countries for the year 2021.

According to the data, Russia ranks first in production, with approximately 5 million tons, closely followed by Ukraine, which has a similar production volume. Additionally, Argentina, Romania, Türkiye, Bulgaria, and France have been recognized as significant contributors to sunflower oil production. In terms of exports, Ukraine holds the leading position, followed by Russia in second place. Furthermore, Türkiye, France, and the Netherlands are also notable exporters of sunflower oil. It is noteworthy that countries such as the Netherlands, the United Kingdom, South Korea, Indonesia, and Japan, which do not produce sunflower oil, have been engaged in its exportation. This phenomenon occurs as these nations import sunflower oil for re-export. The countries with the highest sunflower oil imports include India, China, Türkiye, and the Netherlands.

Country-level trends further illustrate shifts in production leadership over time, with recent years marked by heightened volatility among major producers (see Supplementary Figure S1) (FAO, 2024e). In particular, the sharp contraction in sunflower seed production in Ukraine highlights the sensitivity of global supply to regional shocks and reinforces the structural vulnerability of concentrated production systems.

Global sunflower oil markets operate within a broader vegetable oil system, where palm oil plays a dominant role as a substitute, influencing price dynamics and trade flows (see Supplementary Table S3).

Production trends across major vegetable oils display divergent patterns, reflecting differences in market structure and end-use dynamics (see Supplementary Table S3) (FAO, 2024f). Palm oil maintains a dominant position within the global vegetable oil complex, while sunflower oil exhibits greater sensitivity to supply-side reallocations and external shocks. Other vegetable oils, such as olive, corn, and coconut oil, show more heterogeneous and volatile production trajectories. Overall, these patterns reinforce the high concentration and vulnerability of global sunflower oil trade, underscoring the relevance of network-based analyses during periods of systemic disruption, including the COVID-19 pandemic and the Russia–Ukraine conflict.

2.2 Empirical studies on production efficiency, trade structure and policy impacts in the sunflower industry

Existing empirical studies on the sunflower seed and sunflower oil sector can be broadly classified into three main strands: production efficiency and structural performance, market integration, and trade policy interventions.

The first group of studies focuses on production efficiency and the structural performance of the sunflower industry (Baryshpolets, 2021). Employs Stochastic Frontier Analysis to examine production efficiency in Ukrainian sunflower seed crushing plants, highlighting the significance of firm heterogeneity and export orientation (Deppermann et al., 2018). Evaluate intensification and recultivation scenarios in Russia and Ukraine and demonstrate that yield improvements generate substantially greater global impacts than land expansion. Similarly, studies on Bulgaria and Romania (Kostova, 2010; Ivanov and Sokolova, 2014; Soare et al., 2014; Popescu, 2018; Hristov et al., 2019) document structural transformations in the sunflower sector following EU accession, emphasizing productivity growth and increasing export specialization. While these studies provide valuable insights into production performance and structural competitiveness, they predominantly rely on descriptive statistics and efficiency modeling, without explicitly linking these dimensions to trade policy frameworks.

The second group of studies examines market integration within the sunflower industry (Parlińska et al., 2015). Compare sunflower oil trade patterns between Poland and Ukraine, drawing attention to Ukraine's persistent trade surplus and price competitiveness (Rahoveanu et al., 2018). Investigate the interdependence between production, consumption, and imports in Romania, emphasizing the structural reliance on both domestic supply and foreign trade (Rath et al., 2022). Employ cointegration analysis to examine the long-run relationship between domestic and international prices in India, thereby highlighting the significance of market integration in edible oil markets. Collectively, these studies contribute to a better understanding of price linkages and trade balances, while predominantly assessing national cases within the sunflower sector in a country-specific context.

The third group of studies addresses trade policy interventions (Mgeni et al., 2018). Evaluate the effects of import tariffs on edible oil in Tanzania and conclude that protectionist measures alone cannot ensure competitiveness in the absence of improvements in production efficiency (Kapsdorferová and Sviridova, 2016). Examine the impact of EU-Russia sanctions on agricultural policies and identify significant price increases in several agricultural products, including sunflower oil, following the 2014 sanction imposed on Russia. These analyses demonstrate that trade restrictions exert a substantial influence on domestic price formation and market dynamics.

The application of complex network analysis to international trade has gained significant attention in recent years and has provided robust frameworks for assessing the trade flows of various global commodities (Shi et al., 2023; Soyyiğit and Yavuzaslan, 2018; Jiang et al., 2019; Alkan, 2021; Alkan and Kocabaş, 2020; Boz et al., 2024). While current literature has used network analysis approaches to examine broad categories such as manufactured goods or grains (Boz et al., 2024; Soyyiğit and Yavuzaslan, 2018; Özekicioğlu et al., 2023; Fracasso et al., 2018), studies specifically examining global sunflower oil trade using this methodology are lacking. Existing studies in the field of sunflower production and trade largely rely on econometric models (Rath et al., 2022; Borodin and Salnikov, 2018; Dereva and Rajcaniova, 2022) or descriptive agricultural economics reports (Titin et al., 2025; Tikhomirova and Popkova, 2023; Baryshpolets and Devadoss, 2021; Vasylkovska et al., 2021). However, these traditional approaches do not always capture the vulnerabilities triggered by crises with sudden geopolitical or global impacts, such as COVID-19. This study fills an important gap in the literature by analyzing global trade data using a network analysis approach, revealing how the sunflower oil trade network was shaped by the shocks of the COVID-19 pandemic and the Russia-Ukraine conflict.

Among the publications mentioned above, only Shi et al. (2023) have conducted an analysis of the evolutionary characteristics of

global sunflower oil trade from 2000 to 2020, employing network analysis methods, as well as examining the policy implications of sunflower oil in China. Their findings indicate that the overall network density and reciprocity in global sunflower oil trade increased by 2.1% and 4.4%, respectively, during this period. They also noted that the direct transaction routes among trading partners have progressively shortened, leading to increasingly closer overall network connections. Furthermore, they found that China's sunflower oil imports have rapidly escalated over the past decade. Additionally, while Russia, Germany, the Netherlands, Belgium, and Türkiye remain key players in the global sunflower oil trade, the authors concluded that Ukraine and China have been enhancing their trade relations.

Existing studies in the literature tend to examine production efficiency, trade performance, or policy interventions in the sunflower industry separately and predominantly through national case analyses. Given their thematic focus and the specific time periods they cover, these studies do not address the structural transformations in sunflower oil trade networks that have emerged under major global shocks, such as the COVID-19 pandemic and the subsequent Russia-Ukraine conflict. This study addresses this gap by applying complex network analysis to evaluate how these crises have affected leading countries in the global sunflower oil trade and how the structure of the trade network has evolved during this period. The findings contribute to a more comprehensive understanding of the dynamics shaping global sunflower oil trade under conditions of systemic disruption.

3 Methodology

The study of social and economic networks has gained significant momentum in recent years and has greatly influenced various disciplines. In economics, network analysis has emerged as an attractive framework for understanding how complex interdependencies shape global activities (Jackson, 2010). Advances in computational power and simulation methods have further facilitated the modeling of complexity economics and enabled the development of more complex models that reflect real-world trade dynamics (Eren, 2013). Grounded in Graph Theory, network analysis is used as a robust tool in both the social and natural sciences to analyze the structural properties of complex systems (Soyyiğit and Yavuzaslan, 2018; Güzeller et al., 2016). Accordingly, this study adopts complex network analysis to examine the structure and evolution of the global sunflower oil trade network and to assess how the shocks of global crises, such as the COVID-19 pandemic and the Russia–Ukraine war, affect countries' positions and the overall network structure.

Networks are represented as graphs in the field of information technology. A graph is typically denoted as G = (V, E), where V signifies the set of vertices (or nodes) and E denotes the set of edges. Each edge connects one or two related vertices. Relationships within networks are represented by edges, while individuals, groups, and institutions are represented as nodes. In directed graphs, the starting and ending points of the edges are specified within the graph structure. In analyses, nodes with a high number of incoming connections from other nodes are referred to as authorities, whereas nodes with a high number of total connections are designated as hubs (Çubukçu and Özbay, 2016).

The Hyperlink-Induced Topic Search (HITS) algorithm generates hub and authority scores in both binary and weighted networks, reflecting the interdependence of nodes. This algorithm leverages information regarding import-export patterns within the network to identify countries that play pivotal roles in trade. In this framework, "authority" denotes the foremost importers, while "hub" signifies the principal exporters. The insights gained from this analysis provide a novel ranking based on centrality, which contrasts with the results derived from the trade shares of countries in trade networks (Fracasso et al., 2018).

The HITS algorithm assigns authority centrality x_i and hub centrality yi to each vertex *i* within a network. A key characteristic of a vertex with high authority centrality is that it is referenced by numerous hubs, indicating its relevance as highlighted by other vertices with high hub centrality. In contrast, a vertex with high hub centrality is defined by its connections to multiple vertices that possess high authority centrality (Newman, 2010).

According to Newman, Kleinberg's approach defines the authority centrality of a vertex as being proportional to the sum of the hub centralities of the vertices that direct connections to it (Newman, 2010).

$$x_i = a \Sigma A_{ij} y_j \tag{1}$$

Here, α is a constant. Similarly, the hub centrality of a vertex is proportional to the sum of the authority centralities of the vertices to which it points.

$$y_i = \beta \Sigma A_{ij} x_j \tag{2}$$

β is another constant. The element Aji of the matrix is substituted into this second equation. These vertices define the hub centrality.

In matrix terms, these equations can be written as:

$$x = \alpha A y$$
$$y = \beta A^T x$$

The combined form of the above equations is;

$$AA^T x = \lambda x$$
$$A^T A y = \lambda y$$

It can also be written in the form. Here, $\lambda = (\alpha\beta)^{-1}$. Consequently, the authority and hub scores are determined by the eigenvectors of AA^T and A^TA, respectively.

The data used in this study were collected from secondary sources, specifically from the Food and Agriculture Organization of the United Nations (FAO) database. For network analysis, export values (in tons) for the years 2019, 2020, 2021, and 2022 were utilized from the FAO for the following countries: Russia, Ukraine, Türkiye, China, Argentina, the United States, Germany, France, Italy, South Korea, Japan, Australia, Indonesia, the United Kingdom, the Netherlands, Bulgaria, Spain, Romania, India, and Hungary. Based on this information, this study analyzes the evolution of sunflower oil trade networks in the aftermath of the COVID-19 pandemic and the Russia-Ukraine

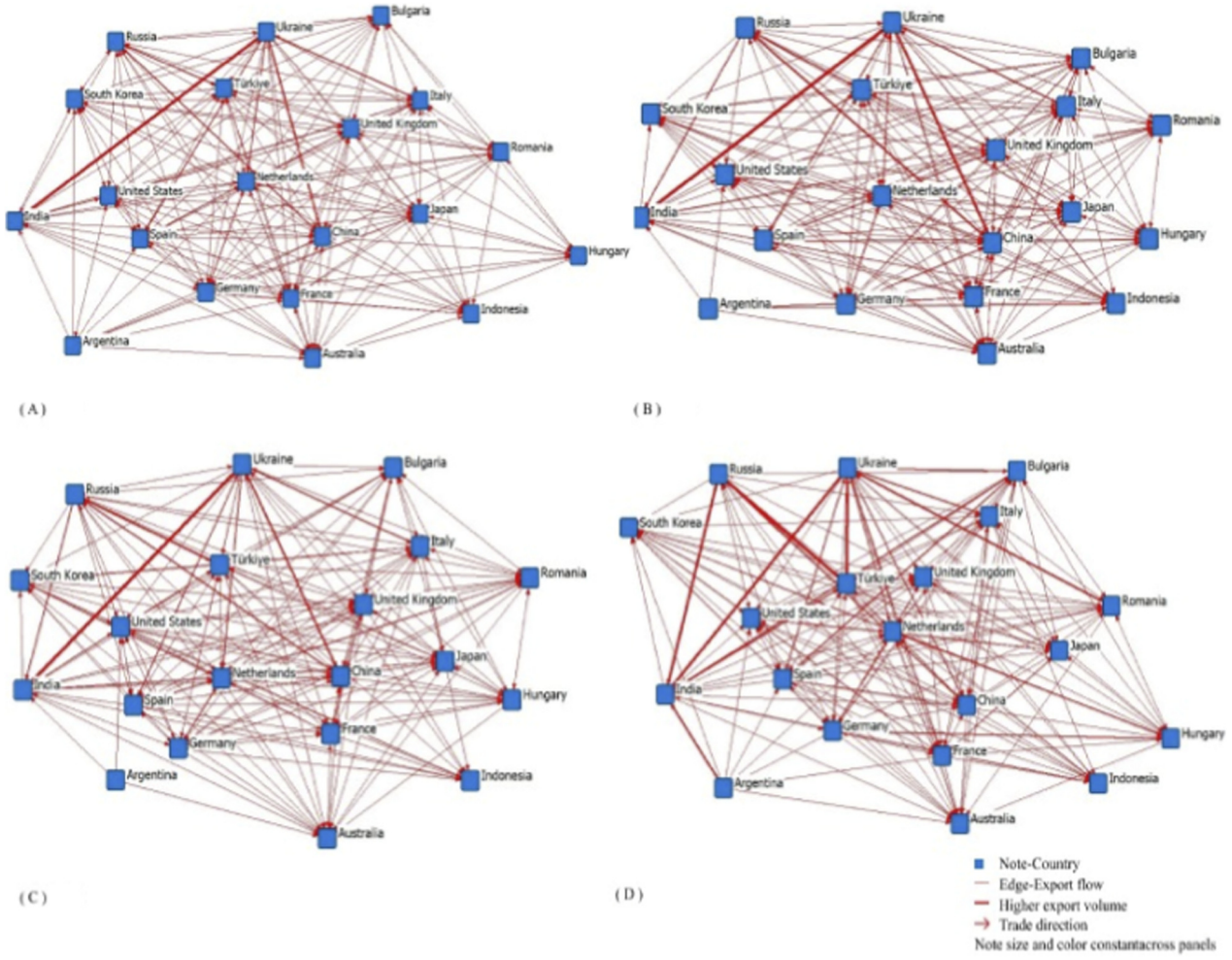

FIGURE 1
Evolution of the global sunflower oil export network (2019–2022). **(A)** 2019. **(B)** 2020. **(C)** 2021. **(D)** 2022.

war that began in 2022, employing the social network analysis method.

4 Results

In network analysis, the points connecting the edges are referred to as nodes or actors, while the lines themselves are termed edges. In networks, edges may be directed or undirected. This study presents an export network characterized by directed connections, where the nodes represent countries and the connections illustrate the trade relationships among them. A notable feature of the constructed export network is that it is an ego network matrix. Ego-centered network data typically involve a specific set of actors (egos) and the individuals to whom these actors are connected (alters) (Van Duijn and Vermunt, 2006).

In Figure 1, panels (A)–(D) present the directed export networks for the years 2019, 2020, 2021 and 2022 respectively. Nodes represent countries and edges represent export flows. Edge thickness corresponds to export volume (in metric tons), and arrows indicate the direction of trade. To ensure cross-year structural comparability, node positions were fixed based on the 2019 force-directed layout and node size and color were kept constant across all panels. Spatial positioning reflects layout optimization rather than geographical proximity. Therefore differences across panels should be interpreted according to changes in connection patterns and edge intensity rather than spatial distance.

Figure 1A depicts the sunflower oil export network for the selected countries in 2019. The analysis results indicate that the network comprises a comprehensive structure and exhibits a complex nature. Furthermore, the network is characterized as directed, demonstrating that the relationships among the actors are reciprocal. The network map highlights a very strong connection between India and Ukraine. Additionally, the connections between Ukraine and the Netherlands, Ukraine and China, Türkiye and Russia, the Netherlands and Germany, as well as China and Russia, are also notable for their near-strong strength.

The export network configuration for 2020 is illustrated in Figure 1B, presenting the structure of sunflower oil trade among the selected countries. The network is characterized by a comprehensive structure and a complex design. The trade

TABLE 3 Centrality analysis results for the sunflower oil export network of selected countries (2019–2022).

Countries	2019		2020		2021		2022	
	Outgoing	Incoming	Outgoing	Incoming	Outgoing	Incoming	Outgoing	Incoming
Türkiye	1	12	1	21	1	34	12	95
China	0	30	0	56	0	39	0	34
Argentina	6	0	5	0	3	0	37	0
The United States	0	3	0	4	0	4	0	13
Russia	28	0	52	0	49	0	106	0
Germany	3	14	2	15	3	18	5	31
France	8	9	6	7	7	10	22	21
Italy	1	15	1	15	11	17	3	34
South Korea	0	2	0	1	0	1	0	2
Japan	0	1	0	1	0	1	0	1
Australia	0	2	0	1	0	1	0	3
Indonesia	0	0	0	0	0	0	0	0
The United Kingdom	0	8	0	9	0	9	0	15
Ukraine	115	1	142	1	135	1	217	0
The Netherlands	13	23	13	23	13	25	26	46
Bulgaria	4	1	6	1	12	1	38	20
Spain	4	15	3	15	4	17	11	36
Romania	5	1	3	1	4	1	14	27
India	0	62	0	70	0	64	0	132
Hungary	10	0	9	1	11	1	26	6

relationship between India and Ukraine is particularly robust. Consistent with the network map presented in 2019, it can be concluded that there is significant trade activity between Ukraine and the Netherlands, Ukraine and China, Türkiye and Russia, the Netherlands and Germany, the United States and China, as well as China and Russia.

As presented in Figure 1C, the 2021 sunflower oil export network reflects the trade relationships among the selected countries. Consistent with the years 2019 and 2020, the network exhibits a complete structure and a complex form. The analysis reveals a robust trade connection between India and Ukraine, as well as significant trade partnerships in exports among Ukraine and China, Türkiye and Russia, and China and Russia.

Figure 1D provides a visualization of the sunflower oil export network in 2022 for the selected countries. The network analysis reveals that, consistent with the network maps from 2019, 2020, and 2021, the export relationship between India and Ukraine remains robust. Additionally, during this period, the trade connections between Russia and Türkiye, as well as India and Russia, are also observed to be strong. In 2022, exports between Ukraine and Romania, Argentina and India, China and Russia, and Türkiye and Ukraine are found to be approaching strong levels. A markedly different configuration has been identified compared to the previous networks. This change is significantly influenced by Türkiye's role as a mediator and its leadership in facilitating the grain corridor in light of the Russia-Ukraine war.

In-degree refers to the number of directed edges directed toward a node from other nodes within the network. It reflects the extent to which the node receives information from its neighbors. In-degree centrality measures a node's popularity within the network. Conversely, out-degree pertains to the number of edges emanating from the node to other nodes, indicating the degree to which the node transmits information to its neighbors. Out-degree centrality represents a node's control or leadership within the network (Salman, 2018). According to Table 3, the directed nature of the connections across all years necessitates an examination of the incoming (in-degree) and outgoing (out-degree) values to identify the significant nodes.

According to the analysis results, in 2019, the most significant incoming (import) node was India (62), while the most prominent outgoing (export) node was Ukraine (115). During this period, it was also noted that Russia, an important producing country, had the second most significant outgoing connection (28), and China held the second most important incoming connection (30). In 2020, there was an increase in the number of outgoing connections for Ukraine (142) and Russia (52), while incoming connections for India (70) and China (56) also increased, maintaining the same rankings as the previous year. Additionally, despite 2020 being the period in which

TABLE 4 Eigenvector centrality values for selected countries in the sunflower oil export network (2019–2022).

Nr	Countries	2019	2020	2021	2022
1	Türkiye	27	83	99	455
2	China	245	388	318	155
3	Argentina	40	31	26	137
4	The United States	15	17	18	27
5	Russia	110	234	166	404
6	Germany	36	30	40	41
7	France	53	46	66	63
8	Italy	107	95	91	113
9	South Korea	6	4	6	5
10	Japan	3	2	2	3
11	Australia	8	6	7	5
12	Indonesia	1	0	0	1
13	The United Kingdom	39	37	50	27
14	Ukraine	696	666	685	529
15	The Netherlands	167	178	199	147
16	Bulgaria	11	18	25	166
17	Spain	120	116	125	104
18	Romania	9	7	7	142
19	India	617	533	564	543
20	Hungary	17	15	14	48

the COVID-19 pandemic was most acutely felt, there was no negative impact on sunflower oil export connections, which is believed to be due to the available stocks of sunflower oil. In 2021, Ukraine (135) and Russia (49) continued to be the two most important actors in terms of outgoing connections in sunflower oil exports, while incoming connections featured India (64), China (39), and Türkiye (34) as significant contributors. By 2022, Ukraine (217) and Russia (106) became the leading actors in outgoing connections for sunflower oil exports, while India (132) and Türkiye (95) were prominent in incoming connections. This period marked the moment when Türkiye surpassed China in sunflower oil imports, a situation believed to have been influenced by the COVID-19 pandemic. Overall, degree centrality results clearly demonstrate that Ukraine and Russia form the backbone of global sunflower oil supply, while India and Türkiye act as the main demand centers. These patterns remained stable until 2021 but shifted sharply in 2022 due to the war and the Grain Corridor.

Eigenvector centrality is a refined measure of centrality that builds upon the concept of degree centrality. In eigenvector centrality, a node's importance is determined not only by the number of connections it has but also by the significance of those connections (Tunalı, 2016; Kervankıran et al., 2018). This measure evaluates the quality (weight) of connections within a network, rather than merely considering their quantity. Consequently, it identifies the most influential nodes in the network. A node with numerous low-weight connections will exhibit lower eigenvector centrality than a node with fewer but more significant connections. A higher centrality value indicates a greater level of importance attributed to the node (Kervankıran et al., 2018).

According to Table 4, the most significant nodes in the network for the year 2019 are Ukraine (696), India (617), China (245), the Netherlands (167), and Russia (110). In 2020, these countries remained prominent, with Ukraine (666), India (533), China (388), the Netherlands (178), and Russia (234) continuing to feature prominently. In 2021, Ukraine (685), India (564), China (318), the Netherlands (199), and Russia (166) retained their positions, a trend attributed to excess stocks. By 2022, in addition to the key countries in sunflower oil exports, Ukraine (529), India (543), China (155), the Netherlands (147), and Russia (404), Türkiye (455) also emerged as a significant player, a development linked to transit trade. The rise of Türkiye in 2022 shows that influence within the trade network is no longer determined solely by production capacity but also by geopolitical positioning and transit-based trade.

In Table 5 the leading hub country in 2019 was Ukraine (987), while the leading authority country was India (879). In 2020, consistent with 2019, the hub country remained Ukraine (944), and the authority country continued to be India (758). In 2021, Ukraine again served as the hub country (973), with India as the authority country (803). By 2022, the hub country was still Ukraine (758), but the authority country shifted to Türkiye (647). This change can be attributed to the "Grain Corridor" agreement signed and implemented between Ukraine and Russia under Türkiye's leadership in July 2022, which facilitated the distribution of millions of tons of grain seized by Russia.

Ego network analysis, utilized to examine foreign trade between countries, serves to elucidate trade relationships and interactions among nations. This analysis investigates the direction and magnitude of trade flows, thereby defining the topology of the network.

According to Table 6, in 2019, the ego network role received values of 19 and 18. The leading countries in the sunflower oil export network are identified as China (19), Germany (19), France (19), Italy (18), Japan (18), the United Kingdom (18), and Spain (18). The countries with the highest number of connections include China (223), Germany (218), the Netherlands (218), France (217), Italy (208), the United Kingdom (207), Japan (205), Spain (202), and Ukraine (202). The countries with the highest volume are China (342), Germany (342), France (342), and the Netherlands (342). Additionally, the countries with the highest density percentages are Hungary (82), Indonesia (82), Bulgaria (77), Russia (76), Argentina (76), South Korea (74), and Ukraine (74).

In 2020, the ego network role recorded values of 19 and 18. As a result, the leading countries in the sunflower oil export network are identified as Australia (19), Germany (19), France (19), Ukraine (18), the United Kingdom (18), Türkiye (18), and China (18). The countries with the highest number of connections are China (212), Germany (208), Ukraine (207), France (206), Türkiye (202), and the United Kingdom (202). The countries with the highest export volumes are Germany (342), France (342), and Australia (342), while the countries with the highest density percentages are Argentina (80), Romania (79), and Hungary (76).

TABLE 5 Hub and authority values for sunflower oil exports from selected countries (2019–2022).

Countries	2019		2020		2021		2022	
	Hub (exporter)	Authority (importer)	Hub (exporter)	Authority (importer)	Hub (exporter)	Authority (importer)	Hub (exporter)	Authority (importer)
Türkiye	2	34	2	114	2	134	56	647
China	0	347	0	551	0	452	0	239
Argentina	57	0	45	0	37	0	200	0
The United States	0	18	0	19	0	21	0	22
Russia	144	0	325	0	226	0	606	0
Germany	9	16	7	8	10	5	8	22
France	12	61	6	57	10	84	116	66
Italy	0	146	1	134	2	127	2	156
South Korea	0	7	0	5	0	8	0	5
Japan	0	2	0	3	0	2	0	3
Australia	0	11	0	8	0	9	0	7
Indonesia	0	1	0	0	0	0	0	0
The United Kingdom	1	46	1	42	0	64	0	26
Ukraine	987	2	944	3	973	2	758	0
The Netherlands	9	224	3	244	2	272	28	173
Bulgaria	7	8	16	9	32	2	109	134
Spain	5	164	3	161	5	174	6	128
Romania	11	0	5	5	7	2	25	188
India	0	879	0	758	0	803	0	627
Hungary	22	0	12	8	15	0	30	36

In 2021, the ego network role recorded values of 19 and 18. Consequently, the leading countries in the sunflower oil export network are identified as the United States (19), Türkiye (18), Germany (18), Ukraine (18), the Netherlands (18), the United Kingdom (18), and Spain (18). The countries with the highest number of connections are Ukraine (195), the United States (194), the United Kingdom (191), and the Netherlands (190). Additionally, the countries with the highest export volumes include the United States (342), Türkiye (306), the United Kingdom (306), the Netherlands (306), Germany (306), Ukraine (306), and Spain (306). In terms of density percentages, the countries with the highest values are Indonesia (78), Hungary (73), Romania (71), and Bulgaria (71).

In 2022, the ego network role received values of 19 and 18. Consequently, the leading countries in the sunflower oil export network are identified as the Netherlands (19), Spain (19), Türkiye (18), Germany (18), the United States (18), and France (18). The countries with the highest number of connections are Spain (197), the Netherlands (193), and Türkiye (191). Additionally, the countries with the highest export volumes are the Netherlands (342), Spain (342), Türkiye (306), the United States (306), France (306), and Germany (306). Meanwhile, the countries with the highest density percentages include Argentina (76), Indonesia (75), Romania (74), Japan (72), and Hungary (71). Ego network results indicate that countries with diversified trade ties, such as Germany, China, Spain, and the Netherlands, consistently remain highly embedded in the network, while temporary shocks affect countries with limited or unbalanced connections more severely.

The core and periphery analysis (Table 7) indicates that Ukraine and India were the primary core countries in sunflower oil exports from 2019 to 2021. However, in 2022, Türkiye, Russia, Ukraine, and India emerged as core countries, with Russia gaining significance due to its control over Ukrainian grains and Türkiye's pivotal role in the "Grain Corridor." This initiative has facilitated grain imports for underdeveloped countries, helping to prevent famine while underscoring the importance of sustainable agriculture and sustainable financing in agriculture. Sustainable financing is vital for promoting efficient, eco-friendly agricultural production, particularly in the sunflower oil sector, which is critical for both environmental sustainability and economic development (Chiu et al., 2022). Given the strategic importance of sunflower oil for Russia, Ukraine, and Türkiye, it is essential to evaluate the impact of sustainable financing on sustainable agriculture. The expansion of the core from two countries (Ukraine and India) to four countries

TABLE 6 Ego network analysis results for sunflower oil exports for selected countries (2019–2022).

Countries	2019				2020				2021				2022			
	Ego network	Connection	Volume	Density	Ego network	Connection	Volume	Density	Ego network	Connection	Volume	Density	Ego network	Connection	Volume	Density
Türkiye	17	191	272	70	18	202	306	66	18	189	306	66	18	191	306	62
China	19	223	342	65	18	212	306	69	17	188	272	69	17	178	272	65
Argentina	10	69	90	76	6	24	30	80	3	4	6	66	8	43	56	76
The United States	17	179	272	65	17	69	272	62	19	194	342	56	18	79	306	58
Russia	15	161	210	76	14	24	82	68	6	165	240	68	14	118	182	64
Germany	19	218	342	63	19	208	342	60	18	189	306	61	18	182	306	59
France	19	217	342	63	19	206	342	60	7	171	272	62	18	180	306	58
Italy	18	208	306	67	17	181	272	66	7	172	272	63	17	73	272	63
S. Korea	16	178	240	74	16	170	240	70	15	137	210	65	17	161	272	59
Japan	18	205	306	66	15	59	20	75	16	166	240	69	13	13	156	72
Australia	17	184	272	67	19	25	342	62	17	168	272	61	16	159	240	66
Indonesia	13	128	156	82	15	44	210	68	1	86	110	78	13	118	156	75
The United Kingdom	18	207	306	67	18	202	306	66	18	191	306	62	16	159	240	66
Ukraine	17	202	272	74	18	207	306	67	18	195	306	63	17	177	272	65
The Netherlands	9	218	342	63	17	185	272	68	18	190	306	62	19	193	342	56
Bulgaria	15	162	210	77	17	190	272	69	15	151	210	71	16	63	240	67
Spain	18	202	306	66	17	185	272	68	18	189	306	61	19	197	342	57
Romania	16	163	240	67	13	124	156	79	15	151	210	71	14	136	182	74
India	15	153	210	72	16	153	240	63	6	130	240	54	15	128	210	60
Hungary	10	74	90	82	13	119	156	76	14	34	182	73	13	112	156	71

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TABLE 7 Core and periphery analysis results for selected countries in sunflower oil exports (2019–2022).

2019	Core: Ukraine, India Periphery: Others
2020	Core: Ukraine, India Periphery: Others
2021	Core: Ukraine, India Periphery: Others
2022	Core: Türkiye, Russia, Ukraine, India Periphery: Others

(Türkiye, Russia, Ukraine, and India) in 2022 suggests a fundamental restructuring of global sunflower oil trade. This shift is largely driven by geopolitical dynamics rather than changes in agricultural productivity.

5 Discussion: implications for sustainable finance and agricultural policy

The network analysis results indicate that global sunflower oil trade is exposed to external shocks however, the nature and magnitude of these shocks differ significantly over time. Although the COVID-19 pandemic constituted a major global disruption, the structure of the sunflower oil trade network remained largely stable between 2019 and 2021. Centrality rankings, hub–authority relations, and core–periphery configurations exhibited limited variation during this period, suggesting that existing trade relationships and stock availability buffered the impact of the pandemic.

In contrast, the Russia–Ukraine conflict in 2022 triggered a pronounced structural reconfiguration of the network. The emergence of Türkiye and Russia as core actors, together with shifts in eigenvector centrality and authority roles, indicates that the war functioned as a systemic shock rather than a temporary disturbance.

These findings underline that while the COVID-19 pandemic primarily tested the resilience of the existing trade network, the Russia–Ukraine conflict fundamentally reshaped trade pathways and power relations within the global sunflower oil market.

The results highlight that geopolitical conflicts, rather than global health crises, have a stronger capacity to alter the structural organization of agricultural trade networks. This distinction is critical for understanding how global food supply chains respond to different types of external shocks. From a financial perspective, these structural shifts matter because changes in centrality, dependency, and core–periphery positions translate into trade-finance exposure, settlement risk, and liquidity needs along newly dominant routes.

5.1 The role of sustainable finance in enhancing resilience in sunflower oil trade systems

In this study, sustainable finance is defined not as a broad environmental policy concept, but as a set of resilience-oriented financial mechanisms that become particularly relevant in trade networks characterized by concentration and dependency. Our network results directly support this framing. Between 2019 and 2021, the global sunflower oil trade system remained structurally stable despite the COVID-19 shock, suggesting that existing trade relationships provided a certain buffering capacity within the network (ESCAP, 2023).

However, the results for 2022 reveal a fundamentally different dynamic. The main vulnerability was not a lack of trading partners, but a redistribution of systemic influence across the network. Significant shifts in eigenvector centrality, changes in hub–authority roles, and the expansion of the network core indicate that trade flows became increasingly dependent on newly dominant actors and corridors (Huang et al., 2025). This structural reconfiguration highlights how geopolitical shocks can reshape network power relations even when overall connectivity remains high.

These structural changes carry direct financial implications. For import-dependent countries and economies that emerged as central trade corridors, shifts in centrality translate into increased exposure to trade finance risks, settlement disruptions, and liquidity constraints. As bargaining power and risk profiles adjust rapidly, financial mechanisms that support trade continuity become essential to prevent localized disruptions from propagating across the network.

From this perspective, sustainable finance contributes to resilience by targeting the vulnerabilities identified through network analysis. Instruments such as trade credit guarantees, insurance-backed working capital, and resilience-oriented financing can help stabilize trade flows under conditions of heightened uncertainty. Aligning financial support with the structural realities revealed by network indicators—rather than focusing solely on production efficiency—may strengthen both short-term trade stability and the longer-term adaptive capacity of climate-sensitive agri-food supply chains, thereby reinforcing the structural resilience identified in our analysis.

5.2 Linking network reconfiguration to sustainable finance mechanisms

Our network analysis points to a specific type of vulnerability in the global sunflower oil trade system under geopolitical stress. The main risk is not the disappearance of trade links, but the rapid concentration of systemic influence and dependence in newly central corridors. The 2022 results show clear shifts in hub–authority roles, eigenvector centrality, and core membership, indicating that certain countries and trade routes became essential to the functioning of the system within a short period of time (Huang et al., 2025).

Such rapid reconfiguration generates financial risks that spread through several interconnected channels. As trade becomes concentrated along fewer routes, credit and liquidity pressures intensify, especially for import-dependent countries facing sudden supply disruptions or price volatility. At the same time, the emergence of new core actors introduces settlement and counterparty risks, since payment flows and contractual arrangements increasingly rely on actors whose operational and regulatory capacity may not yet be fully adapted to their new

systemic role. In addition, the reallocation of centrality creates investment gaps, as newly central nodes often lack sufficient storage, logistics, or adaptive capacity to absorb shocks without transmitting them across the network.

Sustainable finance—understood here as financing that targets systemic resilience rather than production efficiency alone—becomes relevant in this context because it can address vulnerabilities revealed by network structure. Trade credit guarantees and shipment risk insurance can reduce liquidity and settlement pressures along critical corridors (Oriekhoe et al., 2024). Insurance-backed working capital may help firms operating in newly central positions manage cash-flow volatility, while blended finance and resilience-linked lending can support investments in logistics and buffering capacity where systemic importance has increased.

The value of sustainable finance in this system lies in its ability to maintain trade continuity under structural stress. Aligning financial support with the concentration, dependency, and reconfiguration patterns identified through network indicators can help limit systemic spillovers and preserve the functional integrity of climate-sensitive agri-food supply chains during periods of geopolitical uncertainty (Halliday, 2023).

These findings imply differentiated policy priorities depending on countries' positions within the network. For major importers characterized by high incoming dependence and authority scores, policy priorities include strategic stockholding and risk-hedging mechanisms supported by public–private guarantees. Export-oriented hub countries require access to working-capital and insurance instruments that sustain production and logistics continuity under uncertainty. Trade hubs and corridor countries that gained centrality after 2022—Türkiye being a clear example—face a particular need for settlement-risk mitigation and trade facilitation finance. These instruments help stabilize payments, streamline documentation processes, and reduce corridor-specific operational risks.

6 Conclusion

This study provides a comprehensive assessment of sunflower seed and sunflower oil production by analyzing how global trade networks evolved during the COVID-19 pandemic and the Russia–Ukraine conflict. Sunflower production increased until 2020, then declined in 2021, while Russia and Ukraine consistently remained the leading producers. Argentina, Romania, Türkiye, China, Bulgaria, and France also contributed substantially to global supply throughout the period.

In relation to RQ1, the network analysis shows that recent crises reshaped global trade structures in a significant way. Ukraine and India maintained central positions across all years, while Türkiye and Russia gained greater prominence in 2022. These changes reflect the strong economic and geopolitical pressures that altered the configuration of the sunflower oil trade network.

Regarding RQ2, the findings indicate that India, Ukraine, and Türkiye were among the countries most affected by fluctuations in production and trade, as evidenced by significant changes in their positions within the trade network over the study period. Ukraine experienced substantial variations in outgoing degree and hub centrality, particularly in 2022, reflecting its pivotal but volatile role as a major exporter (Tables 3, 5). India consistently exhibited the highest incoming degree and authority scores, yet these values fluctuated across years, indicating sensitivity to supply-side disruptions (Tables 3, 5). Türkiye showed the most pronounced increase in eigenvector centrality and authority status in 2022 and entered the network core, highlighting a marked shift in its trade position during the crisis period (Tables 4, 5, 7). In this context, being "most affected" refers to measurable shifts in centrality rankings, hub–authority roles, and core–periphery status rather than changes in trade volumes alone.

For RQ3, the social network analysis reveals persistent and complex interactions among key trading nations. Strong ties—such as the India–Ukraine, Ukraine–the Netherlands, and Türkiye–Russia connections—remained intact despite the crises. By 2022, relationships such as Russia–Türkiye, India–Russia, Ukraine–Romania, and Türkiye–Ukraine intensified, illustrating how trade routes were reconfigured under geopolitical pressure.

Centrality measures reinforce these patterns. Ukraine consistently exhibited the highest outgoing connections, while India dominated incoming connections. Türkiye's increasing incoming links in 2022 indicate its expanding role as a major importer. Eigenvector centrality results similarly show that Ukraine and India remained the most influential nodes throughout the period, with Türkiye gaining substantial prominence in 2022. Hub–authority analysis further demonstrates that Ukraine functioned as the principal hub from 2019 to 2021, while India acted as the primary authority. In 2022, Türkiye emerged as the main authority country, reflecting the effects of the Grain Corridor agreement.

Core–periphery analysis indicates a stable two-country core—Ukraine and India—from 2019 to 2021. In 2022, however, the core expanded to include Türkiye and Russia, highlighting significant structural shifts in the global trading system and underscoring the influence of geopolitical developments.

From a financial and policy perspective, the network-based evidence presented in this study suggests that resilience in sunflower oil trade depends less on expanding the number of trade links and more on managing concentration, dependency, and corridor-specific risks revealed by structural reconfiguration. In this sense, sustainable finance becomes relevant not as a general sustainability objective, but as a mechanism for maintaining trade continuity through risk-sharing, liquidity provision, and resilience-oriented investment aligned with the network positions of key actors. Overall, the findings show that sunflower oil production and trade persisted despite major global crises, reaffirming the strategic importance of this commodity. The resilience of trade connections—even under pandemic conditions and armed conflict—demonstrates the essential role of edible oil supply chains in safeguarding food security. Türkiye's increased prominence in 2022 illustrates how geopolitical initiatives, such as the Grain Corridor, can reshape global trade networks.

The results align with previous research, such as Shi et al. (2023), while providing new insights into the combined effects of the COVID-19 pandemic and the Russia–Ukraine conflict. The study also suggests that broader transformations in global food trade—particularly involving vegetable oils and grains—warrant deeper examination in future research.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: FAOSTAT – Food and Agriculture Organization of the United Nations https://www.fao.org/faostat/en/#dataUN.

Author contributions

FB: Conceptualization, Writing – original draft, Writing – review and editing, Data curation, Investigation, Methodology, Resources. BY: Data curation, Investigation, Writing – review and editing. HÖ: Data curation, Supervision, Validation, Writing – review and editing. HT: Writing – review and editing, Project administration, Resources, Validation. UÜ: Validation, Writing – review and editing, Conceptualization, Formal Analysis, Writing – original draft.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2026.1757181/full#supplementary-material

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