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The Network Structure of International Research Collaboration in Secondary Batteries

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The secondary battery market continues to grow, driven by the increasing demand for sustainable energy storage solutions. However, recent international environmental changes have increased technological protectionism for this key technology. This policy shift will require closer cooperation among allies. This study examined the structure and changes in international research collaboration in secondary batteries. Utilizing the Web of Science database, we applied scientometric analysis techniques to publication data and co-authorship networks. In particular, we identified the structure of the network and key patterns and trends over the last decade to identify dynamic changes. The proportion of collaborative research in secondary battery research papers has steadily increased. Our key findings show that international collaboration in secondary battery research is increasing and that China's influence continues to grow. In particular, the secondary battery international research collaboration network is path-dependent on previously established networks. This path-dependence should be considered for strategic alliances and joint international research in secondary battery research. These findings provide valuable insights into the dynamics of collaboration and can inform policy efforts to promote international collaboration in secondary batteries.

Keywords: Co–authorship networks, Research dynamics, S&T policy, Scientometrics, Web of science

Introduction

Secondary batteries are semipermanent batteries that can be charged and discharged repeatedly and are used in various applications, including electric vehicles, portable electronics, and renewable energy systems. The market for rechargeable batteries is continuously growing owing to the widespread use of wireless portable devices, especially smartphones and eco-friendly electric vehicles,[1] and the demand for more efficient and sustainable energy storage solutions is increasing.

However, the recent intensification of trade conflicts between countries has led to the emergence of a new cold war, requiring the establishment of strategies to reorganize Global Supply Chains (GVCs) considering the international situation,[2] and the COVID-19 pandemic has accelerated the new cold war.[3] In particular, the United States has recently strengthened its closed technology protectionism through the Chips and Science Act and the Inflation Reduction Act (IRA) to build domestic production plants and curb the rise of China.

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This policy shift toward closed technology protectionism is expected to affect international collaborative science and technology research. Secondary batteries are one of the key areas of the US-China trade conflict, in which industry plays a large role. The emphasis on national techno-protectionism has resulted in closed-door practices such as reshoring, which involves bringing overseas manufacturing plants back to the United States and legislation for closer cooperation among allies.

Recent research has highlighted the importance of International Research Collaboration (IRC) to enhance global innovation competitiveness,[4] but it is susceptible to changes in national policies.[5] Nevertheless, there remains a dearth of research on the structural characteristics and changes of IRC networks in the secondary battery sector. This study aimed to address this gap by analyzing the structure and changes in IRC networks in the secondary battery sector using a data-driven approach. Specifically, we employed a scientometric methodology to analyze article data from the Web of Science database, focusing on co-authorship relationships to gain insights into the structure and changes in IRC networks in the field of secondary batteries. Our study is expected to provide valuable insights into the structural characteristics of and changes in IRC networks in this field, which can inform policy researchers and Research and Development (R&D) policymakers studying international cooperation in the field of secondary batteries.

Literature Review

International Research Collaboration (IRC)

As long as the laws of nature remain immutable and unaffected by socioeconomic and political considerations, science will be studied at a transnational level.[6] International collaboration is a significant driver of scientific and technological advancement[7] and exhibits a strong correlation with research productivity.[8] At the national level, countries situated prominently within the IRC network possess a greater capacity to harness their internal capabilities and attract foreign investments for R&D.[9] Collaborative research has gained prominence at the level of researchers due to its numerous advantages, including research dissemination, cost reduction, convergence projects, complementarity, and the shared use of experimental equipment. Thus, major nations have prioritized enhancing international cooperation as a central element of their national policies to strengthen global competitiveness.[10] Consequently, international cooperation in Science and Technology (S&T) has experienced consistent growth.[11,12] Non-scientific factors such as geography, politics, and language play crucial roles in determining the nations with whom international research collaborations are pursued.[13,14]

Various attempts have been made to measure the IRC in S&T. Luukkonen *et al.*[15] measured the IRC based on authors' institutional affiliations using data from scientific literature databases. Nguyen *et al.*[16], McManus *et al.*[17], and Dua *et al.*[18] analyzed the co-authorship relationships in the Web of Science article data to identify patterns and factors influencing S&T collaboration in specific countries. Wagner *et al.*[19] combined the Web of Science and SCOPUS databases to analyze the relationship between IRC and novel research. Plotnikova and Rake[14] employed a gravity model based on the Web of Science database to analyze the determinants of IRC in specific fields. Recent studies, such as Gui *et al.*[20], have applied scientometric methodologies to analyze trends in IRC using Web of Science databases. Chen *et al.*[21] used multiple methodologies to analyze international research collaborations and proposed potential topics for further IRC research.

Co-authorship based on article databases is often used to analyze IRCs in S&T. While there are various indicators to measure IRC in S&T, co-authorship of research articles is a widely used metric; currently, alternative methodologies are not available.[21] Moreover, co-authorship can be considered a more active and tangible form of collaboration than just exchanging materials and information.[15]

The Structure and Changes of Network

Analyzing the structure and evolution of networks is crucial because it provides insights into collaborative relationships within a particular field. By scrutinizing the network's structure, researchers can identify key actors, groups, and relationships; analyze changes over time; and gain insights into the evolution of the network. This information can help formulate research policies that promote collaboration in the field. Barabasi *et al.*[22] studied the evolution of collaboration networks using a network analysis methodology. They utilized a database of journals in the fields of mathematics and neuroscience and proposed a direction for analyzing changes in network characteristics over time. Choe and Lee[23] analyzed the structure of and changes in research collaboration networks in Korea. They focused on patent data, an indicator of technological cooperation, and analyzed it using scientific econometric methodology. They proposed implications for the establishment of national research policies. Scientific econometrics methodology is mainly used to analyze the structure and changes in the network. The key findings of this analysis can be used to suggest the main direction for establishing national S&T policies.

This study builds on previous research and suggests implications for S&T policy researchers and policymakers studying international cooperation. To analyze networks in a specific S&T field, we selected the field of secondary batteries, which has been continuously increasing in research and is an issue in international politics. Using a database of papers, we constructed international research collaboration networks through co-authorship relationships. We analyzed the structural characteristics and changes in the constructed networks and proposed insights for policy researchers and policymakers.

Data & Methodology

To fulfill the research objectives, this study used a scientometric methodology. Scientometrics is the study of the scientific literature and is one of the most reliable methods for tracking scientific and technological activities.[24] It has been mainly utilized in quantitative science policy research,[25] for example, at the national level to make general assessments of how well a country performs in a particular field.[26] The detailed analysis procedure is shown in Fig. 1.

Data Collection

The analysis was performed using the Clarivate Web of Science database. Web of Science is a scholarly citation indexing database developed in the 1960s that provides full-text access to historical Science Citation Index (SCI) research papers and includes several high-quality academic journals.[27,28] Through expert review of chemical materials, we extracted 54,082 secondary battery research papers from 2012 to 2021 by specifying the scope of secondary batteries with keywords such as "batter*,""rechar*," and "char*" and creating conditional query search expressions to include secondary battery-related materials such as "lithium*"and "Li-*." As most international collaborations are inter-institutional,[15] thus 38,088 (as of July 2022) papers involving two or more institutions were used in the analysis.

Methodology

Blockmodeling

Focusing on the network of coauthors (institutions) established through data collection, we converted the network attributes into relationships between countries through block modeling. Block modeling was employed to analyze networks by attributes by grouping and blocking network actors by specific criteria or attributes.[23] Because this study defines international collaborative research as research involving at least two countries, self-loops were removed from the block modeling process to ensure that collaboration between the same countries does not affect the entire network.

Network Analysis

Through block modeling, a network matrix required for the final analysis was built, and the centrality was analyzed using network analysis methods. Different centralities can provide different interpretive insights; in this study, we utilized Degree Centrality (DC), Betweenness Centrality (BC), and Eigenvector Centrality (EIC). Degree centrality is measured based on the connections between nodes,[29] BC is measured based on the number of times a node appears in the shortest path between different nodes,[30] and EIC is measured in a different way than the first two centralities. It is measured by considering the weight of the direct and indirect connections and reflects the overall pattern of the network.[31]

Quadratic Assignment Procedure (QAP)

A quadratic assignment procedure was performed to analyze the correlation between networks across the years. The quadratic assignment procedure measures the reproducibility by randomly rearranging the network matrix,[32] and the p-value is calculated based on the Pearson correlation coefficient. The higher the number of iterations, the smaller the variation in the p-value. In this study, we performed 1,000 iterations.

Results

Number of Publication Trends

The growth in secondary battery research papers over the past decade is illustrated in Fig. 2. The red

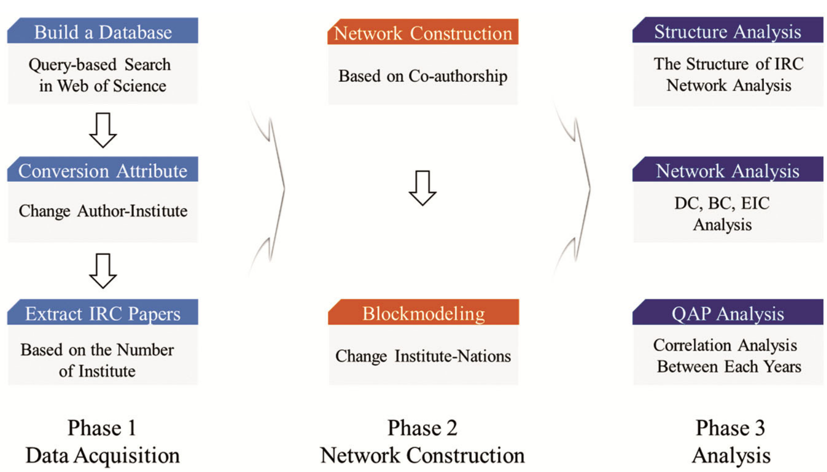

Fig. 1 — Data analysis process

line indicates the total number of secondary battery research papers, and the black line shows the number of collaborative papers among secondary battery research papers, which has been continuously increasing until recently. The recent slowdown in growth may be due to peer review delays at the time of data extraction. However, identifying this mechanism is beyond the scope of this study.[33]

Structure of the IRC Network

The structure of the secondary battery IRC network across 162 countries over the past decade is shown in Table 1. Over time, the number of links and network density increased, accompanied by an increase in the average connectivity of individual countries. Inclusiveness has also increased, indicating that the IRC network is continuously expanding. Additionally, the overall structure of the IRC network undergoes a change, with the average shortest distance and diameter decreasing, and the connections becoming wider and denser.

Changes in Key Actors in IRC Network

To identify the key factors in the secondary battery IRC network, we analyzed the degree, betweenness, and eigenvector centralities. In the network map presented by centrality, the size of the circles is proportional to the centrality. Degree centrality is calculated based on the degree of connectivity between countries. A high DC indicates that a country is connected to many other countries in its IRC network. The leading country in DC from 2012 to 2021 is shown in Table 2. The results of the 2012 and 2021 analyses are shown in Figs. 3 and 4, respectively. The analysis of DC showed that in 2012, the United States, China, and Germany collaborated with the most partners in the secondary battery IRC network, followed by France and Japan. However, in 2021, the ranking changed to China, the US, the United Kingdom, Germany, and India. Over time, France and Japan have become less influential as core countries, based on DC. This implies that their collaborative influence on the secondary battery IRC network decreased. As observed in the analysis of the IRC network structure, while the actual number of cooperating countries may have increased, their relative influence decreased compared with that in 2012. We also analyzed the BC and EIC, which provided additional insights into the importance of the nodes in the network. The results of the analyses are discussed in the following sections.

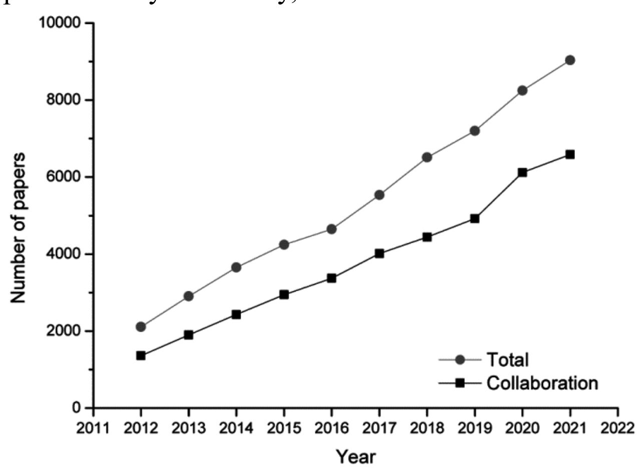

Fig. 2 — The growth in secondary battery research papers over the past decade

Betweenness centrality is the degree to which a country is on the shortest path to a country-to-country connection. In other words, a country with a high BC is more likely to be on the path to another country-to-country connection within the IRC network. The leading country in BC from 2012 to 2021 is shown in Table 3. The results of the 2012 and 2021 analyses are shown in Figs. 5 and 6, respectively. For BC, a measure of mediating IRC networks between countries, the 2012 ranking was US, Germany, China, France, and Japan, similar to the DC ranking. In 2021, the order changed to China, the US, Spain, South Korea, and India. Notably, Spain, which did not appear in the DC or BC rankings in 2012, appears in the BC ranking in 2021. While these countries do not directly play a key role in the secondary battery IRC network, they play a role in mediating research between various countries. Betweenness centrality

Table 1 — Topological structure of international research collaboration network in secondary batteries

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
# of Links	180	222	279	291	372	439	492	593	703	773
Density	0.014	0.017	0.021	0.022	0.029	0.034	0.038	0.045	0.054	0.059
Average Degree	2.222	2.741	3.444	3.593	4.593	5.42	6.074	7.321	8.679	9.543
Inclusiveness	0.321	0.364	0.432	0.407	0.432	0.463	0.537	0.531	0.586	0.605
Mean Distance	2.24	2.294	2.305	2.287	2.082	2.06	2.19	2.125	2.098	2.058
Diameter	4	6	4	5	4	4	5	5	5	4

connects the flow of information or resources within a network.[34,35] Key countries with high BCs can play a role in bridging research between different areas of secondary battery research.

Table 2 — Leading countries in degree centrality

2012		2021	
USA	0.168	CHINA MAINLAND	0.404
CHINA MAINLAND	0.130	USA	0.366
GERMANY (FED REP GER)	0.124	ENGLAND	0.298
FRANCE	0.118	GERMANY (FED REP GER)	0.298
JAPAN	0.118	INDIA	0.286
SOUTH KOREA	0.106	SOUTH KOREA	0.261
ENGLAND	0.099	AUSTRALIA	0.255
SWEDEN	0.099	SAUDI ARABIA	0.255
CANADA	0.093	CANADA	0.248
AUSTRALIA	0.087	FRANCE	0.242

Eigenvector centrality is a measure of how connected a network is to key countries with a strong influence within the network. This implies that countries with a high EIC will primarily collaborate with those with a high influence on the secondary battery IRC network. The leading country in EIC from 2012 to 2021 is shown in Table 4. The results of the 2012 and 2021 analyses are shown in Figs. 7 and 8, respectively. In 2012, the United States, China, South Korea, Germany, and France were ranked at the top, and unlike other centralities, the United States is still the first in 2021. This was followed by China, Germany, England, and South Korea. Hong Kong and Saudi Arabia are found in the rankings, which are not present in other centrality analyses, suggesting that researchers from these countries conduct research primarily with countries

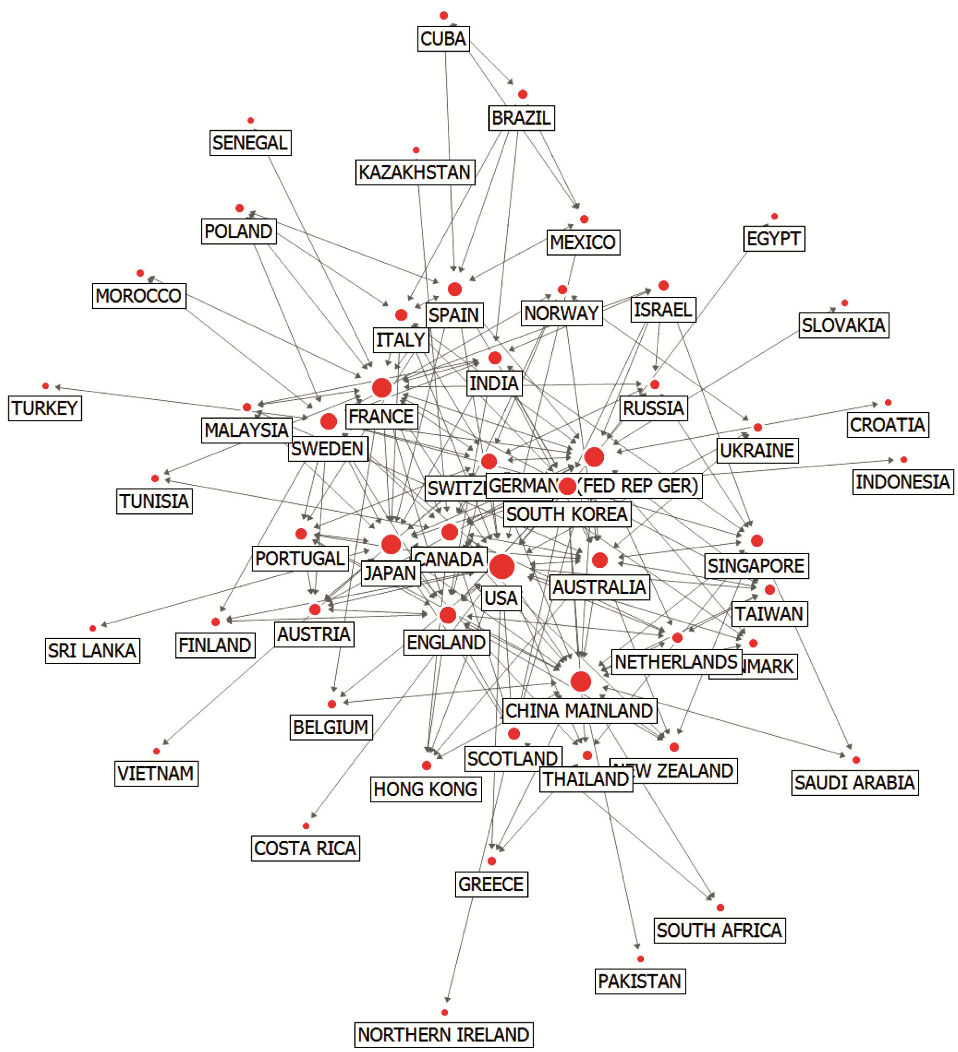

Fig. 3 — Network map based on degree centrality in 2012

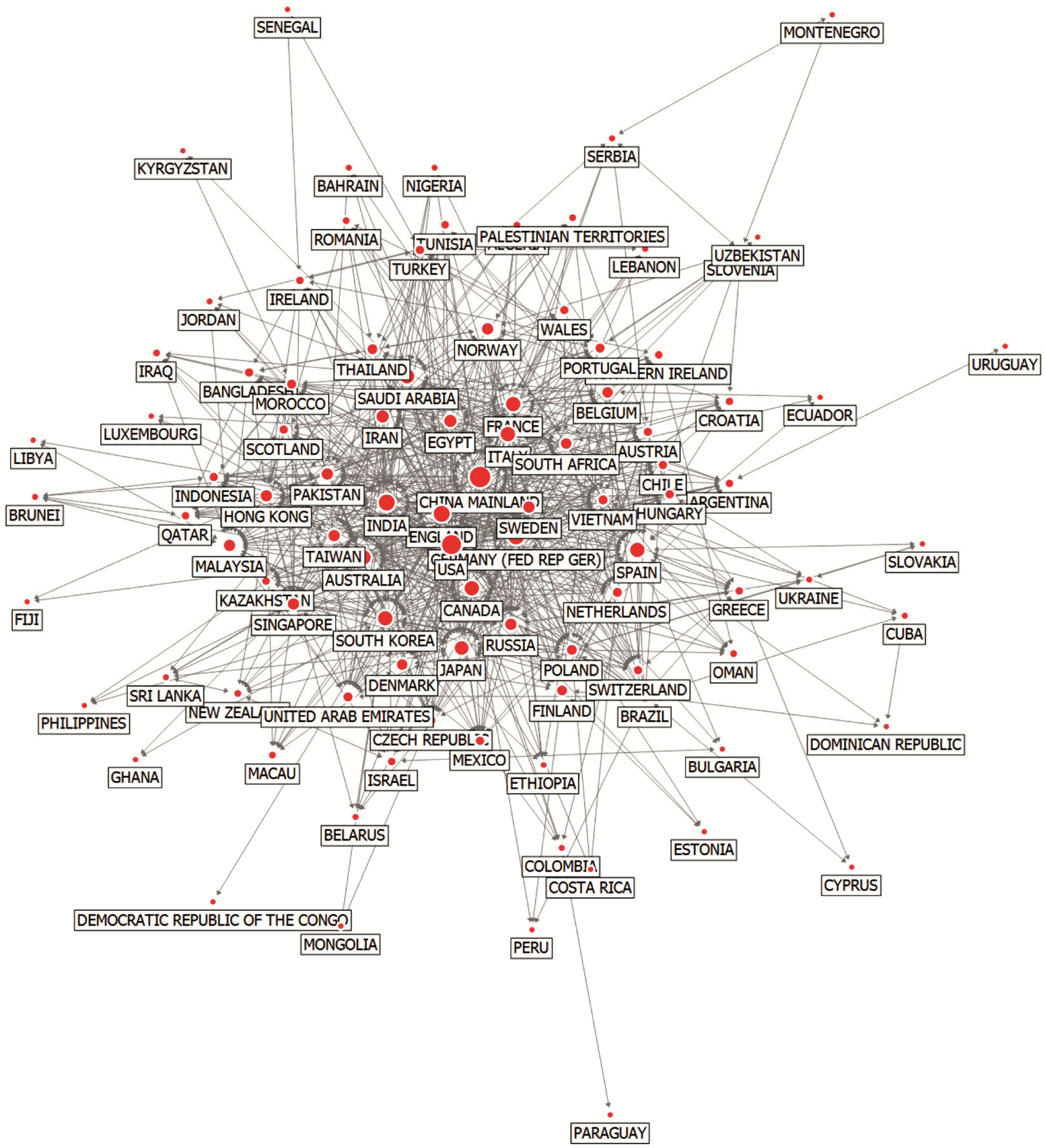

Fig. 4 — Network map based on degree centrality in 2021

Table 3 — Leading countries in betweenness centrality

2012		2021	
USA	0.021	CHINA MAINLAND	0.048
GERMANY (FED REP GER)	0.015	USA	0.032
CHINA MAINLAND	0.014	SPAIN	0.025
FRANCE	0.012	SOUTH KOREA	0.023
JAPAN	0.012	INDIA	0.018
SWEDEN	0.008	GERMANY (FED REP GER)	0.015
CANADA	0.008	SAUDI ARABIA	0.014
SOUTH KOREA	0.008	AUSTRALIA	0.014
SCOTLAND	0.005	CANADA	0.013
SPAIN	0.005	JAPAN	0.013

such as the United States and China, which have a strong presence in the IRC network. They have less of a quantitative impact on secondary battery IRC, but they do conduct collaborative research with key countries and may have strong research capabilities in certain specific areas.

QAP Analysis of IRC Network

We performed a QAP analysis to statistically test whether the secondary IRC network has been path-dependent over the past decade. The results of the QAP analysis is shown in Table 5. The analysis indicated that the correlation between networks is

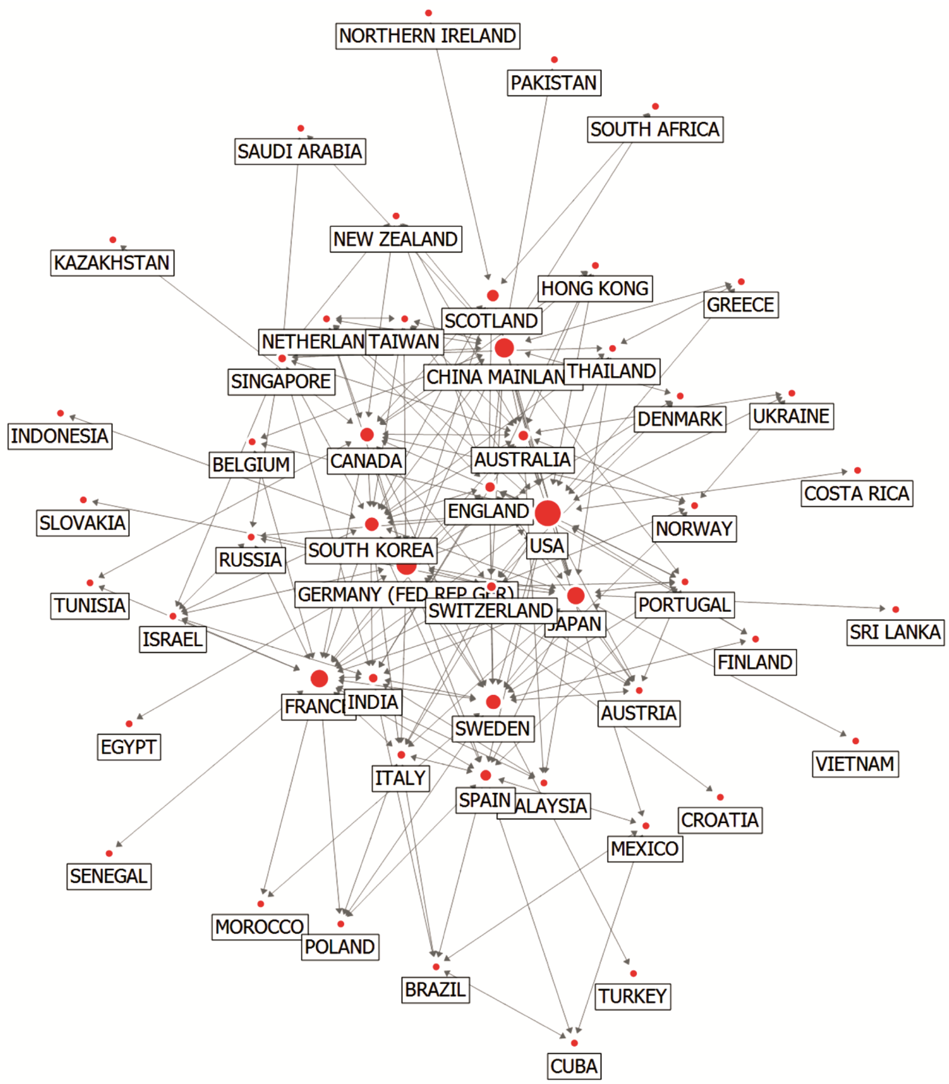

Fig. 5 — Network map based on betweenness centrality in 2012

greater than 0.7 in most years, suggesting that the IRC networks are correlated over the period analyzed. Thus, the IRC networks of secondary batteries continue to influence the formation of subsequent cross-border networks. Notably, in most years, the correlation coefficient was the highest in the previous year. This will also be true for 2021 during the COVID-19 global pandemic. While it is noteworthy that the IRC network persists despite external shocks, it should be interpreted in light of the ongoing pandemic.

Discussion

Key Findings

The key findings of this study are as follows. First, IRC networks in secondary batteries are increasing over time, with a steady increase in new countries participating in research and stronger connections with existing countries. Given the continued growth of secondary battery research papers, IRC networks are predicted to continue to grow. This is analogous to the dynamic changes in international scientific collaboration networks.[20,36] Second, the core countries of the secondary battery IRC network are shifting from the United States to China. These results are based on a centrality analysis of the IRC network. Although centrality values are relative to the network and, therefore, not absolute, the United States had the highest DC and BC in 2012, but it will shift to China by 2021. This means that China has the largest number of IRC in secondary batteries, while simultaneously playing a key role in mediating

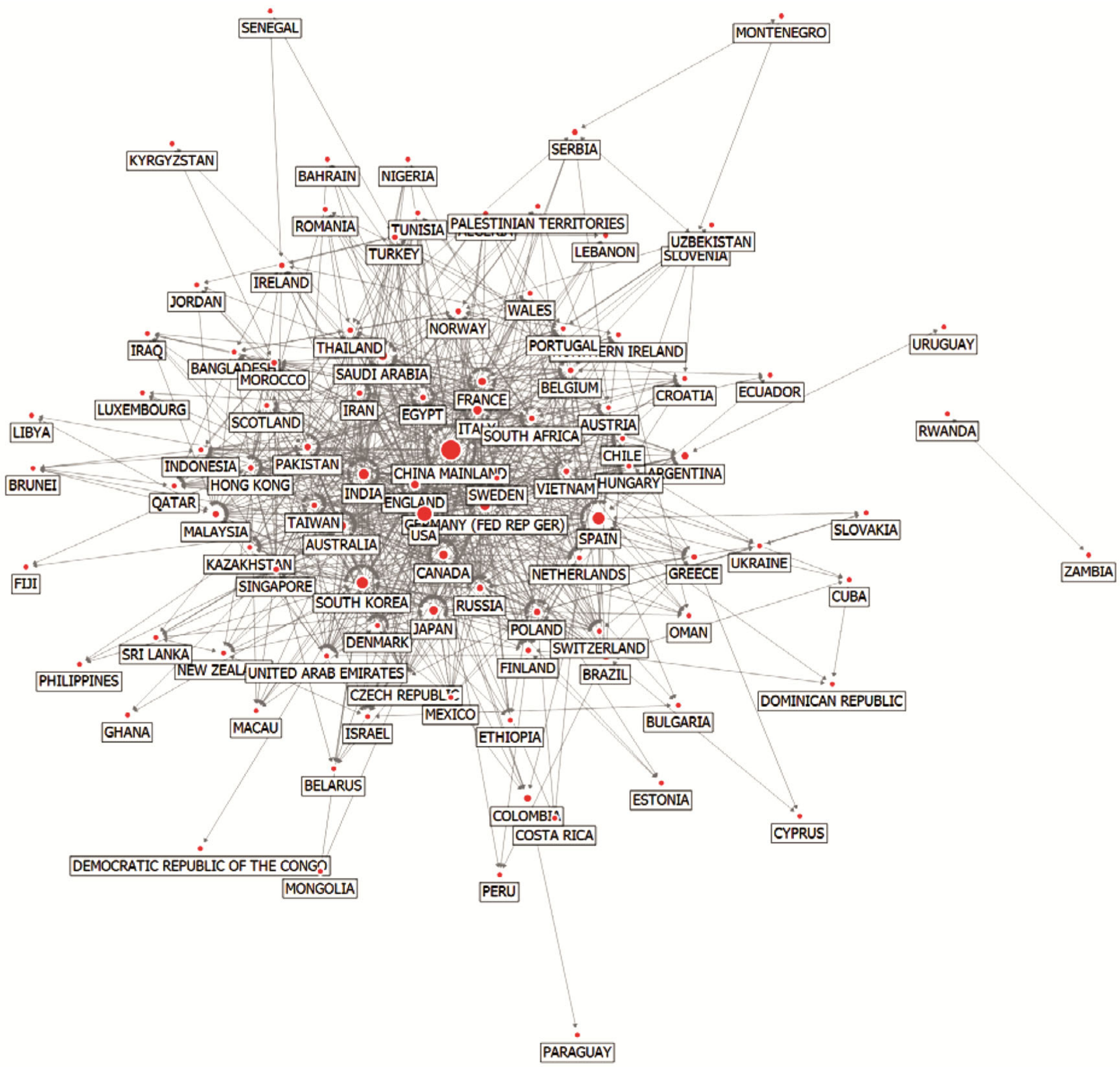

Fig. 6 — Network map based on betweenness centrality in 2021

Table 4 — Leading countries in eigenvector centrality

2012		2021	
USA	0.636	USA	0.552
CHINA MAINLAND	0.552	CHINA MAINLAND	0.549
SOUTH KOREA	0.210	GERMANY (FED REP GER)	0.256
GERMANY (FED REP GER)	0.209	ENGLAND	0.227
FRANCE	0.206	SOUTH KOREA	0.198
JAPAN	0.154	FRANCE	0.192
AUSTRALIA	0.148	INDIA	0.184
ITALY	0.141	CANADA	0.177
HONG KONG	0.129	AUSTRALIA	0.167
CANADA	0.122	SAUDI ARABIA	0.130

different research areas. Countries that have dropped in rankings, including the United States, do not represent a reduction in collaborations, but rather a decrease in influence in the ever-growing IRC network of secondary batteries. Given the dynamic changes in DC and BC over the past decade, this trend is expected to continue. Nevertheless, given that the United States still has the highest EIC, it is undeniable that it had a strong influence on secondary battery IRC networks until recently. Because EIC considers the influence of cooperating countries, we can see that the secondary battery IRC network is still a strongly Western network dominated by the United States. Evidence of this result can be seen by analyzing scientific metrics. A detailed analysis of the number of

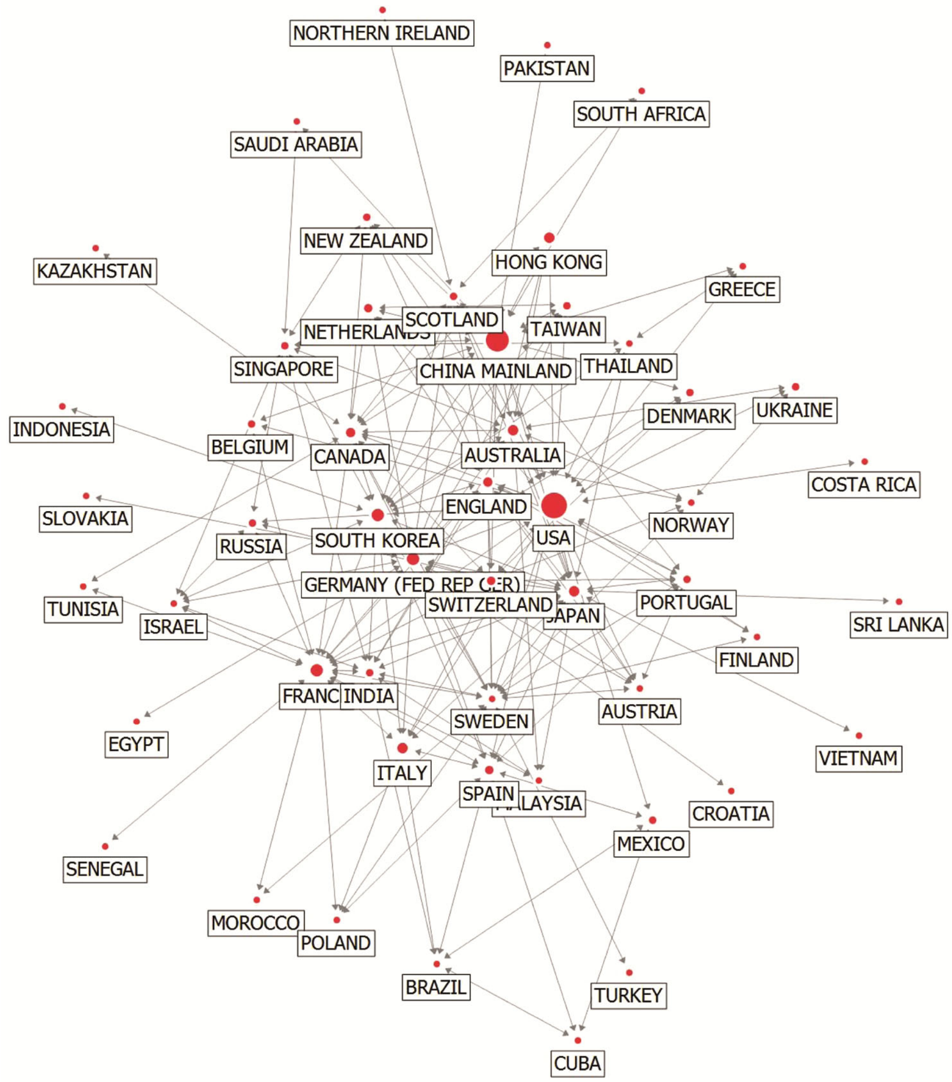

Fig. 7 — Network map based on eigenvector centrality in 2012

paper citations by institution reveals that the top rankings are Chinese institutions, but there are also a number of US institutions and universities. We believe that the EIC rankings were a result of this analysis. This trend may change if emerging countries that have recently shown strengths in secondary battery research prefer collaborating with China. Further analysis of scientific metrics, such as the study by Kumar *et al.*, could lead to even higher levels of insight.[37] However, because this study focuses on analyzing the structure of IRC networks across countries, such an analysis will be conducted in a follow-up study. Third, the secondary battery IRC network is path-dependent compared to existing networks. As the QAP analysis showed, the correlation coefficient between networks in all years was above 0.7. This indicates that the initially established cross-country research networks continue to affect the formation of subsequent years' networks. Notably, the correlation between networks has remained high despite closed technology protectionism over the past three years and the COVID-19 pandemic. However, this will require ongoing monitoring and follow-up studies after a sufficient time has passed since the pandemic.

Implication

The findings of this study offer vital insights and strategic guidance for S&T policy researchers and policymakers to foster international cooperation in light of the challenges posed by the COVID-19 pandemic and the heightened tensions during the neo-Cold War.

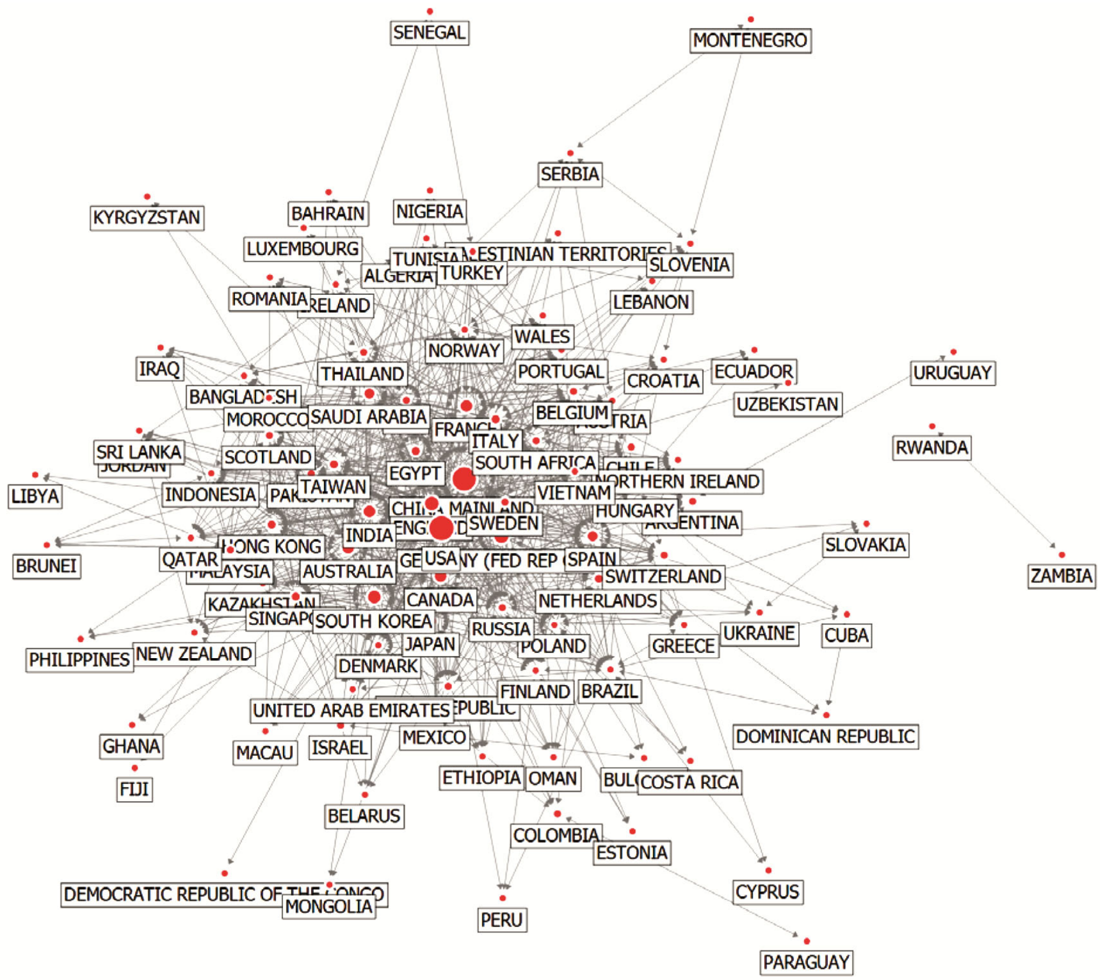

Fig. 8 — Network map based on eigenvector centrality in 2021

Table 5 — Pearson correlation coefficients by year from quadratic assignment procedure analysis

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
2012	—	—	—	—	—	—	—	—	—	—
2013	0.787**	—	—	—	—	—	—	—	—	—
2014	0.815**	0.772**	—	—	—	—	—	—	—	—
2015	0.861**	0.788**	0.837**	—	—	—	—	—	—	—
2016	0.835**	0.757**	0.837**	0.906**	—	—	—	—	—	—
2017	0.823**	0.751**	0.839**	0.901**	0.923**	—	—	—	—	—
2018	0.823**	0.739**	0.827**	0.907**	0.938**	0.931**	—	—	—	—
2019	0.806**	0.718**	0.803**	0.858**	0.887**	0.885**	0.897**	—	—	—
2020	0.818**	0.740**	0.844**	0.857**	0.860**	0.875**	0.881**	0.862**	—	—
2021	0.791**	0.735**	0.799**	0.848**	0.824**	0.843**	0.839**	0.831**	0.888**	—

● * p <0.05 indicates statistical significance, ** p <0.01 indicates highly statistical significance.

Countries aiming to enter the field of secondary battery research should consider strategic collaborations with influential nations within existing IRC networks such as China and the United States. Such collaborations can effectively compensate for their own research limitations.[18] To effectively select detailed areas of collaboration, both top-down and bottom-up approaches are required in national science and technology policies.[12] The top-down approach is centered on government plans, whereas the bottom-up approach is centered on researchers' interests. The results of this study are particularly important for the top-down approach of driving IRC around government plans. Research collaboration based on each country's innovation capacity and infrastructure must be promoted. The findings of this study can help determine the direction in which countries should move forward in the field of secondary batteries. Considering that several studies have already been conducted to analyze international cooperation patterns at the national level and to propose policies, this study can serve as a basis for establishing strategic directions for countries engaged in secondary battery research and conducting research on cooperation patterns within the secondary battery sector.

Conclusions

Secondary battery technology is a rapidly expanding field that has become one of the most prominent research topics recently. The results of this study show that the IRC in secondary batteries is on the rise, especially in China, despite the rapidly changing external environment, including the US–China trade conflict and the COVID-19 pandemic. This study analyzed the structural characteristics and changes in IRC networks in the field of secondary batteries using article data; however, it did not consider the network characteristics according to the material-specific characteristics of secondary batteries. It would be helpful for future policy researchers to conduct analyses of material-specific IRC networks to establish more effective S&T policies. Finally, given the recent growth of the secondary battery market in Asia and North America, future studies should consider the correlation between market growth and IRC networks.

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