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Global food supply chain resilience assessment: A case in the United Kingdom

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ABSTRACT

With the development of globalisation, countries such as the United Kingdom (UK) heavily rely on shipping for food imports and supplies. With the unpredictable impacts of black swan events, such as the Coronavirus disease (COVID-19) outbreak and the armed conflict between Ukraine and Russia, which are traditional food export countries, global freight supply chains could dramatically change, which significantly affects the global food supply chain (FSC) resilience, requiring new solutions to be found. Therefore, it is vital to assess a country's food importing system by sea to ensure its FSC resilience. However, it is challenging to analyse different food supply resilience levels on a national scale given the high uncertainties in the key relevant elements (e.g. food supplies and transportation) influencing FSC resilience. This paper aims to develop a new method to assess FSC resilience at a country level by pioneering the combination of the two most relevant attributes, its production-to-supply ratio and shipping transport connectivity, used to present food supply security separately in the current literature. Within this context, food production and import distance affecting the connectivity of various food supplies are selected to estimate FSC resilience in this study. The findings, including a new index framework to assess national food resilience, significantly contribute to a country's food security and the rational development of countermeasures and policies when necessary. To demonstrate the significance of the findings, the resilience of the UK FSC is first evaluated in a real case study, followed by a comparative study with Canada, Australia, Democratic Republic of the Congo (DRC) to identify the strengths and weaknesses of the FSCs of different countries. The findings of the studies can be used to monitor FSC resilience of the countries and provide rational policies for enhancing FSC resilience.

1. Introduction

The global food supply chain (FSC) is a critical component of our interconnected world, shaping the accessibility and availability of food resources across nations. However, this complex network faces various challenges, including disruptions caused by black swan events such as the Coronavirus disease (COVID-19) pandemic (Zhang et al., 2021) and the conflicts between food export countries. As food production and trade continue to evolve, understanding and assessing the resilience of a country's FSC becomes paramount (Suweis et al., 2015; Monit, 2016).

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Countries heavily reliant on food imports are particularly susceptible to disruptions in the global FSC. In this context, assessing the resilience of a nation's FSC in general and understanding its vulnerability against different types of food become essential. To address this, this paper aims to a new method to assess FSC resilience at a country level by pioneering the combination of the two most relevant attributes, its production-to-supply ratio and shipping transport connectivity (Liu et al., 2020), used to present food supply security separately in the current literature (Marchand et al., 2016).

In pursuit of this goal, the study seeks to answer the following research questions: 1) How can a robust method be developed for assessing FSC resilience at a country level? 2) What insights can be gained by applying this new assessment method to different countries for realising risk informed FSC resilience policy making? In this process, we combine scientometric literature review and empirical analysis (Davidson et al., 2022) to develop our research approach. It begins with a comprehensive review of the existing FSC resilience literature to establish the state-of-the-art in the field (Suweis et al., 2015; Monit, 2016). Building upon this foundation, the innovative method for assessing FSC resilience at a national level is realised with the capacilty to detect the vulnerability of a country's FSC resilience aginast different food types. Specifically speaking, Liner Shipping Bilateral Connectivity Index (LSBCI), developed by the United Nations Conference on Trade and Development (UNCTAD), is first chosen to understand countries' transport network connectivity, which is used to model the food trade network and hence the associated food security level in terms of local or global supplies. Second, food balance sheets by the UN Food and Agriculture Organization (FAO) of various food products in a country are analysed to understand the food production-to-supply ratio. Third, food trade between import and export countries by the United Nations Commodity Trade (UN COMTRADE) is evaluated to determine the food import distances against different food types.

A comparative analysis of four nations, the UK, Canada, Australia and the Democratic Republic of the Congo (DRC) representing different FSC resilience levels, has been undertaken to accomplish these goals. The countries are chosen to quantify the varying scenarios of FSC resilience, and to draw valuable insights into the factors/vulnerabilities contributing to their respective resilience levels.

Following this introduction, the paper is organised as follows. Section 2 offers a comprehensive literature review, setting the state of the art for the development of a new FSC resilience assessment method. Section 3 presents the new method for assessing FSC resilience. Section 4 consists of a case study involving our countries (the UK, Canada, Australia, and DRC) to demonstrate the applicability and value of the assessment framework. Finally, the conclusions and discussions about the contributions of the work are presented in Section 5.

2. Literature review

This section first undertakes a scientometric literature review of the research manuscripts on global FSC resilience published in globally recognised peer-reviewed journals. By integrating a systematic literature network analysis (e.g. Wan et al., 2018), this review is divided into two steps: data collection from the Web of Science (WoS) and document co-citation analysis (DCA) by Citespace (Chen, 2018). The bibliometric review has been widely used in the past (e.g. Poo et al., 2018), as it can provide valuable insights for observing knowledge developments and precisely defining the corresponding research gaps in science (Ekanayake et al., 2022). After understanding the background information and the development of corresponding research areas by the scientometric literature review in Sections 2.1 and 2.2, respectively, it is revealed that the food trade network assessment is closely associated with this study. Therefore, a discussion on food trade network assessment is provided in Section 2.3. Finally, the new contributions are shown in Section 2.4.

2.1. Facts and figures

The United Nations (UN) Sustainable Development Goals (SDGs) aim to achieve a more sustainable future for all, and improving the resilience of FSCs is one of the components of SDG 2: Zero Hunger. SDG 2 can aid to end hunger and malnutrition and to double the agricultural productivity and income of small-scale food producers, particularly in developing countries. SDG 12, Responsible Consumption and Production, is closely related to these efforts. SDG 12 emphasises sustainable consumption and production patterns, including reducing food waste and promoting efficient resource use through the development of resilient FSC. Apart from food production, food trade is also crucial in maintaining resilience by strengthening food trade networks and fostering regional food trade (Ratajczak et al., 2016). By aligning with both SDG 2 and SDG 12, society can work towards a more sustainable and resilient global food system.

FSC resilience is defined as an FSC system's capacity to maintain a desired food security state when exposed to stress and shocks (Ingram et al., 2020). Global crises, including climate change, wars, and pandemics, usually disrupt the global shipping network (Notteboom et al., 2021). Global food insecurity threats could be raised with the fluctuation of shipping freight rates (Michail and Melas, 2020) during and after such shocking events. Many children, adolescents, and their families worldwide are at risk of developing food insecurity. In addition, the lack of sufficient nutrition from various food types is associated with severe humanitarian disasters (Paslakis et al., 2021). Unprecedented reductions in food production and FSC efficiency driven by various issues, including economic downfall and political uncertainties, require attention from policymakers (Laborde et al., 2020).

The COVID-19 outbreak has been affecting people's lives and work across the globe. As the latest survey of economists' Gross domestic product (GDP) predictions decreased by an average of 4.9 % for 2020, the global shipping capacity can decline drastically as long as the maritime connectivity between countries drops seriously (Clarkson Research, 2020). The global outbreak has significantly impacted global FSC. Studies have delved into various dimensions of this issue, including the influence of trust and risk perception on the acceptance of measures to reduce COVID-19 cases (Siegrist et al., 2021), potential strategies for managing supply chain disruptions during the pandemic (Moosavi et al., 2022), assessment of social distancing obedience behaviour post-epidemic (Yuan et al., 2021), and the implementation of public health strategies through educational initiatives (Khorram-Manesh et al., 2021). Systematic reviews and bibliometric network analyses have shed light on pandemic-related supply chain research (Swanson and Santamaria, 2021), while others have outlined the challenges supply chains face under COVID-19 disruptions and proposed research agendas (Pujawan and Bah, 2022).

Most FSCs were harmed or threatened by the outbreak of COVID-19 as the outbreak heavily impacted the seaborne trade (Tazir et al.,2020). The development of the seaborne trade is shown in Fig. 1. The economic cycle can be observed, as there was a negative seaborne trade in 2009 after the financial crisis and 2020 after the COVID-19 pandemic. Compared to the trade mentioned above downturn in 2020 due to COVID-19, the 2008–2009 financial crisis had far-reaching effects on the global FSC (Notteboom et al., 2021). Economic downturns reduced consumer purchasing power and altered consumption patterns. Decreased investment and rising agricultural input costs impacted farming practices. Supply chain disruptions emerged, causing delays in logistics and distribution networks. Export and import challenges hindered the movement of food across borders. Production and employment were affected, leading to decreased planting and potential labour shortages.

Apart from international shipping disruption by COVID-19, an economic crisis is devastating for arousing a food crisis (Holt-Gimenez and Patel, 2012). The situation evolves daily, and the impacts could be long-term, as evident by the high inflations in significant global economies. Despite the challenge and the high demand, studies on food resilience assessment have yet to be witnessed in the whole picture in the literature. European Maritime Safety Agency (EMSA) provides datasets to analyse the pandemic's impact on shipping networks. It is relevant to food supply resilience, which is only one relevant dimension. Food security is determined by local production (i.e. production-and-supply ratio) and shipping network resilience by the connectivity between the export and import countries. Food supply resilience should, therefore, be assessed by investigating shipping traffic data and generating insights (European Maritime Safety Agency, 2020) to guide the countries facing food supply security risks and to develop reasonable control measures from the perspectives of adjusting their participation in global shipping networks (e.g. multiple supply countries strategy and carbon footprint reduction).

Climate change can also lead to shifts in temperature, precipitation patterns, and extreme weather events, all of which directly impact agricultural productivity (Farooq et al., 2022; Leal Filho et al., 2022). These changes can affect crop yields, growing seasons, and the overall quality of produce. Increased temperatures can lead to heat stress for plants, while altered rainfall patterns can cause droughts or floods that damage crops. Changes in pest and disease patterns are also linked to shifts in climate conditions. All these factors can result in reduced agricultural output, affecting food availability and affordability. Climate change-induced disruptions also extend to the logistics of FSC (Horn et al., 2022). Extreme weather events can damage transportation infrastructure, such as roads, bridges, and ports, leading to delays and interruptions in the movement of goods. Additionally, disruptions in transportation networks can lead to the spoilage of perishable goods due to extended transit times. Rising sea levels and changing weather patterns can affect shipping routes and port operations, impacting the timely delivery of food products across the globe.

The United Kingdom's decision to leave the European Union, known as Brexit, has raised concerns about trade disruptions and regulatory changes that can affect FSC (Brooks et al., 2021). The UK heavily relies on imports for a significant portion of its food supply, especially fruits, vegetables, and processed foods. Brexit has disrupted established trade routes, introduced new trade barriers, and impacted the flow of goods, including food products, between the UK and the EU. This disruption can lead to delays, increased costs, and potential shortages in the availability of certain food items. To mitigate these challenges, policymakers must negotiate trade agreements and establish new regulatory frameworks to ensure food imports' smooth flow and security.

The conflict between Russia and Ukraine can severely affect regional food security (Ben Hassen and El Bilali, 2023). The conflict in Ukraine has led to a series of severe challenges for its agricultural sector. Export capacity has been hampered due to disrupted trade

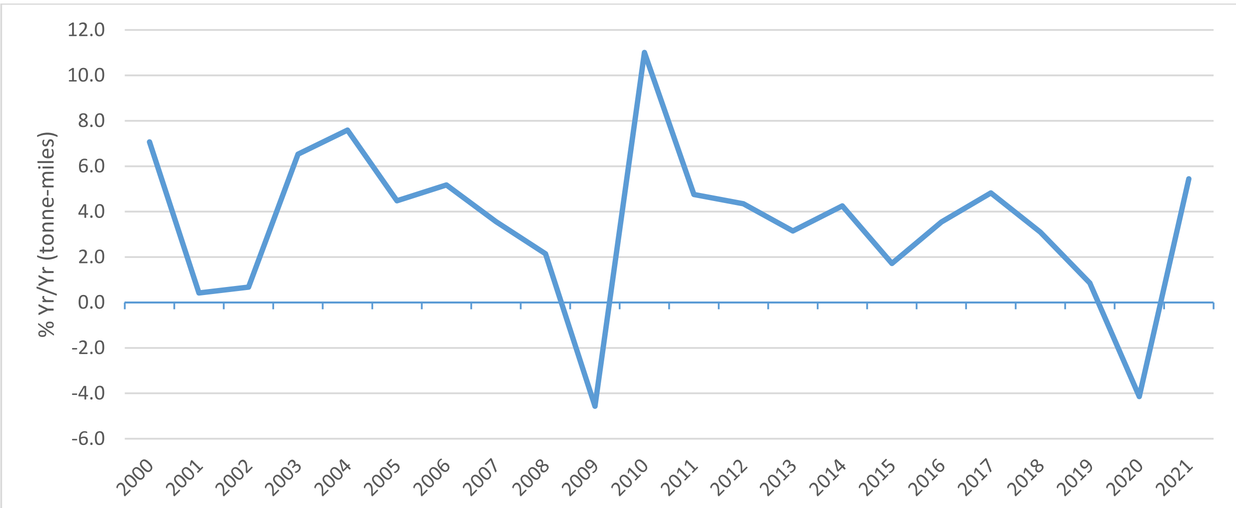

Fig. 1. Trend of world seaborne trade from 2000 to 2021 (Clarkson Research, 2020).

routes and infrastructure, while conscription and population displacement have caused labour shortages. Access to vital agricultural inputs, particularly fertilisers, has been constrained, potentially affecting crop yields. Uncertainty looms over future harvests as conflict-related disruptions could delay planting and harvesting. These challenges have cascading effects, such as rising fertiliser costs potentially reducing crop productivity. Like past crises, export restrictions and speculation are elevating global food prices. Additionally, panic buying is contributing to supply shortages. Resolving these issues requires a comprehensive approach involving diplomatic resolution of the conflict, targeted support for agriculture, and measures to stabilise food markets and ensure accessibility. Factors like pandemics, conflicts, climate change, and trade disruptions threaten global FSC and their security.

The FAO has advised that a high food import ratio (FIR) could expose a country to food shortage risk by logistics disruptions in international supply chains (Sohal et al., 2022). For example, the Dover Strait maritime route is critical for the UK food import system. There was a long lorry waiting queue at Dover because of the extra paperwork caused by Brexit, and there were heavy disruptions for all supplies, including food supplies (Forrest, 2022). Disruption could lead to a shortage of food supplies in the UK. Furthermore, trade restrictions by importing countries to safeguard food security can cause food supply disruptions and price rises, as evidenced by a few relevant restriction policies recently announced by the Thailand and Vietnam governments (Ling et al., 2021). In the global food system, about half (53 %) of the food supply from the UK is imported from more than 180 countries, of which the EU is the leading supplier (28 %). Each of Asia, Africa, South America, and North America accounts for a 4 % supply (National Statistics, 2019). Beverages, fruit, vegetables, and meat are the most significant imported commodity groups in value at 2018 prices.

Fig. 2 presents a picture of the UK Food production-to-supply ratio. The provided data presents the UK's food production and the production of Indigenous-type food from 1988 to 2021 (DEFRA, 2022). The data indicates that the UK's overall food production has gradually declined. However, the production of indigenous-type food considered the food products that can be produced in the UK, has remained relatively stable during the same period. The result suggests that the UK has maintained a consistent level of domestic food production, particularly regarding indigenous food. In 2021, the food production-to-supply ratio was 61 % for all food and 74 % for indigenous-type food. The result compares with 60 % and 74 %, respectively, in 2020, showing minor changes annually after 2005.

It is noticed that some food imports are highly coming from a few key countries or regions. For example, 69 % of imported fresh vegetables and fruits are brought from the Netherlands and Spain (Garnett et al., 2020). The high food supply from very few selected countries makes the UK FSC resilience questionable. It calls for a careful investigation for its reconfiguration, if necessary, by considering the risk factors beyond the currently dominant ones from economic and geographical perspectives, which are, however, overlooked in the existing literature. Furthermore, the UK trade in different food groups has various attention and importance levels, as shown in Table 1 (DEFRA, 2020, DEFRA, 2022). "Fruits and vegetables" have the most massive trade deficit. In 2019, imports were valued at £11.5 billion while exports were valued at £1.3 billion, giving a trade gap of £10.2 billion. "Fruits and vegetables", "Meats", "Beverages", "Cereals", "Dairy & eggs", "Fishes", and "Stimulants" are the seven most essential food groups. "Fruits and vegetables" have the highest trade and "Meats" are the second highest. A food trade deficit represents heavy reliance on importing goods. Therefore, the corresponding food groups are exposed to high risks throughout the supply chain system, requiring extra attention in food resilience index studies. However, the current food resilience studies see few investigations considering the food trade deficit as an embedded risk factor, revealing a new research gap to be urgently filled. In 2021, the UK's trade gap for "Fruits and vegetables" narrowed slightly compared to 2019. Imports were valued at £10.5 billion, while exports were £0.9 billion, resulting in a trade deficit of £9.6 billion. "Fruits and vegetables" had the highest trade deficit among the seven most essential food groups, while "Meats"

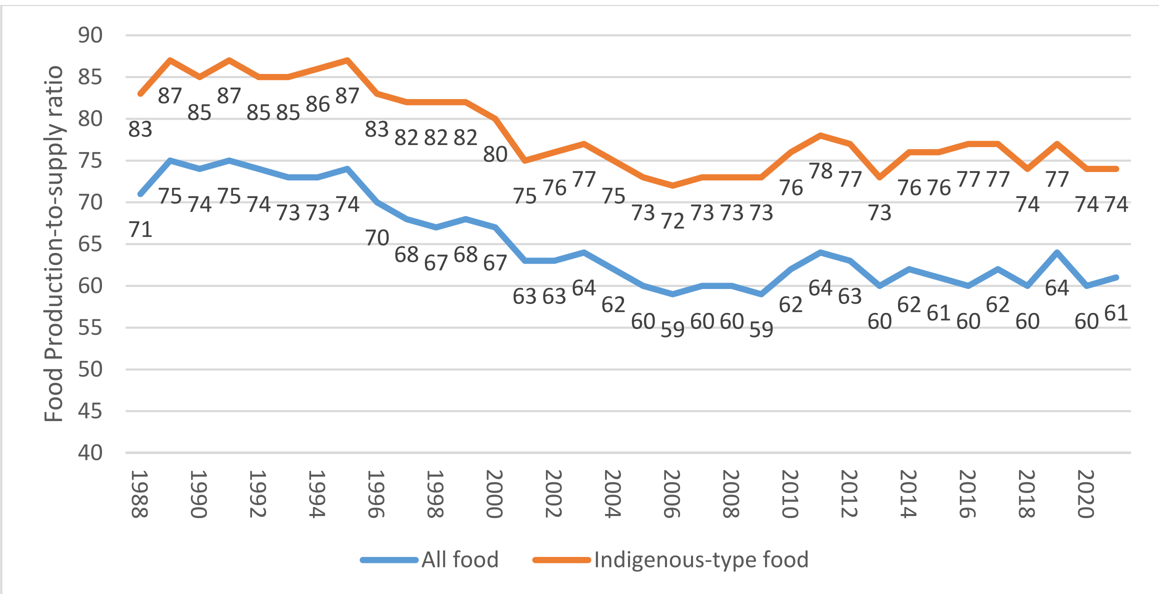

Fig. 2. UK Food production to supply ratio.

Table 1
The United Kingdom food trade balance sheet.

	Exports (£billion)		Imports (£billion)		Balance (£billion)	
	2019	**2021**	**2019**	**2021**	**2019**	**2021**
Fruits and vegetables	1.3	0.9	11.5	10.5	−10.2	−9.6
Meats	2.1	1.8	6.6	5.8	−4.5	−4
Beverages	7.9	7	6	6.2	+1.9	+0.8
Cereals	2.4	2	4.2	4.2	−1.8	−2.2
Dairy and eggs	2	1.5	3.3	3.5	−1.2	−2
Fishes	2	1.6	3.5	3.1	−1.5	−1.5
Misc	2.2	2	3.4	3.2	−1.2	−1.2
Stimulants (Coffee, tea, cocoa etc.)	1.5	2	3.8	3.2	−2.3	−1.2
Animal feed	1.1	1	2.4	2.6	−1.3	−1.6
Oils	0.6	0.7	1.9	2.5	−1.3	−1.8
Sugar	0.4	0.3	1.2	1.2	−0.8	−0.9

remained the second highest. The persisting trade deficits in these food groups highlight the country's heavy reliance on importing goods, posing increased risks throughout the supply chain system. Consequently, these food groups require heightened attention in food resilience index studies. Notably, the research gap surrounding the investigation of the food trade deficit as an essential risk factor persists, with limited attention in current food security studies. This gap emphasises the urgency to address this critical area of research in order to enhance the UK's food security and mitigate potential vulnerabilities in its FSC.

2.2. *Scientometric analysis by Citespace*

The first step of the scientometric analysis is to collect the papers on global FSC resilience from all peer-reviewed academic journals on the WoS, one of the most recognised multi-disciplinary searching platforms for educational research works, in August 2022. Peer-reviewed core journals are the chosen document types for further analysis. Accordingly, this research's central themes are defined as assessments or indices for global FSC resilience. Initially, the related keywords were recognised and placed into different strings by the combinations of the elements from the sets of "global AND food AND (supply OR security OR insecurity OR production OR import) AND resilience AND (indicator OR index OR assessment OR analysis)".

A list of 384 journal articles was obtained by searching WoS Core Collection, and then 355 articles remained after the abstract screening. The delimitation criteria included peer-reviewed journal articles discussing factors related to FSC resilience and identifying and excluding duplicated pairs of records. This list included articles with Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), Emerging Sources Citation Index (ESCI), and Arts & Humanities Citation Index (A&HCI). The trend of studies gradually rose from the first related paper published in 2007 and reached the highest number at 82 in 2021, indicating this

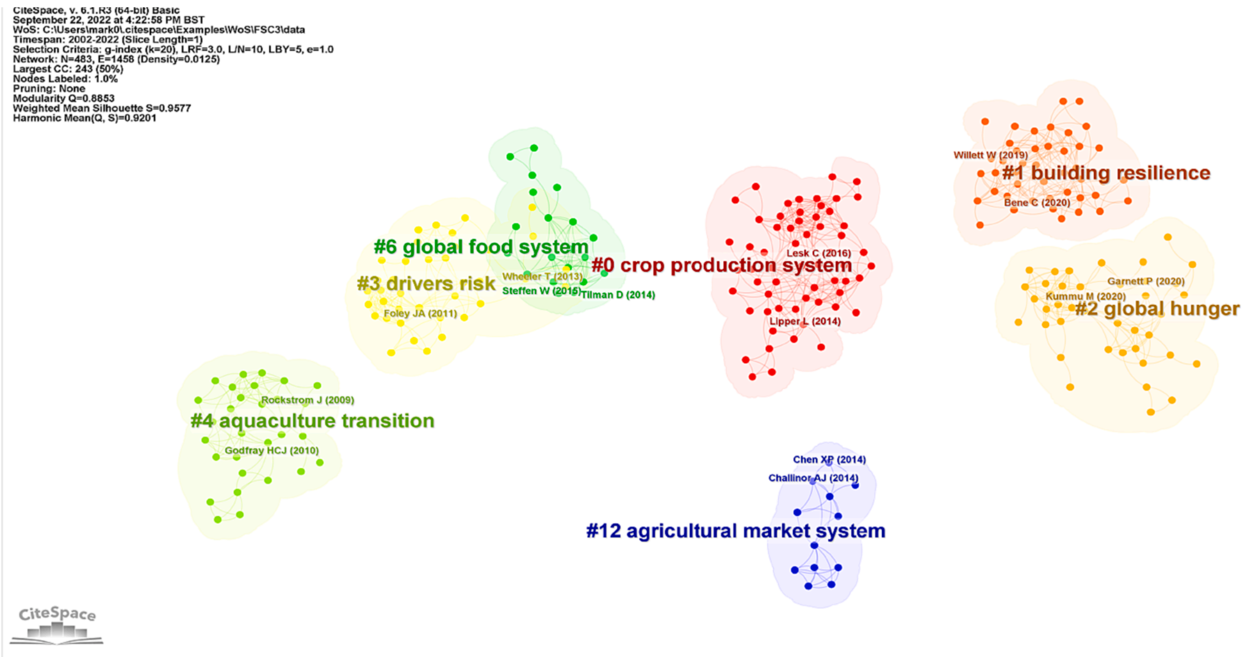

Fig. 3. Document co-citation analysis by paper impact.

study's importance and research value.

Citespace version 6.1.R3 was employed to implement the scientometric analysis. Node selection was chosen to form a stable social network for all references, including the 355 journal articles filtered in the previous section. In the coming section, the DCA with references will be implemented. First, all references provide a timeline view to observe the development of different clusters. Then, burst, degree, and centrality assessments are set up to identify the most influencing articles for FSC studies. Also, the total citation counts and major citing articles of different clusters are listed for accelerating discussions and the state-of-the-art survey for this paper.

2.2.1. Distribution co-citation analysis by paper impact

The network consists of seven clusters, as shown in Fig. 3. The details of the clusters are shown in Table 2. IDs are presented based on the result generated by Citespace. Therefore, some minor clusters are not listed, and the IDs are therefore not in strictly increasing order. Locally linear representation (LLR) is used to label the clusters. Cluster 0 ("crop production system") is the largest cluster. Then the remaining clusters are listed as follows: Cluster 1 ("building resilience"), Cluster 2 ("global hunger"), Cluster 3 ("driver risk"), Cluster 4 ("aquaculture transition"), Cluster 6 ("global food system"), and Cluster 12 ("agricultural market system"). The silhouette values range from 0.931 to 1, which measures how similar an object is to its cluster compared to others (Aranganayagi and Thangavel, 2007). Cluster 0 provides insights into food production shock and supply diversity (Zampieri et al., 2020). Cluster 1 describes the issue of how to build resilience for a local food system (Priyadarshini and Abhilash, 2021), and Cluster 2 assesses global hunger problems (Raj et al., 2022). The most cited papers in Cluster 1 and Cluster 2 were published in 2020 and related to the impacts of COVID-19 (Béné, 2020; Garnett et al., 2020). Cluster 3 focuses on regime shifts in a food system in a sustainable and eco-friendly context (Rocha et al., 2015), while Cluster 4 presents the latest development in aquaculture harvesting technologies (Bush and Marschke, 2014). Cluster 6 provides an overview of the global food system through qualitative and quantitative studies (Chaudhary et al., 2018), and Cluster 12 provides the economic assessments for food production and supply (Barrueto et al., 2017).

Furthermore, Table 3 shows the most influential papers with the highest citation counts to define the state-of-the-art from an individual cluster perspective. Béné (2020) explores and discusses the concept of local food system resilience in light of the disruptions brought to those systems by the COVID-19 pandemic. However, it is a qualitative analysis and has not provided a methodology to assess other shocks and stressors, including climate change and economic fall. Lesk et al. (2016) and Ray et al. (2015) describe the impacts of climate disasters on crop production worldwide, and they successfully overview a part of the food supply system. Willett et al. (2019) propose a concept of a sustainable food system by the UN SDGs and the Paris Agreement. Godfray et al. (2010) list all the challenges to food security in the whole world. They both provide a solid direction but have yet to implement a statistical analysis concept. According to previous studies, Wheeler and Von Braun (2013) and Lipper et al. (2014) support the need for considerable investment in adaptation and mitigation actions for FSC.

2.2.2. Burst analysis

A burst refers to a frequency surge of a particular event influencing FSC resilience (Kleinberg, 2003). For example, events can be extreme weather events, climate change, economic regression, and global pandemics. The first item shown in Table 5 is Godfrey et al. (2010) in Cluster 2, with a burst of 4.04, which means a high surge influencing studies relating to FSC resilience. The second one is Foley et al. (2011) in Cluster 4, with a burst of 4.12. The third is Wheeler and Von Braun (2 0 3) in Cluster 4, with a burst of 3.72. The 4th is Lipper et al. (2014) in Cluster 1, with a burt of 3.68. The 5th is Lesk et al. (2016), with a burst of 3.36. The 6th is Puma et al. (2015), with a burst of 3.32. Finally, the 7th is Willett et al. (2019), with a burst of 3.63. Godfray et al. (2010) contributed one of the most influential articles for the world's food security studies. All the burst references in Table 4 are influenced and published during the burst period.

Alternatively, the references in Table 4 can be used to observe the possible events that influence the global food supply resilience assessment development. First, the global financial crisis in 2008 impacted the budget of people in developing countries to buy sufficient food, and climate change is another main threat to FSC resilience (Godfray et al., 2010). In 2007, the Intergovernmental Panel on Climate Change (IPCC) published the Fourth Assessment Report, which provided a complete and authoritative assessment of scientific knowledge on all aspects of climate change, including food security (Füssel, 2009). Therefore, the studies describing the influences of climate change on FSC are bursting (Foley et al., 2011). Second, the Paris Agreement of 2015 required all countries to stabilise the global temperature rise to below 2 °C this century, which is above pre-industrial levels (Doelman et al., 2019). Therefore, there was a second burst of climate change studies from 2016 until 2020 (Wheeler and Von Braun, 2013; Lipper et al., 2014; Lesk et al., 2016). Besides FSC systems, transportation systems, which contribute to the globalisation of food trade, are also influenced heavily by climate change. Third, Willett et al. (2019) consolidated a pioneering concept for the sustainable food system, which was still a very

Table 2
Summary of seven clusters of co-citation analysis by references.

ID	Label (LLR)	Size	Silhouette	Average Year	Most influencing article
0	crop production system	60	0.933	2019	(Zampieri et al., 2020)
1	building resilience	44	0.957	2021	(Priyadarshini and Abhilash, 2021)
2	global hunger	40	0.941	2021	(Raj et al., 2022)
3	driver risk	38	0.964	2015	(Rocha et al., 2015)
4	aquaculture transition	29	0.997	2014	(Bush and Marschke, 2014)
6	global food system	20	0.971	2018	(Chaudhary et al., 2018)
12	agricultural market system	12	1	2017	(Barrueto et al., 2017)

Table 3
Top 10 cited references on global food supply resilience assessment development.

Rank	Reference	Citation count	Cluster ID
1	(Béné, 2020)	11	2
2	(Lesk et al., 2016)	10	1
3	(Willett et al., 2019)	9	2
4	(Godfray et al., 2010)	8	5
4	(Foley et al., 2011)	8	4
6	(Puma et al., 2015)	7	1
6	(Marchand et al., 2016)	7	1
6	(Ray et al., 2015)	7	1
6	(Wheeler and Von Braun, 2013)	7	4
6	(Lipper et al., 2014)	7	1

Table 4
Bursting references on global food supply resilience assessment development.

Rank	References	Influences	Year	Strength	Begin	End
1	(Godfray et al., 2010)	Economic crisis, Climate change	2010	4.04	2011	2015
2	(Foley et al., 2011)	Climate change	2011	4.12	2014	2016
3	(Wheeler and Von Braun, 2013)	Climate change	2013	3.72	2016	2018
4	(Lipper et al., 2014)	Climate change	2014	3.68	2017	2019
5	(Lesk et al., 2016)	Climate change	2016	3.36	2019	2020
6	(Puma et al., 2015)	Globalisation, Climate change	2015	3.32	2019	2020
7	(Willett et al., 2019)	COVID-19 outbreak	2019	3.63	2020	2022

trendy topic until 2022 because of the COVID-19 outbreak.

2.3. Food trade network assessment

There are multiple ways to maintain FSC resilience from the previous related literature. Apart from introducing new IoT technologies (Qader et al., 2022), inventory management tools (David et al., 2022), and government support (Doelman et al., 2019), having multiple suppliers and sources of food helps mitigate the impact of disruptions in one area (Liu et al., 2020). Therefore, the food trade is essential in maintaining FSC resilience and adaptability. In the existing literature, scholars are working on network analyses to investigate the food trade network's vulnerability, as shown in Table 5.

Scholars have collected food trade datasets from the United Nations Commodity Trade (UN COMTRADE) and analysed the structural characteristics of the whole food trade network (Suweis et al., 2015), rice trade networks (Monit, 2016) and cereal trade networks (Dupas et al., 2019; Zhang et al., 2021; Chen and Zhang, 2022). Furthermore, there are several indicators for assessing food resilience or security within food nutrient adequacy, ecosystem stability, and food affordability and availability (Chaudhary et al., 2018; Davidson et al., 2022). However, there is still a lack of studies providing a referencing indicator for food trading network analyses.

2.4. New contributions

FSC studies are diverse, including qualitative and quantitative analyses with different scales of regions across different domains, including environment, nutrition, sociocultural well-being, resilience, food safety, affordability and availability (Seekell et al., 2017). Furthermore, assessments are often conducted from the perspectives of specific single food types, including seafood (Lover et al., 2021), livestock (Godde et al., 2021), and crops (Mishra et al., 2021). From a national perspective, FSC resilience is highly related to the functionality of shipping, particularly liner shipping (Liu et al., 2018), and a delay in maritime logistics of food products will result in massive impacts (Lam and Bai, 2016). Therefore, food trade network assessments should be enhanced and standardised by incorporating shipping connectivity into the FSC resilience analysis (Marchand et al., 2016). Furthermore, although assessing the FSC

Table 5
Summary of food trade network assessments.

Reference	Food Type	Remarks
(Suweis et al., 2015)	N/A	Mapping the countries, whether they are importers or exporters, and whether they are in danger.
(Monit, 2016)	Rice	Linking Material Flow Analysis (MFA) with resilience using rice: A global case study, visual MFA of a key food product.
(Dupas et al., 2019)	Cereal	Showing how MFA can be combined with resilience research by rice trading focused around Thailand.
(Zhang et al., 2021)	Cereal	Investigating the international cereal trade network of global food crisis under the background of the pandemic.
(Chen and Zhang, 2022)	Cereal	Investigating cereal trade networks' structural characteristics and spatiotemporal dynamics among the "Belt and Road" countries.

resilience of a country is complex and challenging, it is necessary to assess them, and it is beneficial to compare the FSC resilience situations with different countries (Macfadyen et al., 2015) as situational awareness of food supply and production of different food types from export countries will be critical for the resilience of the investigated nation. Despite the increasing recognition of the importance of incorporating traditional food resilience on production into transport network connectivity for FSC resilience analysis, no evidence in the existing literature addresses how the two perspectives can be analysed simultaneously from empirical and modelling perspectives.

With the overarching aim of pioneering a comprehensive FSC resilience assessment methodology, this research makes several contributions. Firstly, it establishes a standardised framework for quantitatively assessing food trading and logistics, ensuring consistency and comparability in FSC resilience evaluations. Additionally, it enables integrating local food production data with global food logistics, fostering a holistic understanding of FSC resilience across diverse countries and providing a comprehensive view of food security. Furthermore, it endeavours to conduct granular assessments of FSC resilience by scrutinising individual food types, analysing production-to-supply ratios and trade balances for specific food categories, and ultimately constructing a comprehensive evaluation of national food connectivity. This holistic approach introduces noteworthy contributions, including integrating production-to-supply ratios and shipping transport connectivity, facilitating a deeper understanding of a country's FSC security. The research's real-world applicability is emphasised through case studies, demonstrating how the proposed methodology can assess and enhance a nation's FSC resilience. Additionally, a comparative analysis among the UK, Canada, Australia, and the DRC illuminates the strengths and weaknesses of their respective FSCs, providing a valuable benchmark for fortifying FSC resilience. Ultimately, the research empowers policymakers and stakeholders with actionable insights to formulate tailored policies and countermeasures that enhance FSC security against global disruptions.

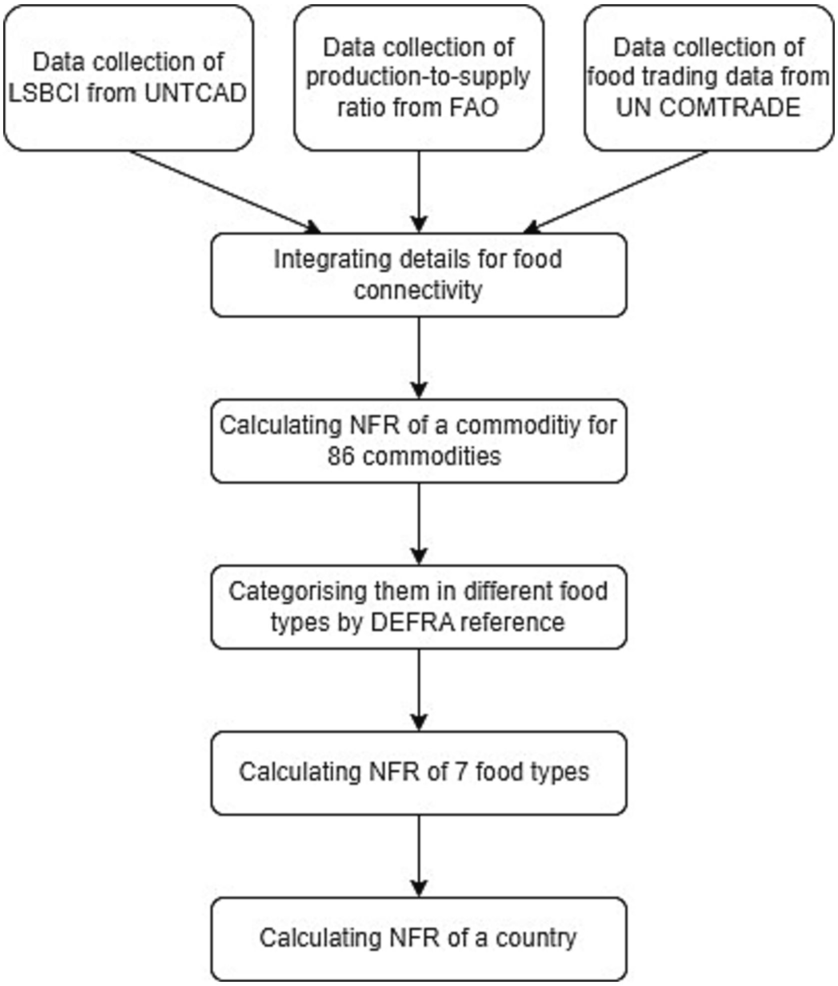

Fig. 4. Methodology of NFR assessment for a country.

3. A new model for evaluating global FSC resilience

There are various methods to assess global FSC resilience, such as those listed in Section 2. However, none of them has simultaneously addressed the food shipping network connectivity and food production and supply. Local supply and production provide more resilience for the whole food system than foreign food imports (Schmitt et al., 2016). Therefore, a new framework that combines food import and local food production is developed in this section to investigate nations' food connectivity. Such a framework can aid the calculation of the FSC resilience nationally and globally, which can be used to monitor food resilience in different scales and countries. Logistics and food trade datasets from several organisations and units are required to overview the possibilities of setting up a national FSC resilience (NFR) assessment, supported by three indices (i.e. LSBCI, FAO and COMTRADE). as shown in Fig. 4.

After comprehensive data collection, some commodities described by FAO and UN COMTRADE must be matched and standardised, and the complete conversion with both definitions and categories takes place to address the minor differences among the definitions of commodities. For instance, "Sun-flower seed, safflower or cotton-seed oil and their fractions; whether or not refined, but not chemically modified" (HS Code: 1512) defined by UN COMTRADE is matched with commodities defined by FAO, namely "Sunflowerseed Oil" (FAO item code: 2573) and "Cottonseed Oil" (FAO item code: 2575). The definition by UN COMTRADE is used in the upcoming steps, and therefore, the import quantity and domestic supply quantity of two items from FAO are summarised as one commodity for the assessment. The full commodity conversion list can be found in Appendix 1.

Next, food types are developed based on the categories defined by DEFRA in Table 1. Eighty-eight commodities in Appendix 1 are categorised into the seven food types by DEFRA, and each commodity's category can also be found in Appendix 1. Then, NFR of each food type is calculated. In this process, some commodities not in the seven food types, such as oil, are calculated as the "others" category and included in the overall NFR of a country. Afterwards, the whole formulation setup is developed in Section 3.2. Consequently, the NFR of a chosen target country can be calculated, and the NFRs of the other relevant countries (e.g. the relationship of import–export pair countries against food types or having similar or different FSC features) can also be evaluated for comparative analysis to draw valuable insights to guide rational policymaking.

3.1. Collection of data supporting NFR analysis

The production-to-supply ratio is an important index to observe the stability of food supply and import from different countries, which is needed to maintain a country's food supply (Davidson et al., 2022). Therefore, suitable datasets are investigated to assess a nation's global FSC based on its production-to-supply ratio and distance from its food export countries. As the FSC resilience is influenced by food import and export countries, a bilateral connectivity index between different countries is first analysed to understand countries' shipping network closeness independently. Second, food balance sheets of various food products are required as the FSC resilience varies against different food types. Third, food trade between the import and multiple export countries is also crucial for determining the food import distance of various items. Its relevance and influence on FSC resilience lie in the previous findings that local food supplies are more secure and resilient than those from long distances. Finally, as a country's income level is positively related to its food supply ratio, the countries with similar Human Development Index (HDI) and GDP per capita are selected for a comprehensive analysis. Therefore, the datasets of Australia and Canada are considered for a comparative study with the UK to show the significance and policy implications of the new NFR assessment methodology. Furthermore, The DRC's database is also collected to demonstrate the significance of the NFR index in a country with a different FSC feature.

FAO offers an invaluable digital dataset that enables users to evaluate the food security stance of various nations (Barrett, 2010). This dataset gives a holistic view of a country's FIR over a designated timeframe, as expanded upon by Desiere et al. (2018). The food balance sheet provides insights into factors like production, quantities of imports and exports, variations in stocks, and the total local supply. To analyse the resilience of FSC, the FIR, which represents the ratio of import quantity to local supply, is essential. Once FIR values are determined, it is imperative to delve deeper into the intricacies of food import logistics.

The LSBCI is a concept introduced by UNCTAD that assesses the efficiency and quality of shipping connections between two nations. Fugazza and Hoffmann (2016) provided a comprehensive breakdown of LSBCI, which encompasses five distinct components: transhipment, a direct standard link, the geometric average of direct connections, competitiveness in shipping services, and the size of the ships. An impressive 160 nations have undergone evaluation using this index, with landlocked nations being assessed to their closest coastal counterparts. LSBCI updates are released quarterly by UNCTAD and have become a staple in the analysis of shipping networks, as recognised by Saeed and Cullinane (2023). To provide a practical example: In 2019, the LSBCI value for connections between the UK and Germany was 0.4206, whereas it stood at 0.2768 for the UK and the United Republic of Tanzania on average. These values indicate a stronger shipping connection between the UK and Germany.

The resilience of ports often correlates with the frequency of ship arrivals and the volume of cargo traded between two countries, a concept underscored by Notteboom et al. (2021). It is crucial to note that FIR, which essentially inversely represents local food production levels, plays a pivotal role in creating models for food supply resilience, as Thilmany et al. (2021) mentioned. The UN COMTRADE Statistics Database, which contains intricate details about imports and exports as reported by almost 200 nations, offers invaluable data in this context. By harnessing data from UN COMTRADE (2003), analysts can compute the distance of food imports, aiding in painting a clearer picture of the global FSC. This analysis enables a detailed view of FSCs for various food types across different nations by the formulations in Section 3.2. It is worth noting that these food commodities are sorted using the 2002 version of the Harmonised Commodity Description and Coding System (HS02) from UNCTAD, a globally recognised classification system developed by the World Customs Organization (WCO).

3.2. Problem formulation

By gathering the data needed, NFRs of all food commodities on the food balance sheet are calculated by accumulating the connectivity and the FIR. Eighty-eight food commodities listed on the FAO food balance list and the UN COMTRADE database are used (Dahdouh et al., 2019). The range of NFR is from 0 to 1. A higher value represents a higher resilience level.

3.2.1. Notations

Sets:
N : Setofimportingcountries
C : Setofcommodities
T : Setoffoodtypes
$C_1, \cdots, C_T$: Subsetsofcommoditieswithinthesamefoodtype
C_0 : Subsetofcommoditieswhichcannotbecategorisedinanyofthedefiendsevenfoodtypes
Indices:
n : Indexofanimportingcountry
o : Indexofthecountryunderassessment
t : indexofafoodtype
c_t : indexofacommoditywhichiscategorisedasfoodtypet
Symbols:
$\alpha_{c_t}^{n\bullet o}$: Totalimportofcommodity$c_t$tocountryofromcountryninUS$
$\beta_{c_t}^{o}$: Totaldomesticsupplyofcommodity$c_t$ofcountryoinUS$
$SCIR_{c_t}^{n\bullet o}$: Singlecountryimportratioofcommodity$c_t$tocountryofromcountryn
$FIR_{c_t}^{o}$: Foodimportratioofcommodity$c_t$ofcountryo
$LSBCI^{n\bullet o}$: LSBCIbetweenthecountryoandcountryn
$NFR_{c_t}^{o}$: NFRofcommodity$c_t$ofcountryo
NFR_{t}^{o} : NFRoffoodtypetofcountryo
NFR^{o} : NFRofcountryo

3.2.2. Formulation

$$SCIR_{c_t}^{n\bullet o} = \frac{\alpha_{c_t}^{n\bullet o}}{\sum_{m=1}^{N}\alpha_{c_t}^{m\bullet o}} \forall n \in N, t \in T, c_t \in C_T (1)$$

$$FIR_{c_t}^{o} = \frac{\sum_{m=1}^{N}\alpha_{c_t}^{m\bullet o}}{\beta_{c_t}^{o}} \forall t \in T, c_t \in C_T \ (2)$$

$$NFR_{c_t}^{o} = \left(1 - FIR_{c_t}^{o}\right) + FIR_{c_t}^{o} \times \sum_{n=1}^{N}\alpha_{c_t}^{n\bullet o}\left(LSBCI^{n\bullet o} \times SCIR_{c_t}^{n}\right) \forall t \in T, c_t \in C_T \ (3)$$

$$NFR_{t}^{o} = \frac{\sum_{c_t=1}^{C_T} NFR_{c_t}^{o}}{C_t} \forall t \in T, t \neq 0 \ (4)$$

$$C = C_0 + C_1 + \cdots + C_T (5)$$

$$NFR^{o} = \frac{\sum_{t=0}^{T}\sum_{c_t=1}^{C_T} NFR_{c_t}^{o}}{C} \ (6)$$

3.2.3. Formulation explanation

Equation (1) provides the import ratio of a single country from the total import amount of a food commodity for the country under assessment, and the import amount is collected from UN COMTRADE. Equation (2) provides the import ratio of a food commodity for the country under assessment from FAO. Then, Equation (3) incorporates the productions with imports of a food commodity for a country to present its NFR against that commodity. Afterwards, NFR of a food type can be obtained by averaging all NFRs of commodities of that food type in Equation (4). By Equation (5), it is noticed that the sum of subsets of commodities with the same food types and the subset of commodities which cannot be categorised in any food type equals the sum of commodities. If $t = 0$, the commodity is not categorised in any of the defined seven food types. Then, the commodity is classified in food type t. Therefore, NFR of a country can be presented in Equation (6) by averaging NFRs of all commodities. It is essential to calculate the NFR against each food type in between the NFRs of each food commodity and each nation because some relevant food policies are often developed based on food types.

4. Result analysis

The global food crisis encompasses both developed and developing countries, with the latter often experiencing more acute impacts due to socio-economic, political, and environmental challenges. In developing nations, extreme hunger and food insecurity are prevalent, as highlighted by the World Food Program USA (2023), where such countries as the DRC (Jansen et al., 2022) grapple with severe hunger crises caused by conflict, economic instability, climate change, and inadequate agricultural infrastructure. This situation is exacerbated by market inefficiencies and access to food. Incorporating the situations in the DRC into a broader assessment provides a more holistic view of the global food security challenges. This approach in the following sections highlights the stark differences and unique challenges faced by developing countries, as opposed to their developed counterparts, underscoring the need for inclusive and globally considerate strategies and policies to effectively address the multifaceted nature of global food insecurity.

A UK case study is undertaken to present the methodology and use of NFR assessment in Section 4.1. For utilising the analysis, datasets from Australia, Canada, and the DRC are collected and analysed comparatively. Moreover, a comparative analysis with three other countries are presented in Sections 4.2 and 4.3 in terms of FIO and FNR, respectively. Some numerical settings need to be clarified at the beginning of this section. First, there are 159 exporting countries ($N = 159$) as there are 160 countries, and one of them is under assessment. Second, eighty-eight commodities ($C = 88$), as listed in Appendix 1, are analysed. There are seven food types ($T = 7$) based on the categories defined by DEFRA, "Fruits & vegetables" ($C_{Fruits\&vegetables} = 18$), "Meats" ($C_{Meats} = 9$), "Beverages" ($C_{Beverages} = 6$), "Cereals" ($C_{Cereals} = 8$), "Dairy & eggs" ($C_{Dairy\&eggs} = 5$), "Stimulants" ($C_{Stimulants} = 5$) and "Fishes" ($C_{Fishes} = 8$). Due to the complexity of the commodity definition, corresponding codes of commodities in HS02 are used to represent each of the eighty-eight commodities. For instance, $SCIR^{Egypt\bullet UK}_{Potatoes;freshorchilled}$ is substituted by $SCIR^{Egypt\bullet UK}_{0701}$.

4.1. The UK NFR and sensitivity analysis

A commodity type imported to the UK is chosen as an example of describing the mechanism and providing a sensitivity analysis for calculating the NFR of a commodity. "Potatoes; fresh or chilled" (HS Code: 0701) in the UN COMTRADE database is chosen for an illustrative purpose before obtaining the UK NFR value. The UK imports 926,000 tons, and the domestic supply is 6,745,000 tons. Therefore, the import ratio is 13.73 % by Eq. (2). Also, Egypt, Morocco, and Israel are the three exporting countries with trades in US $2709027 ($SCIR^{Egypt\bullet UK}_{0701} = 0.1185$), US$35819 ($SCIR^{Morocco\bullet UK}_{0701} = 0.0016$), and US$20122362 ($SCIR^{Israel\bullet UK}_{0701} = 0.8800$) by Eq. (1), respectively, and the total importing trade value is US$22867208. The corresponding values of the LSBCI between the UK and the three countries are 0.5112, 0.4244, and 0.6304, respectively. The complete mathematical calculation in Appendix 2 shows that the corresponding NFR of the UK against Potatoes is 0.9224 based on Equation (4), which means a high resilience value as 1 means the maximum. Then, a sensitivity analysis is carried out based on "Potato products" by observing the impact of the changes of SCRI and FIR on NFR, to show the significance of the proposed NFR for policy making. Six scenarios are set up, as shown in Table 6, with letting the number of exporting nations be fixed. Comparing the baseline (real) scenario with the six scenarios, Scenarios 5 and 6 contribute an enormous change, which means that NFR is more correlated to FIR than SCIR. It is noticed that FIR plays a more critical role in affecting NFR of products compared to SCIR. It is shown that the production-to-supply ratio is more crucial than shipping transport connectivity on NFR (Schreiber et al., 2021).

Furthermore, both analyses changed in sensible ways. Also, Scenarios 1 to 4 prove the positive correlation between SCIR and NFR. Therefore, the results reflect the established findings from the previous studies (Davidson et al., 2022; Rahaman et al., 2021) but generate new insights, such as the impact multitude in a quantitative manner, which the previous studies fail to deliver.

Based on the data presented in Table 6, it is evident NFR is more sensitive to fluctuations in the FIR of the UK than to changes in SCIR of other countries, whether they have high or low LSBCI values. Specifically, adjustments in the FIR by a magnitude of 0.1 results in significant shifts of over 6 % in NFR. In contrast, similar magnitude tweaks to the SCIR, whether for a high LSBCI country like Israel or a low LSBCI country like Morocco, only lead to less pronounced variations in the NFR, all staying below a 1.5 % change. This disparity underscores the pronounced influence of the UK's own FIR on its food reliance compared to the influence of supply chain dynamics from external nations.

4.2. Comparative analysis on food import ratio

In this case study, the UK's NFR value is analysed and evaluated using the proposed new indexing methodology in Section 3. Based on the collected data, the total trading numbers of the eighty-eight commodities by shipping are analysed. No shipping data for the corresponding commodity indicates that the FIR of the commodity from the involved countries is zero. The drawn findings (see Table 7) from the FIR values of Australia, Canada, the UK, and the DRC, at different food types' and nations' levels are used for comparative analysis and possible policy insights.

The UK's FIR data presents a picture of significant reliance on imported food across various categories. This is particularly evident in essential food types like "Fruits & Vegetables", "Meats", "Beverages", "Cereals", "Dairy & Eggs", and "Fishes", where the FIR values are consistently high. The maximum FIR for "Stimulants" indicates the country's complete dependence on their imports. Such a high dependency on international trade for food supplies makes the UK vulnerable to global supply chain disruptions, as witnessed during

Table 6
Sensitivity analysis by potato products for the United Kingdom.

Scenario	Change	New NFR	Change in percentage
1	SCIR of high LSBCI country (Israel) increases by 0.1, and the others decrease by 0.1 in total	0.9247	0.242 %
2	SCIR of high LSBCI country (Israel) decreases by 0.1, and the others fall by 0.1 in total	0.9224	0.000 %[1]
3	SCIR of low LSBCI country (Morocco) increases by 0.1, and the others decrease by 0.1 in total	0.9212	−0.132 %
4	SCIR of low LSBCI country (Morocco) decreases by 0.1, and the others increase by 0.1 in total	0.9346	1.315 %
5	FIR of the UK increases by 0.1	0.8659	−6.125 %
6	FIR of the UK decreases by 0.1	0.9786	6.089 %

[1] There is a slight reduction in NFR after four decimal places.

Table 7
Food import ratio of different food types.

Country Name		Fruits & vegetables	Meats	Beverages	Cereals	Dairy & eggs	Stimulants	Fishes
Australia	2019	0.2315	0.0658	0.6488	0.1458	0.3043	1[2]	0.7838
	2020	0.2485	0.0626	0.6715	0.1895	0.3101	1[2]	0.7838
Canada	2019	0.7975	0.4148	0.4856	0.4182	0.2667	0.6	0.7832
	2020	0.7972	0.4493	0.4719	0.4167	0.2591	0.6	0.7832
The UK	2019	0.7530	0.5049	0.8447	0.4721	0.6970	1[2]	0.9811
	2020	0.7581	0.5170	0.8555	0.4951	0.6974	1[2]	0.9811
The DRC	2019	0.1569	0.4212	0.4074	0.4660	0.7411	0.0167	0.5963
	2020	0.1330	0.4328	0.4023	0.3625	0.6406	0.0848	0.5962

[2] The calculated import rate FIR is higher than 1 as other uses can consume the import. FIR is capped as 1 for utilising the calculation.

the COVID-19 pandemic. The UK's situation underscores a need for a strategic approach to food security, balancing import reliance with strengthening domestic production capabilities.

The DRC provides a stark contrast to the developed nations in the study. As a developing country, its FIR values reveal substantial reliance on imported "Dairy & Eggs", "Meats", and "Cereals". However, the lower FIR for "Fruits & Vegetables" suggests a level of local production sufficiency. The significant year-over-year change in the FIR for "Stimulants" reflects the dynamic nature of the DRC's FSC, influenced by various socio-economic factors. The DRC's scenario highlights the complex challenges in achieving food security in a developing country context, where economic, infrastructural, and political factors play a crucial role.

Australia and Canada exhibit different patterns of reliance on food imports. Australia shows greater self-sufficiency in "Fruits & Vegetables", "Meats", "Beverages", and "Cereals", with lower FIRs suggesting robust domestic production. However, its high FIR for "Stimulants" and "Fishes" indicates reliance on the imports of these items. Canada demonstrates a higher dependency on imported "Fruits & Vegetables" and "Meats", while maintaining lower FIRs for "Dairy & Eggs" and "Fishes" indicates the areas of self-sufficiency. These patterns suggest that both countries have managed to balance import dependence and domestic production in different food categories.

The FIR data of the UK, Australia, Canada, and the DRC offer insights into diverse food security strategies shaped by each country's unique circumstances. Compared to Australia and Canada's mixed reliance, the UK's high dependency on food imports highlights the need for diversified strategies in food security planning. Australia and Canada's approach to balancing domestic production with imports could provide valuable lessons for the UK in enhancing its food resilience. The DRC's experience, with its unique challenges, underscores the importance of contextual and tailored approaches in addressing food security. This comparative analysis emphasizes the need for countries to evaluate their food supply strategies critically, considering global FSC dynamics and domestic production capabilities.

The comparison between 2019 and 2020 reveals some changes potentially influenced by the COVID-19 pandemic. While slight FIRs increase for certain food types in Australia and Canada, the UK's FIR remains relatively stable, indicating sustained import dependence. In the case of the DRC, the decrease in FIR for "Fruits & Vegetables" and "Dairy & Eggs" from 2019 to 2020 possibly suggests a shift towards local production or altered import patterns due to the pandemic. This analysis reveals the diverse food import dependencies of different countries and highlights the importance of understanding these dynamics in the context of global events like the COVID-19 pandemic, which can significantly impact international trade and food security.

4.3. Comparative analysis on national FSC resilience

Upon analysing the data using the new NFR index (Equation (1) to Equation (5)), NFR values for the four countries were calculated and presented in Table 8. NFR values measure the resilience of a country's FSC, considering factors like transport network closeness and food production.

The NFR values for the UK demonstrate a generally lower resilience compared to Australia and Canada across various food

Table 8
National food connectivity.

Country Name		Overall	Fruits & vegetables	Meats	Beverages	Cereals	Dairy & eggs	Stimulants	Fishes
Australia	2019	0.6084	0.6593	0.7946	0.5076	0.6555	0.6426	0.3599	0.5089
	2020	0.5848	0.5434	0.7316	0.4725	0.7393	0.8298	0.3651	0.5063
	% change	−3.87 %	−17.59 %	−7.93 %	−6.92 %	12.78 %	29.15 %	1.45 %	−0.51 %
Canada	2019	0.5820	0.4884	0.7332	0.6255	0.6271	0.6528	0.6021	0.6376
	2020	0.5672	0.3830	0.6613	0.6238	0.7395	0.8512	0.6022	0.6179
	% change	−2.54 %	−21.58 %	−9.80 %	−0.27 %	17.93 %	30.39 %	0.01 %	−3.08 %
UK	2019	0.5450	0.5544	0.6359	0.4603	0.6950	0.4337	0.4482	0.4793
	2020	0.5194	0.4555	0.5803	0.4847	0.7073	0.6415	0.4164	0.4747
	% change	−4.70 %	−17.84 %	−8.75 %	5.30 %	1.77 %	47.90 %	−7.10 %	−0.95 %
DRC	2019	0.4796	0.6269	0.3856	0.7003	0.3855	0.2856	0.6464	0.2846
	2020	0.4677	0.5272	0.5059	0.7166	0.4755	0.2410	0.5793	0.3039
	% change	−2.48 %	−15.90 %	31.18 %	2.33 %	23.35 %	−15.60 %	−10.37 %	6.77 %

categories. This is indicative of potential vulnerabilities within the UK's FSC. The UK's NFR values for "Stimulants" and "Fishes" are notably lower, suggesting these areas as potential weak spots in its food system. The year-over-year changes, particularly the decline in NFR values, underscore the impact of external challenges, such as the COVID-19 pandemic, on the UK's FSC resilience. This decrease calls for an increased focus on strengthening these areas of the FSC to enhance overall resilience.

The DRC's NFR values provide a reference for understanding food system resilience in a developing country context. The significantly lower NFR values for the DRC in 2019 and 2020, as compared to the UK, Australia, and Canada, highlight the stark differences in food security challenges faced by developing countries. The situations of the DRC, marked by political unrest, economic struggles, and vulnerability to natural disasters, emphasizes the critical need for robust food security strategies in developing nations. Australia's overall NFR value is relatively higher, indicating a more resilient food supply system, except for "Stimulants" which has the lowest NFR value, even comparing the DRC. Canada shows lower resilience in "Fruits & Vegetables" and "Stimulants", highlighting these as potential areas of vulnerability in its FSC.

The decline in NFR values from 2019 to 2020 for all four countries underscores the influence of global events, such as the COVID-19 pandemic, on the resilience of food supply systems. This analysis reveals the critical importance of ongoing monitoring and adaptive food security strategies. In the case of the UK, there is a specific need to enhance resilience in the "Stimulants" and "Fishes" categories. While Australia and Canada generally exhibit resilience, addressing specific vulnerabilities identified through their NFR values is essential. The DRC requires targeted strategies to bolster their food system resilience, taking into account their unique challenges.

Furthermore, some intriguing contrasts emerge within the data. Notably, NFR values for "Dairy & eggs" increased in the three developed countries, while the NFR values for "Cereals" became higher in all the four countries. Surprisingly, the NFR value for "Meats" also increased in the DRC. These disparities demonstrate that NFR values of specific food types are not necessarily uniformly consistent with the overall country FSC resilience situations. This approach to evaluating FSC resilience can therefore provide valuable insights to help countries better detect the vulnerabilities and prepare for and respond to future food security challenges.

5. Discussions and implications

The results obtained in Section 4 enable an insightful discussion on global FSC resilience, focusing on the four investigated countries' overall NFR values. The observed consistent decline in these values across the UK, Australia, Canada, and the DRC indicates a decreasing resilience in food supply across 2019–2020. This trend, reflecting the consequences of supply chain decoupling, is attributable to disruptions such as the COVID-19 pandemic, heightenes political tensions, and economic downturns, which significantly impact global FSCs. The declining NFR values underscore the critical need for countries to proactively address vulnerabilities within their FSCs, especially in a world facing evolving global challenges. This situation reaffirms the significance of the new NFR framework, highlighting its value as a practical and comprehensive tool for evaluating and quantifying a nation's FSC resilience status. It emphasizes the importance of this framework in providing structured insights for policymakers and stakeholders, enabling them to understand and strengthen the vulnerabilities and capacities of FSCs in an increasingly interconnected global landscape.

Indeed, FSC resilience is intricately tied to geographic factors. Geographical considerations play a crucial role in shaping the robustness and adaptability of FSC in the face of various challenges, including climate change, geopolitical conflicts, and other disruptions. Geographic elements such as proximity to sources of production, transportation networks, distribution hubs, and market access all influence the efficiency and vulnerability of FSC. Additionally, the geographical distribution of agricultural regions, trade routes, and infrastructure can impact a region's ability to respond to sudden shocks and maintain consistent food availability. Therefore, understanding the geographic dynamics of FSC is essential for crafting effective strategies to enhance their resilience, secure food access, and mitigate potential disruptions. The ranges of NFR values of the three countries and various food types are diverse. NFR value range of Australia in 2019 and 2020 is [0.6283, 0.6055]. Then, those of Canada and the UK in 2019 and 2020 are [0.5287,0.5187] and [0.4660,0.4628], respectively. Comparatively, those of the DRC in 2019 and 2020 are [0.4796, 0.4677], respectively. As a result, the NFR framework can reflect the FSC's resilience in reality and provide a basis for comparing countries and impact assessments of global events by NFR values.

Furthermore, it is worth noting that the sensitivity analysis conducted in Section 4.1 offers valuable statistical insights into the factors influencing NFR values. Notably, FIR emerges as a more critical determinant of NFR values than SCIR. This statistical finding underscores the prioritisation of measures aimed at enhancing NFR values. Promoting local food production is identified as a top priority, as indicated by the rise in FIR. However, the geographical limitations of each country necessitate consideration of transportation connectivity to ensure specific NFR values are achieved. This holistic approach to understanding resilience priorities provides a valuable framework for governments and stakeholders to strategically strengthen FSC and enhance overall resilience in an increasingly globalised and dynamic world.

5.1. Theoretical implications

This study emphasises the crucial factors of the production-to-supply ratio and shipping transport connectivity within the context of FSC resilience. This innovative approach has several theoretical implications. One notable implication is the amalgamation of critical factors traditionally assessed independently for gauging FSC resilience. By combining these attributes within a unified model, the study acknowledges the intricate relationship between a country's production capacity and its connectivity to global shipping networks in determining its food resilience. This integration underscores the necessity for a comprehensive approach to FSC resilience research. Another theoretical implication is the recognition of the interdependencies among various elements that influence FSC resilience. The model acknowledges that a country's capacity to produce food domestically is closely linked to its connectivity within the global shipping network. This recognition highlights the importance of considering multiple factors and their interactions when evaluating the resilience of complex systems like FSCs.

Furthermore, the passage underscores the significance of addressing uncertainties associated with critical factors affecting FSC resilience, such as food supplies and transportation. This theoretical implication emphasises the need to incorporate uncertainty and risk analysis into food security research, acknowledging that real-world FSCs are susceptible to unpredictable events like the COVID-19 pandemic and conflicts. Developing a fresh index framework for assessing a nation's FSC resilience also holds theoretical importance, particularly when it can effectively incorporate the resilience level against different food types. This theoretical advancement can lead to more comprehensive food security theories by encompassing a broader array of variables and adopting a systems-thinking approach. Lastly, the passage mentions a comparative study involving varios countries to identify the strengths and weaknesses of their respective FSCs. This theoretical implication highlights the value of comparative analysis in food security research, enabling the discovery of best practices, lessons learned, and transferrable policies across different countries. This study enriches the theoretical framework for enhancing the resilience of FSC.

5.2. Managerial implications

Utilising NFR values, governmental bodies have a powerful tool to identify and address vulnerabilities within their FSCs. By comparing NFR values across various food types and countries, governments can pinpoint where food security risks lie, especially when low NFR values for critical food items indicate potential supply chain disruptions. This insight enables strategic resource allocation to strengthen specific FSC. Additionally, disparities in NFR values can guide governments in incentivising domestic production of certain food types, reducing import dependency and enhancing FSC. Governments can also use NFR values to make informed sourcing decisions and identify countries with higher resilience for strategic diversification of food sources. Furthermore, setting a dynamic threshold for NFR values acts as an early warning system, alerting governments to potential national and international food security risks and prompting proactive measures, including diplomatic efforts and boosting local production, to tackle these challenges pre-emptively.

Beyond governmental use, the NFR value also offers valuable insights for food traders and businesses involved in international trade. Food traders can utilise the index to identify potential markets with low connectivity, signifying longer logistics footprints and less frequent liner shipping services. Armed with this knowledge, they can make informed decisions about sourcing and distribution strategies, optimising their operations for efficiency and reliability in the dynamic landscape of international food trade.

In summary, NFR value provides a multifaceted tool for governments to enhance their food security strategies. It enables them to identify vulnerabilities, promote targeted development, make informed sourcing decisions, and take proactive measures to safeguard FSCs. Additionally, it offers valuable insights for food traders, contributing to more resilient and efficient international food trade practices.

5.3. Policy recommendations

This section presents targeted policy recommendations to enhance FSC resilience based on this nuanced understanding. These recommendations are designed to guide governments in developing robust, adaptable, and sustainable food security strategies. They address the need for strategic diversification of food sources, reinforcement of local food production systems, and establishment of proactive measures to mitigate risks associated with supply chain disruptions. The suggested policies are rooted in the data-driven insights provided by the NFR analysis, offering a roadmap for governments to safeguard their FSC against the backdrop of an increasingly interconnected and dynamic global landscape. These strategies are instrumental in ensuring the well-being of populations and maintaining food security in the face of diverse and unforeseen global challenges and disruptions.

Governments are advised to prioritize diversifying their food sources by forming partnerships with countries with higher NFR values for essential food items, a strategy that mitigates risks from supply chain disruptions and bolsters overall food security. Concurrently, it's critical to invest in and encourage local food production, particularly for commodities with low NFR values, through infrastructure development, research and development, and support for local farmers, thereby enhancing self-sufficiency and resilience against external shocks in the global FSC. Establishing early warning mechanisms based on NFR values and dynamic thresholds is also essential for proactive food security management, where falling below a certain index threshold would activate predetermined response actions and contingency plans. Strengthening trade agreements, with a focus on the NFR values of potential partners, can ensure a more stable and varied supply of crucial food items. Additionally, fostering research and innovation in the food and agricultural sectors is vital to enhance FSC resilience, supporting technological progress, sustainable farming methods, and innovations that decrease vulnerabilities while boosting supply system efficiency. Developing strategic food stockpiles placed strategically and rotated regularly will further serve as a buffer during supply disruptions, providing a safety net in times of crisis.

In summary, based on the insights from NFR values, these policy recommendations empower governments to build a more resilient and reliable FSC, safeguarding the well-being of their populations in the face of unforeseen challenges and disruptions.

5.4. Research limitations and future directions

The study acknowledges several limitations that significantly shape the interpretation of our findings, particularly concerning the use of LSBCI data. Primarily, our analysis is concentrated on the trade aspect of FSC, leveraging LSBCI as a critical data source. While LSBCI offers valuable insights into shipping connectivity, it represents only one dimension of the complex network influencing FSC resilience. Future studies could investigate other crucial elements, such as local production capacity, distribution infrastructure, and broader socio-economic factors, which are vital for a holistic understanding of FSC resilience.

Additionally, the study's reliance on historical data, while providing a baseline, may not fully capture the fluid and rapidly evolving nature of global FSC. Contemporary data, reflecting recent global events and trends, is essential for a more current and comprehensive analysis. Future studies would benefit from incorporating this up-to-date information to understand the current state of FSC resilience better, when the access to the latest data becomes possible. For this reason, futhre studies could also pay attention to the development of new relevant databases.

Moreover, our study emphasizes quantifiable trade relationships and connectivity, highlighting a potential area for future research to include qualitative factors that influence food security. Aspects such as political stability, policy changes, and geopolitical dynamics play a crucial role in shaping FSCs and their resilience. Incorporating these qualitative factors into the analytical framework would provide a more comprehensive evaluation of food security resilience. It will be inspritional to see future studies in the incorporation of both quantitaitve and qualitative factors into the same NFR framework.

Finally, to gain a deeper understanding of these intricate dynamics and effectively address them, it is essential to establish an intricate and refined national FSC resilience assessment framework that collaborates with logistics experts, food producers, and nutrition specialists. This comprehensive framework would enable a thorough evaluation of FSC resilience, taking into account the multifaceted challenges and responses within distinct food categories. Such a collaborative and holistic approach would play a pivotal role in empowering nations to proactively prepare for and adeptly respond to future food security challenges. Ultimately, this initiative would contribute to the development of a more resilient and robust FSC system, safeguarding against potential disruptions.

6. Conclusion

This study marks a significant advancement in food security assessment by integrating logistics elements into traditional food security methodologies. Through the development and application of the NFR framework to case studies in the UK, Australia, Canada, and the DRC, it demonstrates the framework's applicability in diverse global contexts. The research findings emphasize the importance of logistics and connectivity in food security, particularly in regions with varying levels of development and infrastructure. By comparing developed and developing nations, the research highlights the NFR framework's adaptability in assessing FSC resilience across a broad spectrum of conditions.

Key outcomes include the notable influence of FIR on NFR values, underscoring the importance of local food production and transportation connectivity. The comparative analysis reveals different resilience levels for various food types, indicating the necessity for customized approaches to secure global FSCs. The research further stresses the need for establishing NFR threshold values to better anticipate and manage disruptions in FSCs, influenced by geographical factors and global events.

The research results, particularly in light of the COVID-19 pandemic, underline the critical need for adaptive strategies and continuous monitoring in maintaining food security. The dynamic interplay of local production, global trade networks, and socio-economic conditions in shaping resilient food systems is a key takeaway.

Future enhancements to the NFR framework should involve incorporating current data and qualitative factors, such as political stability and geopolitical dynamics, to enrich resilience assessment. Recognising the research limitations, future research should encompass a more holistic view, including local production capabilities, distribution infrastructure, socio-economic dynamics, and the geographical aspects of FSCs. Such a comprehensive approach is essential for a deeper understanding and effective management of food security resilience in various international settings.

CRediT authorship contribution statement

Mark Ching-Pong Poo: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Tianni Wang:** Formal analysis, Validation, Writing – review & editing. **Zaili Yang:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary commodity conversion list

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tra.2024.104018.

Appendix B. Demonstration of calculating national food connectivity

Example 1 National food connectivity of "Potatoes; fresh or chilled" (HS02 code: 0701) for the UK

$$SCIR^{Egypt\bullet UK}_{0701_{\text{Fruits \& vegetables}}} = \frac{US\$2709027}{US\$22867208} = 0.1185$$

$$SCIR^{Morocco\bullet UK}_{0701_{\text{Fruits \& vegetables}}} = \frac{US\$35819}{US\$22867208} = 0.0016$$

$$SCIR^{Israel\bullet UK}_{0701_{\text{Fruits \& vegetables}}} = \frac{US\$20122362}{US\$22867208} = 0.8800$$

$$LSBCI^{Egypt\bullet UK} = 0.5112$$

$$LSBCI^{Morocco\bullet UK} = 0.4244$$

$$LSBCI^{Israel\bullet UK} = 0.6304$$

$$FIR^{UK}_{0701_{\text{Fruits \& vegetables}}} = 13.73\%$$

$$NFC^{UK}_{0701_{\text{Fruits \& vegetables}}} = (1 - 13.73\%) + 13.73\% \times (0.5112 \times 0.1185 + 0.4244 \times 0.0016 + 0.6304 \times 0.8800) = 0.9224$$

Example 2 National food connectivity of "Diary and Eggs" for the UK

"Diary and Eggs" consists of five commodities, "Milk and cream; not concentrated, not containing added sugar or other sweetening matter" (HS02 code: 0401), "Milk and cream; concentrated or containing added sugar or other sweetening matter" (HS02 code: 0402), "Butter and other fats and oils derived from milk; dairy spreads" (HS02 code: 0405), and "Birds' eggs, in shell; fresh, preserved or cooked" (HS02 code: 0407), and "Ice cream and other edible ice; whether or not containing cocoa" (HS02 code: 2105).

$$SCIR^{Ukraine\bullet UK}_{0402_{\text{Diary and Eggs}}} = \frac{US\$36315}{US\$36315} = 1$$

$$SCIR^{NewZealand\bullet UK}_{0405_{\text{Diary and Eggs}}} = \frac{US\$1985474}{US\$1990951} = 0.9972$$

$$SCIR^{USA,PuertoRico,USVirginIslands\bullet UK}_{0405_{\text{Diary and Eggs}}} = \frac{US\$5477}{US\$1990951} = 0.0028$$

$$SCIR^{China\bullet UK}_{0407_{\text{Diary and Eggs}}} = \frac{US\$208023}{US\$208023} = 1$$

$$SCIR^{Brazil\bullet UK}_{2105_{\text{Diary and Eggs}}} = \frac{US\$149347}{US\$8242608} = 0.0181$$

$$SCIR^{Ghana\bullet UK}_{2105_{\text{Diary and Eggs}}} = \frac{US\$362507}{US\$8242608} = 0.0440$$

$$SCIR^{Israel\bullet UK}_{2105_{\text{Diary and Eggs}}} = \frac{US\$454323}{US\$8242608} = 0.0551$$

$$SCIR^{Philippines\bullet UK}_{2105_{\text{Diary and Eggs}}} = \frac{US\$27841}{US\$8242608} = 0.0034$$

$$SCIR^{RepublicofKorea\bullet UK}_{2105_{\text{Diary and Eggs}}} = \frac{US\$21076}{US\$8242608} = 0.0026$$

$$SCIR^{Thailand\bullet UK}_{2105_{\text{Diary and Eggs}}} = \frac{US\$128464}{US\$8242608} = 0.0156$$

$$SCIR^{USA,PuertoRico,USVirginIslands\bullet UK}_{2105_{\text{Diary and Eggs}}} = \frac{US\$7099050}{US\$8242608} = 0.8613$$

$$LSBCI^{BrazilandUK} = 0.4754$$

$$LSBCI^{ChinaandUK} = 0.6972$$

$$LSBCI^{GhanaandUK} = 0.3965$$

$$LSBCI^{IsraelandUK} = 0.4244$$

$$LSBCI^{NewZealandandUK} = 0.3675$$

$$LSBCI^{PhilippinesandUK} = 0.3286$$

$$LSBCI^{RepublicofKoreaandUK} = 0.6708$$

$$LSBCI^{ThailandandUK} = 0.4898$$

$$LSBCI^{UkraineandUK} = 0.3834$$

$$LSBCI^{USA,PuertoRico,USVirginIslandsandUK} = 0.6739$$

$$FIR^{UK}_{0401_{\text{Diary and Eggs}}} = 0\%$$

$$FIR^{UK}_{0402_{\text{Diary and Eggs}}} = 37.50\%$$

$$FIR^{UK}_{0405_{\text{Diary and Eggs}}} = 47.98\%$$

$$FIR^{UK}_{0407_{\text{Diary and Eggs}}} = 11.97\%$$

$$FIR^{UK}_{2105_{\text{Diary and Eggs}}} = 158.43\% \geq 100\%$$

$$NFC^{UK}_{0401_{\text{Diary and Eggs}}} = 1$$

$$NFC^{UK}_{0402_{\text{Diary and Eggs}}} = 0.7688$$

$$NFC^{UK}_{0405_{\text{Diary and Eggs}}} = 0.6970$$

$$NFC^{UK}_{0407_{\text{Diary and Eggs}}} = 0.9638$$

$$NFC^{UK}_{2105_{\text{Diary and Eggs}}} = 0.6403$$

$$NFC^{UK}_{Diary\ and\ Eggs} = \left(NFC^{UK}_{0401_{\text{Diary and Eggs}}} + NFC^{UK}_{0402_{\text{Diary and Eggs}}} + NFC^{UK}_{0405_{\text{Diary and Eggs}}} + NFC^{UK}_{0407_{\text{Diary and Eggs}}} + NFC^{UK}_{2105_{\text{Diary and Eggs}}}\right) \tilde{A} \cdot 5$$
$$= (1 + 0.7688 + 0.8970 + 0.9638 + 0.6403)\tilde{A} \cdot 5 = 0.8140$$

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