Pol. J. Environ. Stud. Vol. XX, No. X (XXXX), 1-14
DOI: *10.15244/pjoes/203046* ONLINE PUBLICATION DATE:

Original Research

Evolution of the Innovation Network of Lithium-Ion Battery Recycling Technologies in China from the Perspective of Patents

Wei Xia[1], Shiyi Zheng[2], Liping Qiu[3], Hao Hu[4]*, Yufeng Chen[5], Shaobin Wei[6], Haiyan Zhou[7]**

[1]Institute of International Business & Economics Innovation and Governance, Shanghai University of International Business and Economics, Shanghai, China
[2]School of Global Governance, Shanghai University of International Business and Economics, Shanghai, China
[3]CEEC Economic and Trade Cooperation Institute, Ningbo University, Ningbo, China
[4]School of Economics, Shanghai University, Shanghai, China
[5]School of Economics and Management, Zhejiang Normal University, Jinhua, China
[6]Institute of Digital Economy and Financial Powerhouse Building, Guangdong University of Finance, Guangzhou, China
[7]Graduate School, Nueva Ecija University of Science and Technology, Cabanatuan, Philippines

Received: 23 October 2024
Accepted: 17 March 2025

Abstract

This study aims to characterize the evolution of the innovation network of lithium-ion battery recycling technologies in China in terms of network structure and influential factors, using social network analysis and GeoDetector based on patent data from 2004 to 2023. The following findings are established. First, the network exhibited a small-world effect, changed from a loose to a dense structure, and developed into a dual-core radial structure. Leading firms in lithium-ion battery recycling technologies have established relatively stable internal cooperation. The network experienced the embryonic stage, the initial exploration stage, and the developmental exploration stage, and is now in the intensive exploration stage. The network connections were dense in eastern China but sparse in western China. Second, in terms of industry–university–research cooperation, the main core was industry–industry cooperation, with industry–university and industry–research cooperation also occupying important positions. Universities and research institutes served as "transit stations" in technological innovation. Third and lastly, China's innovation network of lithium-ion battery recycling technologies was influenced by economic development, tertiary industry development, household consumption, government intervention, and higher education. This study clarifies the technological accumulation and

*e-mail: huhaohn@outlook.com
**e-mail: chenyufeng@gmail.com

evolution in the field of lithium battery recycling in China, providing insights into the construction and governance of an innovation development system for the lithium battery recycling industry.

Keywords: patent, lithium-ion battery, innovation network, spatial distribution

Introduction

The global shift toward renewable energy and electric vehicles has led to an unprecedented surge in demand for lithium-ion batteries. As the Ministry of Industry and Information Technology of the People's Republic of China reported, China produced over 940 GWh of lithium batteries in 2023, representing a year-on-year increase of 25% and a gross output of more than 1.4 trillion yuan[1]. This surge is indicative of the rapid proliferation of electric vehicles (EVs), energy storage systems, and other applications that rely on lithium batteries. However, this rapid growth in the industry is accompanied by challenges in managing discarded lithium-ion batteries, particularly in their recycling and disposal. The sustainability of the lithium-ion battery (LIB) industry, both domestically and internationally, largely depends on China's ability to recycle used batteries efficiently. The efficient recycling of lithium batteries not only creates revenue and reduces resource waste by recycling heavy metals, such as lithium and nickel, in batteries but also mitigates environmental pollution and safety hazards [1-4]. In this context, recycling spent lithium batteries has become a hot research topic and an important direction for industrial development [5, 6]. However, despite establishing advanced battery recycling frameworks in many developed countries in the EU [7], China's recycling infrastructure, technology, and regulatory framework are still catching up. Although China is a leader in battery production, it still faces challenges in the technology and industry of LIB recycling. This gap between production capacity and recycling capacity urgently necessitates research and innovative development in LIB recycling technology, especially in the context of China's dominant position in the global battery market.

Regional innovation systems have always been a key research direction in economic geography [8]. In the space of flows era, innovation activities are said to occur to a greater extent among different actors, and integration into innovation networks helps enhance regional innovation capabilities [9, 10]. Most studies on innovation networks investigated the structural characteristics of these networks, e.g., centrality, structural holes, and small-world effects [11]. These studies focused on how such networks functioned in representative industries, such as biomedicine and photovoltaics, at the global, national, regional, and city levels, using cooperative publications and patents as measurement metrics [12-14]. The dynamic mechanism of network formation has also been successfully investigated by analyzing the proximity, socioeconomic development factors, and policy factors using GeoDetector and quadratic assignment procedure (QAP) regression [15].

In terms of LIB recycling, previous studies have mainly explored recycling systems, evaluation and strategies, technologies, and industrial development [16-18]. However, few studies have examined LIB recycling from the perspective of patents, and innovation network research does not appear to be widely applied to LIB recycling. Moreover, most innovation network studies are based on cross-sectional data of a given year, whereas few have analyzed the structural characteristics of the innovation network of LIB recycling technologies in China from a continuous dynamic evolution perspective. In addition, although prior work has emphasized the role of firms in innovation networks, it has not deeply explored the functions of universities and research institutes [19].

This study utilizes China's LIB recycling patent collaboration data to analyze the spatial dynamics of LIB recycling technology cooperation, aiming to make several innovative theoretical contributions. Specifically, it pioneers the application of social network analysis to quantitatively identify the roles and positions of LIB recycling technology patent applicants and their respective provinces within the innovation network. This approach not only clarifies China's technological accumulation in lithium battery recycling but also overcomes the limitations of traditional single-perspective studies, providing robust scientific evidence for policymakers to design strategies that promote the industry's sustainable development. Moreover, by examining the collaboration pathways that drive LIB recycling technology innovation from an industry-university-research perspective, the study enriches and extends the existing body of knowledge on innovation networks while advancing the practical application of these theories in emerging technological domains. Finally, it delves into the determinants of weighted centrality in provincial-scale innovation networks for lithium battery recycling technologies, offering valuable insights to develop more targeted and effective policy recommendations.

The structure of the rest of this paper is as follows: The second section presents the data and methods used in the research, the third section displays the research results of the evolutionary analysis of the lithium battery recycling technology innovation network, the fourth

1 Available online: https://www.miit.gov.cn/gxsj/tjfx/dzxx/art/2024/art_7de3ac5f07514eec80039a81aa2e22d8.html (accessed on 5th April 2024).

section discusses the influencing factors of the lithium battery recycling technology innovation network in China, and the fifth section summarizes the research conclusions and provides implications.

Material and Methods

Research Data

The data used in this study were collected from the Incopat global patent database. Specifically, patents related to LIB recycling were retrieved. First, patents not related to LIB recycling were excluded. Next, patents with natural person applicants, foreign firm applicants, and single applicants were excluded. This resulted in a total of 1,679 eligible patents covering the 20 years from 2004 to 2023. The first applicants (leaders) and non-first applicants (participants) were differentiated in the measurement of patent cooperation, forming a directional data matrix of innovation cooperation between patent applicants. In terms of cooperation level, although the order of applicants is not related to legal priority, it reflects their contributions to the patent and workload during the invention process to some extent. Therefore, values were assigned according to the order of applicants. Specifically, the cooperation level between the first and second applicants was assigned the highest value of 4, and so forth. For example, suppose a patent has five applicants: A, B, C, D, and E. In that case, it is considered that there is one cooperation between A and B, one between A and C, one between A and D, and one between A and E, which take a value of 4, 3, 2, and 1, respectively, for cooperation level.

The data on the factors influencing the innovation network of LIB recycling technologies in China were obtained from the China Statistical Yearbooks. The indices of the detection factors are based on data from 2023, the final year of the intensive exploration stage defined below.

Methods

Social Network Analysis

The innovation network of LIB recycling technologies in China was characterized using social networks [20-23], specifically by analyzing

- Network size: the number of total nodes in the network,
- Small-world effect: referring to the Six Degrees of Separation theory, a pair of individuals who do not know each other can be connected by a few acquaintances as small-worldness, which can be reflected by the aggregation coefficient and the average shortest path, and
- Connection strength: the extent to which network nodes are interconnected.

GeoDetector

The GeoDetector is a set of statistical methods used to detect spatial differentiation and reveal the underlying driving forces. It can quantitatively identify the contribution of different driving factors to the explained variable. Specifically, the weighted centrality of the provincial innovation network of LIB recycling technologies in China and detection factors, including economic development, openness, tertiary industry development, household consumption, higher education, and government intervention, were analyzed using GeoDetector software, which is designed to identify and analyze spatial characteristics and relationships [24, 25]. The detection factor indices were stratified into five levels by natural breaks using ArcGIS software before employing the GeoDetector.

Results

Evolution Stages

As shown in Fig. 1, the number of Chinese patents for LIB recycling technology increased from 1 in 2004 to 343 in 2023, and the number of patent applicants also increased from 0 in 2004 to 339 in 2023. To avoid abrupt changes in research results due to unusual circumstances in a specific year, the evolution of the innovation network of LIB recycling technologies is divided into four stages based on changes in characteristics: embryonic stage (2004–2008), initial exploration stage (2009–2013), developmental exploration stage (2014–2018), and intensive exploration stage (2019–2023).

In addition, as reported in Table 1, from the embryonic stage to the intensive exploration stage, the network scale continuously expands in terms of network nodes, edges, and diameter, except for network density. We found that both the average degree and average weighted degree increased. The average clustering coefficient was small, and the average path length was large. These features suggest that the nodes in the innovation network of LIB recycling technologies in China required a few transition points to be connected. Close nodes found aggregation easier, with higher connection efficiency, and there were many hub nodes in the network, representing a significant small-world effect. The network expansion rate was slower than the speed of cooperation between applicants. Although the network cohesion decreased, the number and efficiency of cooperation between applicants increased, and network connectivity improved.

Topological Features

Fig. 2 depicts the innovation network topology of LIB recycling technologies in China from 2004 to 2023. It can be seen that the network had a very loose structure in the embryonic stage. At this stage, all cooperative

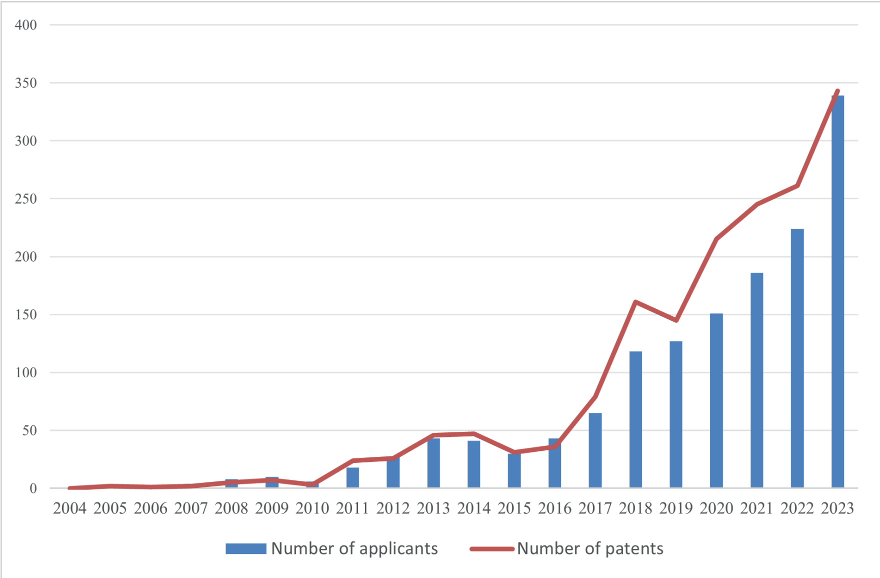


Fig. 1. Number of patents and applicants for LIB recycling technologies in China in 2004–2023.

actions had a level less than five except that between Tianjin University and Tianjin Recyclable Resources Institute, China CO-OP (12) and that between Ludong University and Shandong Zhengyu Technology Co., Ltd. (eight).

In the initial exploration stage, the network connections started to become closer. Specifically, the cooperation levels between the following pairs all ranked in the top five, with a score higher than 20:

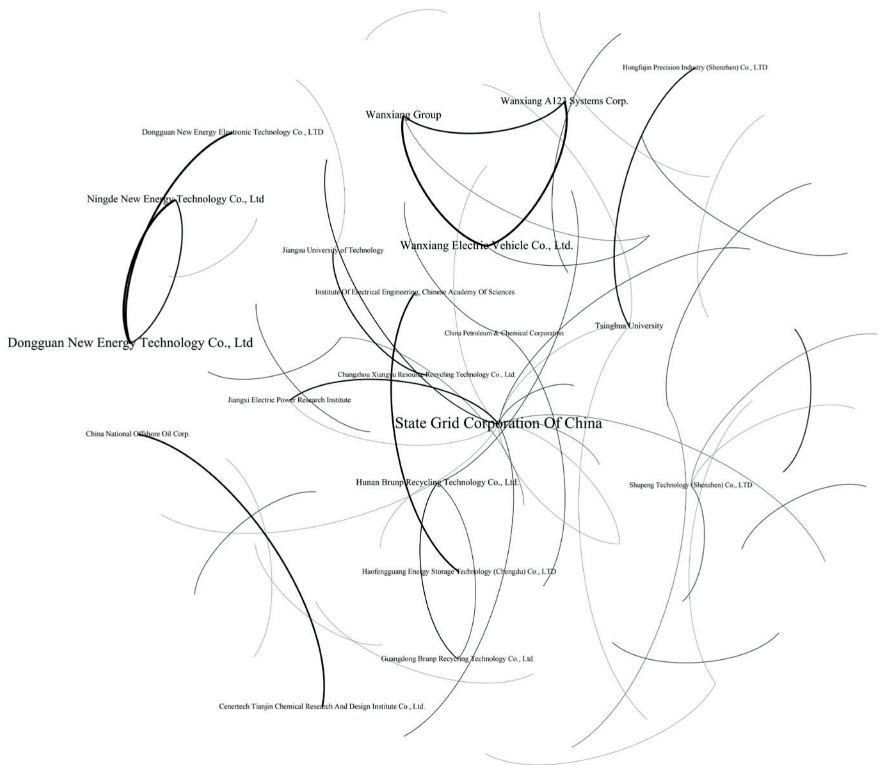
- DongGuan Amperex Technology Limited and Ningde Amperex Technology Ltd.
- DongGuan Amperex Technology Ltd. and Dongguan Amperex Electronics Technology Ltd.
- Wanxiang Electric Vehicle Co., Ltd. and Wanxiang Group Corporation.
- Wanxiang 123 LLC and Wanxiang Electric Vehicle Co., Ltd.
- Haofengguang Energy Storage Technology (Chengdu) Co., Ltd. and Institute of Electrical Engineering, Chinese Academy of Sciences.
- China National Offshore Oil Corporation and CenerTech Tianjin Chemical Research and Design Institute Co., Ltd.

In the developmental exploration stage, the network size increased, forming a multi-core radial structure with State Grid Corporation of China, Guangdong Brunp Recycling Technology Co., Ltd., Hunan Brunp Recycling Technology Co., Ltd., and Guangdong Jiana Energy Technology Co., Ltd. as nodes. Nineteen pairs of nodes had a cooperation level above 20. In particular, the cooperation levels between Jingmen GEM New Materials Co., Ltd. and GEM Co., Ltd., between Hunan Brunp Recycling Technology Co., Ltd. and Guangdong Brunp Recycling Technology Co., Ltd., and between Wanxiang 123 LLC. and Wanxiang Group Corporation were 64, 60, and 52, respectively. As these scores show,

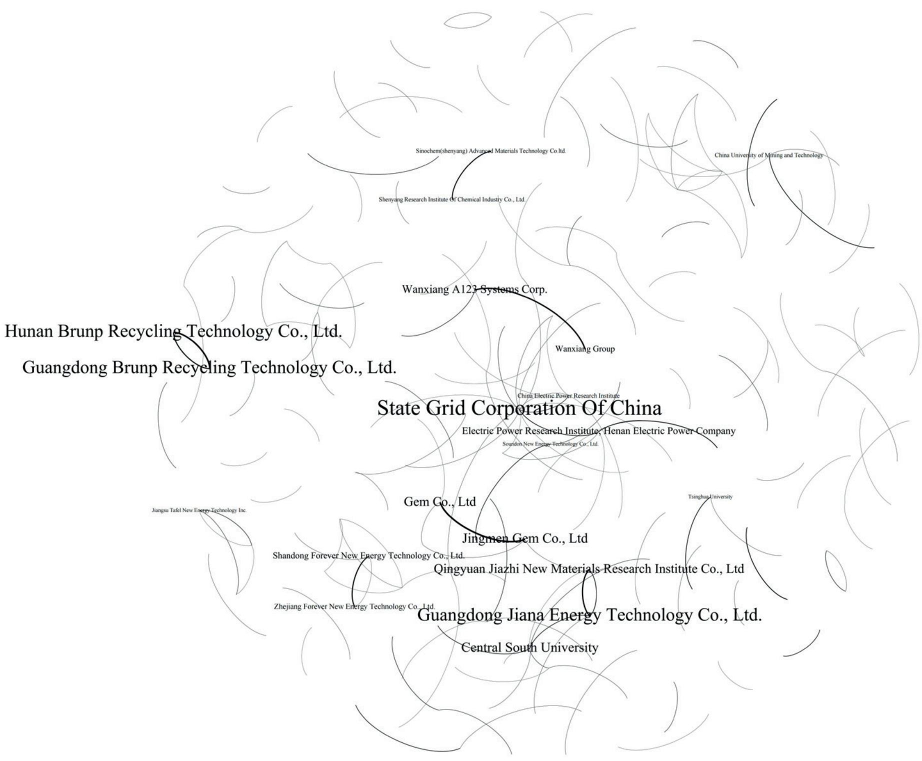
Table 1. Structural indices of the LIB recycling technology innovation network in China in 2004–2023.

Network attributes		Embryonic stage	Initial exploration stage	Developmental exploration stage	Intensive exploration stage
Network size	Number of nodes	13	77	228	752
	Number of edges	7	57	163	573
	Network diameter	1	3	3	5
	Network density	0.045	0.010	0.003	0.001
Small-world effect	Average clustering coefficient	0.000	0.022	0.046	0.037
	Average path length	1.000	1.353	1.357	1.473
Connection strength	Average degree	0.538	0.740	0.715	0.762
	Average weighted degree	3.077	6.584	7.000	7.661

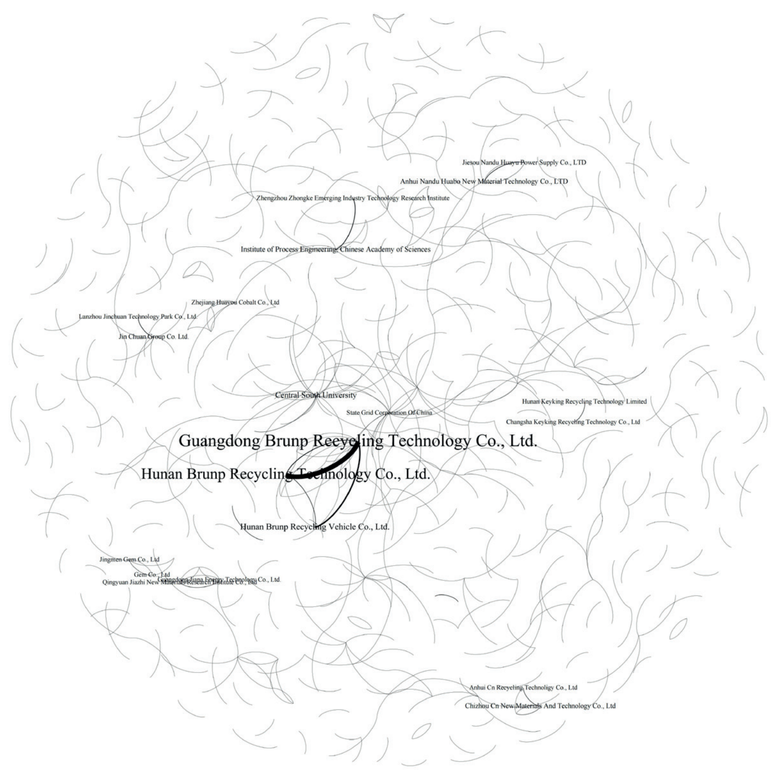
a) Embryonic stage



b) Initial exploration stage



c) Developmental exploration stage



d) Intensive exploration stage

Fig. 2. Innovation network topology of LIB recycling technologies in China 2004–2023. a) Embryonic stage; b) Initial exploration stage; c) Developmental exploration stage; d) Intensive exploration stage.
Note: Only the top 20 network nodes in terms of weighted centrality are displayed.

Table 2. Industry–university–research cooperations in the innovation network of LIB recycling technologies in China 2004 to 2023.

Stage	Index	Industry–industry	Industry–university	Industry–research	University–university	University–research	Research–research
Embryonic stage	Cooperation level	8	8	12	0	12	0
	Proportion	20.00%	20.00%	30.00%	0.00%	30.00%	0.00%
Initial exploration stage	Cooperation level	275	91	133	0	8	0
	Proportion	54.24%	17.95%	26.23%	0.00%	1.58%	0.00%
Developmental exploration stage	Cooperation level	841	253	318	12	136	36
	Proportion	52.69%	15.85%	19.92%	0.75%	8.52%	2.26%
Intensive exploration stage	Cooperation level	3526	903	609	70	395	258
	Proportion	61.20%	15.67%	10.57%	1.22%	6.86%	4.48%

in this stage, the innovation network topology of LIB recycling technologies has begun to take shape, and cooperation between nodes is at the developmental level.

In the intensive exploration stage, the network evolved from a multi-core radial structure to a dual-core radial structure with Guangdong Brunp Recycling Technology Co., Ltd. and Hunan Brunp Recycling Technology Co., Ltd. as the cores. The number of node pairs with a cooperation level higher than 20 reached 41 pairs. The highest cooperation level, 820, was between Guangdong Brunp Recycling Technology Co., Ltd. and Hunan Brunp Recycling Technology Co., Ltd. As the higher scores in this stage show, network cooperation is more frequent in this phase, with major partnerships centered around core nodes, and innovation networks are more tightly knit, with only a few isolated links. It can also be seen that most high cooperation levels were between firms with parent–subsidiary or investment relationships, which represent kinship-based cooperation. This indicates that the leading LIB recycling technology firms have developed relatively stable internal cooperation.

Industry–University–Research Cooperation

Patent applicants are divided into three categories according to their nature: industry, university, and research. In this way, six modalities of cooperation are defined (Table 2). It can be seen that in the embryonic stage, four modalities of industry-university-research collaboration can be observed. Among these, industry–research and university–research account for the highest proportion, becoming the main cooperation modality in this stage. As research deepens and enters the intensive exploration stages, the proportion of the industry–industry cooperation continues to rise, gradually becoming the dominant collaboration mode. In other collaboration modalities, the proportion of the main cooperation modalities from the initial embryonic stage gradually declines each year; although other cooperation modalities have increased, their proportions remain below 10%. In general, an industry–university–research cooperation modality based on "industry" or firms was established in the innovation network of LIB recycling technologies in China. Industry–industry cooperation acted as the main core of this modality, with the cooperation of industry–university and industry–research occupying an important position.

Characteristics of Key Network Nodes

The top 10 nodes in China's innovation network of LIB recycling technologies in terms of weighted centrality and betweenness were determined using Gephi software (Table 3). It can be seen that the weighted centrality of patent applicants continued to increase, along with the cooperation level between them. However, the differences in weighted centrality increased too. Private firms constituted an increasing proportion, becoming the core actors playing a major role in the LIB recycling technology innovation network. This change indicates the leading role of private firms in this field. Nonetheless, universities and research institutes constituted an increasing proportion of the top 10 applicants in terms of betweenness. Moreover, they exhibited increasing betweenness over time and became an important hub in the network, which indicates their role as "transit stations" in technological innovation.

Network Spatial Evolution

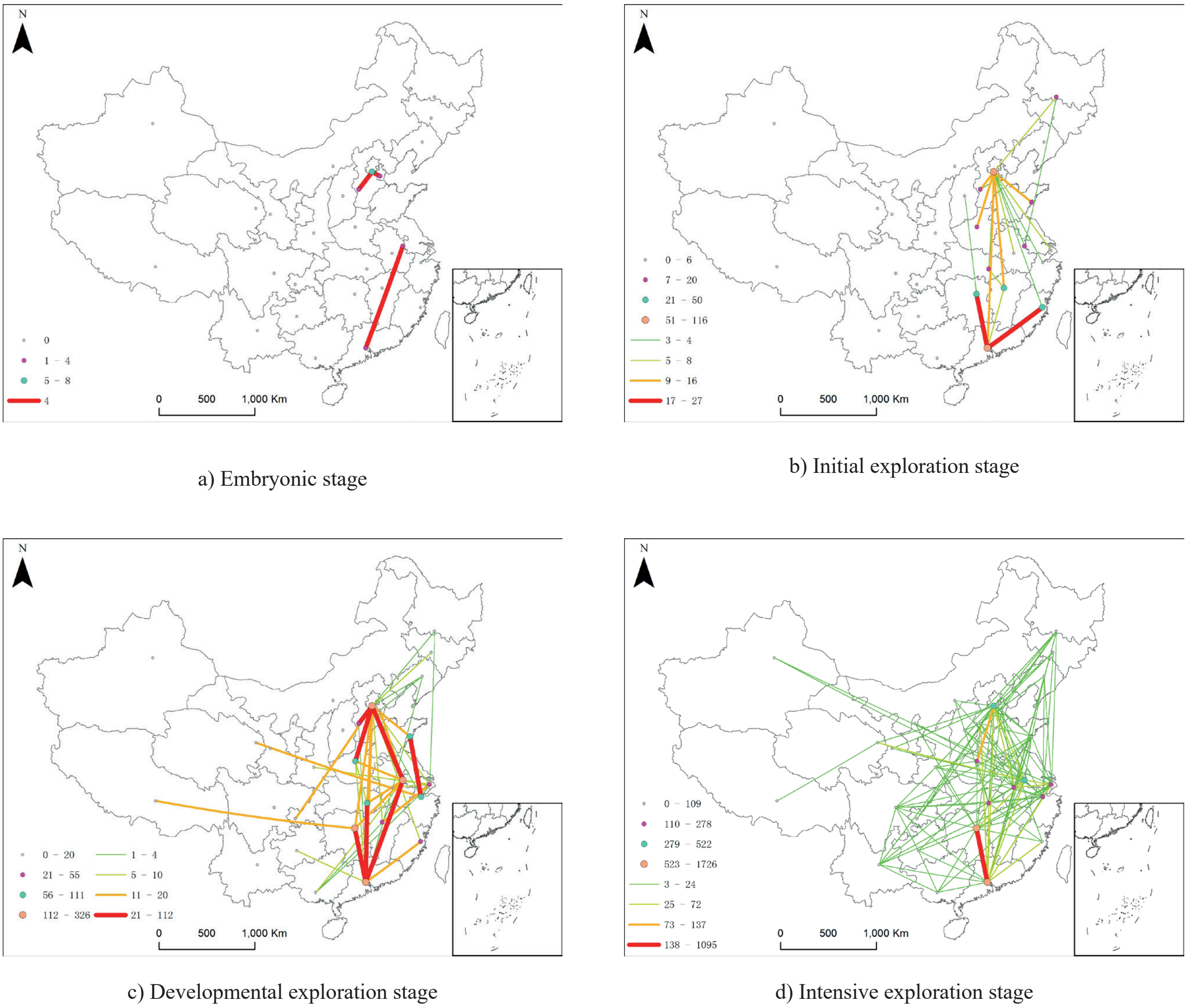
The connections in China's LIB recycling technology innovation network were graded into four levels in each stage according to natural breaks. This was done following the concept of the natural breakpoint method, which is a flexible analysis method that can split large data sets into different subsets, making the analysis more effective. The first stage contained only one level because the connections only had a cooperation level of four. As illustrated in Fig. 3, the innovation network of LIB recycling technologies was not evenly distributed in China. The major participating provinces and innovation connections were mainly located in eastern and central China. Hainan Province had not yet

Table 3. Characteristics of the top 10 key nodes in China's LIB recycling technology innovation network 2004–2023.

Stage	Applicant	Weighted centrality	Applicant	Betweenness
Embryonic stage	Tianjin University	12	Tianjin University	0
	Tianjin Recyclable Resources Institute, China CO-OP	12	Tianjin Recyclable Resources Institute, China CO-OP	0
	Ludong University	8	Ludong University	0
	Shandong Zhengyu Technology Co., Ltd.	8	Shandong Zhengyu Technology Co., Ltd.	0
	China National Offshore Oil Corporation	8	China National Offshore Oil Corporation	0
	Jiangsu Highstar Battery Manufacturing Co., Ltd.	4	Jiangsu Highstar Battery Manufacturing Co., Ltd.	0
	Jiangsu New Power Battery and Its Material Engineering Technology Research Center Co. Ltd.	4	Jiangsu New Power Battery and Its Material Engineering Technology Research Center Co. Ltd.	0
	Nanjing Haitai Nanomaterials Co., Ltd.	4	Nanjing Haitai Nanomaterials Co., Ltd.	0
	Guangzhou Fullriver Battery New Technology Co., Ltd.	4	Guangzhou Fullriver Battery New Technology Co., Ltd.	0
	Tianjin Huayi Co., Ltd.	4	Tianjin Huayi Co., Ltd.	0
Initial exploration stage	State Grid Corporation of China	86	State Grid Corporation of China	22
	DongGuan Amperex Technology Limited	67	Tsinghua University	5
	Wanxiang Electric Vehicle Co., Ltd.	56	Hunan Brunp Recycling Technology Co., Ltd.	2
	Wanxiang Group Corporation	48	DongGuan Amperex Technology Limited	1
	Ningde Amperex Technology Limited	43	Ningde Amperex Technology Limited	0
	Wanxiang 123 LLC	42	Wanxiang 123 LLC.	0
	Hunan Brunp Recycling Technology Co., Ltd.	32	Hunan Brunp Recycling Technology Co., Ltd.	0
	Tsinghua University	28	Tsinghua University	0
	Dongguan Amperex Electronics Technology Limited	24	Dongguan Amperex Electronics Technology Limited	0
	Jiangsu University of Technology	20	Jiangsu University of Technology	0

→

Developmental exploration stage	State Grid Corporation of China	113	State Grid Corporation of China	49
	Guangdong Brunp Recycling Technology Co., Ltd.	100	China Electric Power Research Institute Co., Ltd.	12
	Hunan Brunp Recycling Technology Co., Ltd.	100	Central South University	10
	Guangdong Jiana Energy Technology Co., Ltd.	100	Jingmen GEM New Materials Co., Ltd.	2
	Central South University	80	China University of Mining and Technology	2
	Jingmen GEM New Materials Co., Ltd.	80	Institute of Process Engineering, Chinese Academy of Sciences	2
	GEM Co., Ltd.	76	Shanghai Jiao Tong University	2
	Qingyuan Jiazhi New Materials Research Institute Co., Ltd.	76	Guangdong Jiana Energy Technology Co., Ltd.	1
	Wanxiang 123 LLC	68	Shandong Forever New Energy Co., Ltd.	1
	State Grid, Henan Electric Power Company, Electric Power Research Institute	62	Dongguan Maike Technology Co., Ltd., Ningde Amperex Technology Limited, Beijing Institute of Technology, and Jiangsu Highstar Battery Manufacturing Co., Ltd.	
Intensive exploration stage	Guangdong Brunp Recycling Technology Co., Ltd.	1247	Central South University	120
	Hunan Brunp Recycling Technology Co., Ltd.	1038	Guangdong Brunp Recycling Technology Co., Ltd.	25
	Hunan Brunp Automobile Recycling Co., Ltd.	314	China Electric Power Research Institute Co., Ltd.	22.5
	Central South University	246	Institute of Process Engineering, Chinese Academy of Sciences	19
	Institute of Process Engineering, Chinese Academy of Sciences	163	Hefei University of Technology	19
	Anhui Narada Huabo New Material Technology Co., Ltd.	152	State Grid, Henan Electric Power Company, Electric Power Research Institute	19
	Chizhou CN New Material Technology Co., Ltd.	116	Harbin Institute of Technology	16
	Jieshou Narada Huayu Power Source Co., Ltd.	112	Kunming University of Science and Technology	14
	Jinchuan Group Co., Ltd.	104	Nanchang Hangkong University	13
	Zhengzhou Zhongke Emerging Industry Technology Research Institute	104	Jinchuan Group Co., Ltd. and Zhejiang Huayou Cobalt Co., Ltd.	12



a) Embryonic stage

b) Initial exploration stage

c) Developmental exploration stage

d) Intensive exploration stage

Fig. 3. Spatial evolution of the innovation network of LIB recycling technologies in China from 2004 to 2023.

participated in the network in the intensive exploration stage, whereas Guangdong and Hunan Provinces were the leaders of LIB recycling technology in China and played a crucial role in the innovation network. Beijing, Jiangsu, Shanghai, Hubei, Anhui, Henan, and Zhejiang comprised the sub-core nodes in the network. Meanwhile, western provinces, e.g., Jilin, Tibet, and Xinjiang, were located at the edge of the network.

In the embryonic stage, only five provinces, i.e., Beijing, Guangdong, Jiangsu, Hebei, and Tianjin, participated in the network, and there were few inter-provincial instances of cooperation, namely, Beijing–Hebei, Beijing–Tianjin, and Jiangsu–Guangdong, all with a connection level of four. By the emergence of the initial exploration stage, 16 provinces, including Beijing, Guangdong, Fujian, and Hunan, were participating in the innovation network. The connection strength between Guangdong and Fujian and Guangdong and Hunan increased from zero to 27 and 24, respectively, representing the strongest connections in this stage. Inter-provincial connections with a strength below 10 accounted for approximately 60%.

In the developmental exploration stage, seven new provinces, including Tibet, Guangxi, Qinghai, and Chongqing, participated in the innovation network, and the cooperation level between provinces was significantly enhanced. The strongest connection (112) was observed between Hunan and Guangdong. In the intensive exploration stage, all provinces except Hainan participated in the innovation network, and closer network connections were observed. However, only one first-level connection existed, which was between Guangdong and Hunan (1095). However, the strength of all other network connections increased significantly. In addition, the network connections between provinces began to take shape. Overall, the key connections forged were between Guangdong and Hunan, Henan and Beijing, Hubei and Guangdong,

Table 4. Regression results using GeoDetector.

Influential factor	Detection factor	Index	Q value	Significance
Economic foundation	Economic development	Current-price GDP or gross value added (in 10,000 yuan)	0.6739	0.0000
	Openness	Total imports and exports of foreign-invested enterprises (in 10,000 yuan)	0.4216	0.1645
	Tertiary industry development	Added value of tertiary industry (in 100 million yuan)	0.6275	0.0090
	Household consumption	Per capita disposable income (in yuan)	0.4688	0.0922
Social foundation	Higher education	Number of students in higher education	0.3957	0.0725
	Government intervention	Fiscal expenditure on science and technology as a percentage of GDP	0.4299	0.0658

Henan and Beijing, and Guangdong and Fujian, thereby forming a radial innovation network with Guangdong as the core. Moreover, from a spatial perspective, network connections were dense in the east and sparse in the west.

Discussion

In this section, we broaden the analysis by examining the factors that shape the dynamics of the innovation network for LIB recycling technologies in China. This shift is crucial, as understanding the underlying drivers and barriers to collaboration within the network can provide valuable insights into its evolution and the key factors contributing to its success. Specifically, our goal is to identify and explain how various factors—such as economic development, openness, education, and others—affect the evolution of the network structure.

Selection of Influential Factors

Many factors have contributed to the innovation network of LIB recycling technologies in China. Based on previous studies [26, 27], the weighted centrality of the inter-provincial network in the intensive exploration stage is specified as the dependent variable; the independent variables are (1) current-price gross domestic product (GDP) or gross value added to measure the economic development, (2) total imports and exports of foreign-invested enterprises (in 10,000 yuan) to measure openness, (3) added value of the tertiary industry (in 100 million yuan) to measure tertiary industry development, (4) per capita disposable income (in yuan) to measure household consumption, (5) number of students in higher education to measure the level of higher education, and (6) fiscal expenditure on science and technology as a percentage of GDP to measure government intervention. The correlation coefficients were analyzed using GeoDetector.

Empirical Analysis

As presented in Table 4, all factors except openness and higher education significantly influence the network's weighted centrality. In other words, the innovation network of LIB recycling technologies in China is influenced by economic development, tertiary industry development, household consumption, government intervention, and higher education. All influential factors had an explanatory power of between 12% and 68% and are accordingly classified into major and minor influential factors. The major influential factors are economic development and tertiary industry development, whereas the minor influential factors include household consumption, government intervention, and higher education. Openness is not a significant influential factor.

Economic development and tertiary industry development are decisive factors in developing China's LIB recycling technology innovation network, with Q values of 0.6739 and 0.6275, respectively. This is principally because economic development is a critical foundation for technological innovation. Specifically, a higher level of economic development means more applications and demand for lithium batteries and, consequently, greater demand for LIB recycling and stronger technological innovation capacity, thereby facilitating technology innovation for LIB recycling. Technological innovation is closely related to tertiary industry development. Industrial restructuring boosts the efficient resource allocation for industrial development and technological innovation [28].

Household consumption, government intervention, and higher education moderately affect the development of China's LIB recycling technology innovation network. Specifically, higher household consumption and greater government intervention underpinned a greater vitality for regional technology innovation in LIB recycling. This is mainly because the regions with higher consumption levels have a higher demand for LIB-powered products, such as new energy vehicles and mobile phones, and thus a larger market for LIB recycling. In addition, because LIB recycling technology remains relatively immature in the intensive exploration stage, technological breakthroughs depend on the local government's investment in research and education [29].

In contrast, openness has no significant influence. This is mainly because all provinces have actively participated in the opening-up due to economic globalization. As a consequence, the specific influence of openness on the innovation network of LIB recycling technologies is reduced.

Conclusions

This study investigated the spatiotemporal evolution of China's LIB recycling technology innovation network in terms of network structure and influential factors using social network analysis and GeoDetector based on patent data from 2004 to 2023. Based on this analysis conducted and the results obtained, the following conclusions are drawn:

1. The evolution of China's LIB recycling technology innovation network is divided into four stages: embryonic stage, initial exploration stage, developmental exploration stage, and intensive exploration stage. The network exhibited a small-world effect and improved connectivity, changed from a loose to a dense structure, and eventually developed a dual-core radial structure. The leading firms in LIB recycling technology have established relatively stable internal cooperation, namely, kinship-based cooperation.
2. In the studied LIB recycling technology innovation network, an industry–university–research cooperation modality based on "industry" or firms was established. Industry–industry cooperation was the main core of this modality, with industry–university and industry–research cooperation also occupying important positions. Private firms played a leading role in LIB recycling technology, with universities and research institutes serving as "transit stations" in technological innovation.
3. The innovation network of LIB recycling technologies was not evenly distributed in China. The major participating provinces and innovation connections were mainly located in eastern and central China. Specifically, Guangdong and Hunan Provinces were the leaders of LIB recycling technology in China. Network connections were dense in eastern China but sparse in western China.
4. Economic development and tertiary industry development are decisive factors in developing China's LIB recycling technology innovation network, and household consumption, government intervention, and higher education exert a moderate influence.

Implications and Recommendations

First, China's new energy vehicle industry is at the peak stage of development, and lithium batteries are a crucial power source for new energy vehicles. Given this increased demand, the development of LIB recycling technology is important for environmental protection, resource recycling, and the industry's sustainability. Therefore, national and provincial efforts should be dedicated to increasing investment and cooperation in technology innovation and talent training for LIB recycling and building bridges of cooperation, thereby promoting the development of related industries.

Second, kinship-based cooperation is currently the main innovation cooperation for LIB recycling technology in China. In light of this, national and provincial efforts should aim to detect possible cooperation relationships in related fields and enhance the breadth and depth of cooperation between patent applicants by developing necessary incentives and policies, thereby tapping the potential for cooperation.

Third, efforts should be made to build the industry–university–research cooperation system for LIB recycling technology. It is important to promote extensive and targeted cooperation between universities and research institutes, with firms using the former as bridges while further enhancing the leadership role of leading firms, such as Guangdong Brunp Recycling Technology Co., Ltd. This is expected to create a conducive atmosphere and improve the innovation network ecosystem, thereby boosting the innovation of LIB recycling technology.

Theoretical Contributions

First, this study pioneers using social network analysis to identify the location and position of patent applicants and their provinces in the network of LIB recycling technology to provide quantitative measurements. In this way, it goes beyond the limit of conventional factor network studies that adopt a single-element perspective. It also helps provide objective guidance for government agencies in formulating development policies or plans to boost the industry's growth and contribute to sustainable development [17, 30, 31].

Second, this study investigates the perspective of industry–university–research cooperation, which helps to guide more efficient industry–university–research cooperation for LIB recycling technology in China, extends and advances research on innovation networks, and promotes the application of theoretical research to this emerging field of technology [19].

Third, the order of applicants is an important indicator of the cooperation levels between applicants for a specific patent. However, previous studies on patent cooperation have largely overlooked this aspect. In this study, the cooperation level between applicants is assigned a value according to their order. By doing so, the functions of nodes can be defined more accurately, and more targeted recommendations can thus be made.

Limitations and Directions for Further Research

First, this study only covers LIB recycling technology patents in China. Further work is required to investigate the accumulation of technology and cooperation across countries in the context of globalization.

Second, this study only uses patent data, which may limit the generalizability of the findings. Subsequent research can address this limitation using data from cooperative papers and research activities.

Third, this study investigates the factors influencing the innovation network of LIB recycling technologies in China from the perspective of "attribute data." However, it is also very important to apply the "relational perspective" [32]. In addition, the development of LIB recycling technology is also closely related to and driven by local policy support and the development of related industries; thus, the steps that governments can take in terms of specific policies and measures to support the growth of related industries are other areas to explore to build upon the findings of this research.

Acknowledgments

This work was supported by the National Social Science Fund Project of China (Grant number 22BFX191).

Conflict of Interest

The authors declare no conflict of interest.

References

1. QIU L., XIA W., WEI S., HU H., YANG L., CHEN Y., ZHOU H., HU F. Collaborative management of environmental pollution and carbon emissions drives local green growth: An analysis based on spatial effects. Environmental Research, **259**, 119546, **2024**.
2. HUA Y., LIU X., ZHOU S., HUANG Y., LING H., YANG S. Toward Sustainable Reuse of Retired Lithium-ion Batteries from Electric Vehicles. Resources, Conservation and Recycling, **168**, 105249, **2021**.
3. YU W., GUO Y., XU S., YANG Y., ZHAO Y., ZHANG J. Comprehensive recycling of lithium-ion batteries: Fundamentals, pretreatment, and perspectives. Energy Storage Materials, **54**, 172, **2023**.
4. TIAN H., GRACZYK-ZAJAC M., KESSLER A., WEIDENKAFF A., RIEDEL R. Recycling and Reusing of Graphite from Retired Lithium-ion Batteries: A Review. Advanced Materials, **36** (13), **2023**.
5. LAI X., HUANG Y., GU H., DENG C., HAN X., FENG X., ZHENG Y. Turning waste into wealth: A systematic review on echelon utilization and material recycling of retired lithium-ion batteries. Energy Storage Materials, **40**, 96, **2021**.
6. ZHAO T., LI W., TRAVERSY M., CHOI Y., GHAHREMAN A., ZHAO Z., ZHANG C., ZHAO W., SONG Y. A review on the recycling of spent lithium iron phosphate batteries. Journal of Environmental Management, **351**, 119670, **2024**.
7. GINSTER R., BLÖMEKE S., POPIEN J.L., SCHELLER C., CERDAS F., HERRMANN C., SPENGLER T.S. Circular battery production in the EU: Insights from integrating life cycle assessment into system dynamics modeling on recycled content and environmental impacts. Journal of Industrial Ecology, **28** (5), 1165, **2024**.
8. COOKE P., HEIDENREICH M., BRACZYK H.-J. Introduction: Regional innovation systems–an evolutionary approach. Routledge, **2024**.
9. MIN S., KIM J., SAWNG Y.-W. The effect of innovation network size and public R&D investment on regional innovation efficiency. Technological Forecasting and Social Change, **155**, 119998, **2020**.
10. HU F., QIU L., WEI S., ZHOU H., BATHUURE I.A., HU H. The spatiotemporal evolution of global innovation networks and the changing position of China: a social network analysis based on cooperative patents. R&D Management, **54** (3), 574, **2024**.
11. ZHAO S., LI J. Impact of innovation network on regional innovation performance: do network density, network openness and network strength have any influence? Journal of Science and Technology Policy Management, **14** (5), 982, **2023**.
12. MULLER E., PERES R. The effect of social networks structure on innovation performance: A review and directions for research. International Journal of Research in Marketing, **36** (1), 3, **2019**.
13. GUI Q., LIU C., DU D. Globalization of science and international scientific collaboration: A network perspective. Geoforum, **105**, 1, **2019**.
14. HU F., MA Q., HU H., ZHOU K.H., WEI S. A study of the spatial network structure of ethnic regions in Northwest China based on multiple factor flows in the context of COVID-19: Evidence from Ningxia. Heliyon, **10** (2), e24653, **2024**.
15. DONG S., REN G., XUE Y., LIU K. Urban green innovation's spatial association networks in China and their mechanisms. Sustainable Cities and Society, **93**, 104536, **2023**.
16. CUSENZA M.A., BOBBA S., ARDENTE F., CELLURA M., DI PERSIO F. Energy and environmental assessment of a traction lithium-ion battery pack for plug-in hybrid electric vehicles. Journal of Cleaner Production, **215**, 634, **2019**.
17. FAN E., LI L., WANG Z., LIN J., HUANG Y., YAO Y., CHEN R., WU F. Sustainable Recycling Technology for Li-Ion Batteries and Beyond: Challenges and Future Prospects. Chemical Reviews, **120** (14), 7020, **2020**.
18. YANG Y., OKONKWO E.G., HUANG G., XU S., SUN W., HE Y. On the sustainability of lithium ion battery industry – A review and perspective. Energy Storage Materials, **36**, 186, **2021**.
19. JOHNSTON A., WELLS P., WOODHOUSE D. Examining the roles of universities in place-based industrial strategy: which characteristics drive knowledge creation in priority technologies? Regional Studies, **57** (6), 1084, **2021**.
20. SHAKER R.A., ELBELTAGI E., MOTAWA I., ELMASOUDI I., ELNABWY M.T. Social network analysis for identifying the significant drivers of off-site construction adoption in Egypt. Built Environment Project and Asset Management, **14** (4), 607, **2024**.

21. HUNG M., LAUREN E., HON E.S., BIRMINGHAM W.C., XU J., SU S., HON S.D., PARK J., DANG P., LIPSKY M.S. Social Network Analysis of COVID-19 Sentiments: Application of Artificial Intelligence. Journal of Medical Internet Research, **22** (8), e22590, **2020**.
22. LIAO H., LI X., TANG M. How to process local and global consensus? A large-scale group decision making model based on social network analysis with probabilistic linguistic information. Information Sciences, **579**, 368, **2021**.
23. KNOKE D., YANG S. Social Network Analysis. SAGE Publications, Inc., **2020**.
24. SONG Y., WANG J., GE Y., XU C. An optimal parameters-based geographical detector model enhances geographic characteristics of explanatory variables for spatial heterogeneity analysis: cases with different types of spatial data. GIScience & Remote Sensing, **57**, 593 **2020**.
25. KHEYRURI Y., SHARAFATI A., NESHAT A., HAMEED A.S., RAHMAN A. Analyzing the impact of socio-environmental parameters on wheat and barley cultivation areas using the geographical detector model. Physics and Chemistry of the Earth, Parts A/B/C, **135**, 103630, **2024**.
26. XIE J., TIAN J., HU Y., WANG Q., DAI Z. Imported intermediate goods, intellectual property protection, and innovation in Chinese manufacturing firms. Economic Modelling. **144**, 106960, **2025**.
27. BALLAND P.-A., BOSCHMA R., FRENKEN K. Proximity, innovation and networks: A concise review and some next steps. Handbook of Proximity Relations, 70, **2022**.
28. QIU L., YANG L., ZHOU H., HU F. Deconstruction of green product innovation drivers for regional export-oriented industrial enterprises in China: the product space perspective. Humanities and Social Sciences Communications, **11** (1), 1429, **2024**.
29. ZANOLETTI A., CARENA E., FERRARA C., BONTEMPI E. A Review of Lithium-Ion Battery Recycling: Technologies, Sustainability, and Open Issues. Batteries, **10** (1), 38, **2024**.
30. KING S., BOXALL N.J. Lithium battery recycling in Australia: defining the status and identifying opportunities for the development of a new industry. Journal of Cleaner Production, **215**, 1279, **2019**.
31. HARPER G., SOMMERVILLE R., KENDRICK E., DRISCOLL L., SLATER P., STOLKIN R., WALTON A., CHRISTENSEN P., HEIDRICH O., LAMBERT S., ABBOTT A., RYDER K., GAINES L., ANDERSON P. Recycling lithium-ion batteries from electric vehicles. Nature, **575** (7781), 75, **2019**.
32. CACCAMO M., PITTINO D., TELL F. Boundary objects, knowledge integration, and innovation management: A systematic review of the literature. Technovation, **122**, 102645, **2023**.
33. XIE J., TIAN J., HU Y., WANG Q., DAI Z. Imported intermediate goods, intellectual property protection, and innovation in Chinese manufacturing firms. Economic Modelling. **144**, 106960, **2025**.