IJCCSM
17,1

Received 16 February 2024
Revised 18 May 2024
10 August 2024
9 November 2024
Accepted 24 November 2024

A triple helix model analysis of China's regional industry-university-research collaborative innovation in low-carbon technologies

Tianchong Wang and Baimin Suo
School of Management, Shenyang Normal University, Shenyang, China

Jieshu Jiang
School of Economics and Management, Dalian University of Technology, Dalian, China, and

Wei Jia
China Merchants Taipingwan Development and Investment Co., Ltd, Dalian, China

Abstract

Purpose – Conducting innovation in low-carbon technology is vital to boost the low-carbon economy. Collaborative innovation among industry-university-research (IUR) is an effective mode of developing low-carbon technologies. There is a lack of visualization and analysis of the spatial-temporal of such collaboration among the IUR. This paper aims to serve as insights to guide IUR's collaborative innovation in Chinese universities to promote low-carbon technologies.

Design/methodology/approach – This paper uses IncoPat to collect patent data. Collaborative patent output on low-carbon technologies was selected as the indicator to measure the effectiveness of IUR collaboration. The temporal evolution trend of the collaborative patent output in Chinese universities is analyzed.

Findings – The collaborative patent output of the Chinese IUR varies greatly among the regions, evolving from stronger in the east and weaker in the west, to stronger in the south and weaker in the north region. The triple helix (TH) innovation system in China's low-carbon sector is dominated by intraregional collaborative innovation, while there is a weak bilateral synergy between universities and research institutions.

Originality/value – This paper innovatively developed a novel TH model that characterize the regional differences of the IUR collaboration in low-carbon technology innovation of Chinese universities. A new attempt focuses on the spatial-temporal evolution of the collaborative innovation of IUR to promote low-carbon technologies.

Keywords Collaborative innovation, Industry-university-research, Low-carbon technologies, Patent output

Paper type Research paper

This work is supported by Liaoning Province Education Science 14th Five Year Plan Project (JG24EB254), Research Project on Graduate Education and Teaching Reform in Liaoning Province (LNYJG2024279), China Education Development Strategy Society Lifelong Learning Special Committee Project (ZK202425), National Natural Science Foundation of China (72474043) and Humanities and Social Sciences Project Planning Fund of the Ministry of Education (24YJA630073).

International Journal of Climate Change Strategies and Management
Vol. 17 No. 1, 2025
pp. 848-868
Emerald Publishing Limited
1756-8692
DOI 10.1108/IJCCSM-02-2024-0018

1. Introduction

Environmental and climatological problems are becoming increasingly prominent, and climate change is a common challenge humanity faces. Climate change has led to changes in natural ecological links, such as sea-level rise, increased extreme weather events, ocean acidification and decreased biodiversity. Reducing greenhouse gas emissions directly mitigates or even avoids climate change (Pan and Guo, 2023). Morgan Stanley has released a report pointing out that in the past three years, the losses caused by climate disasters on a global scale amounted to US$650bn. Both short-term damage and long-term climate structural changes bring threats and risks to the global economy that should not be underestimated. Against this background, eco-innovation has become a new focus and direction for economic development in all countries. China is committed to reducing carbon emissions (Pan *et al.*, 2023b). The Chinese government has pledged to "achieve carbon peaking by 2030 and carbon neutrality by 2060." The *State Council Information Office* released a white paper in 2023. It is entitled "China's Green Development in a New Era" and indicates China's determination to pursue a low-carbon and high-quality development path. This path is aimed at fostering a modern lifestyle in harmony with nature.

Low-carbon technology controls greenhouse gases and reduces emissions (Pan *et al.*, 2022). It is one of the most effective ways to solve the energy crisis and curb global warming. A new concept of technology usually accompanies the construction of an eco-economy and green revolution. Existing studies equate low-carbon, green and environmentally friendly technology as alternative concepts (Fujii and Managi, 2016).

The report of *the 20th Party Congress* in the year 2022 has pointed out the crucial role of science and technology. It also emphasized that talent is the leading resource, and innovation is the key driving force. An open and collaborative innovation model is vital in enhancing innovation efficiency. *The 14th Five-Year Plan (2021–2025) for National Economic and Social Development and Vision 2035 of the People's Republic of China* outlined the need to support the development of frontier university research. The plan emphasized the importance of developing new R&D institutions. It also stressed the need to optimize the allocation of scientific and technological resources through industry-university-research (IUR) collaboration. Universities lead the role of nurturing innovation culture, accelerating breakthroughs in basic research and enhancing innovation capabilities (Song *et al.*, 2022). The innovation capabilities could be strengthened through joint patent applications with other universities, research institutes and industries (Pan *et al.*, 2023a; Jia and Wang, 2023). Practical collaborative innovation among universities, research institutions and industries is essential (Wang *et al.*, 2024). It can help accelerate the process of reaching the carbon peak by 2030. Achieving an innovation model based on openness, cooperation and sharing is crucial in globalization. This approach has been proven by practice to enhance innovation efficiency effectively. Mobilizing the enthusiasm and creativity of various innovation entities, such as enterprises, universities and research institutions, is crucial (Zhang *et al.*, 2022). Implementing in-depth cooperation and open innovation across disciplines, departments and industries is becoming increasingly important. This is particularly relevant for accelerating the integration and diffusion of scientific and technological advancements across different fields, industries and stages of the innovation chain.

In practice, different low-carbon technology innovation entities have different interests, cultural differences, institutional barriers and other obstacles that restrict the depth, breadth and sustainability of IUR's collaborative innovation in low-carbon technology. Such limitations affect the performance of regional low-carbon technology innovation. Due to the large territory in China, there are significant differences in natural resource endowments, economic and social development levels, geographical location advantages and low-carbon policy environments among provinces, which leads to significant differences in IUR's collaborative innovation in low-carbon technology across different regions. Therefore, scientifically evaluating the interactive and coupling relationships among IUR's collaborative innovation in low-carbon technology across different regions in China, notably to reveal the regional differences, spatial pattern characteristics and evolutionary trends of IUR's collaborative innovation in low-carbon technology, is crucial to optimize resource allocation and policy formulation in promoting IUR collaborations. The innovation of this article is to use the triple helix (TH) model to empirically analyze the interactive relationship among IUR's collaborative innovation entities in low-carbon technology within and between regions in China from two dimensions: horizontal regional comparison and vertical temporal evolution.

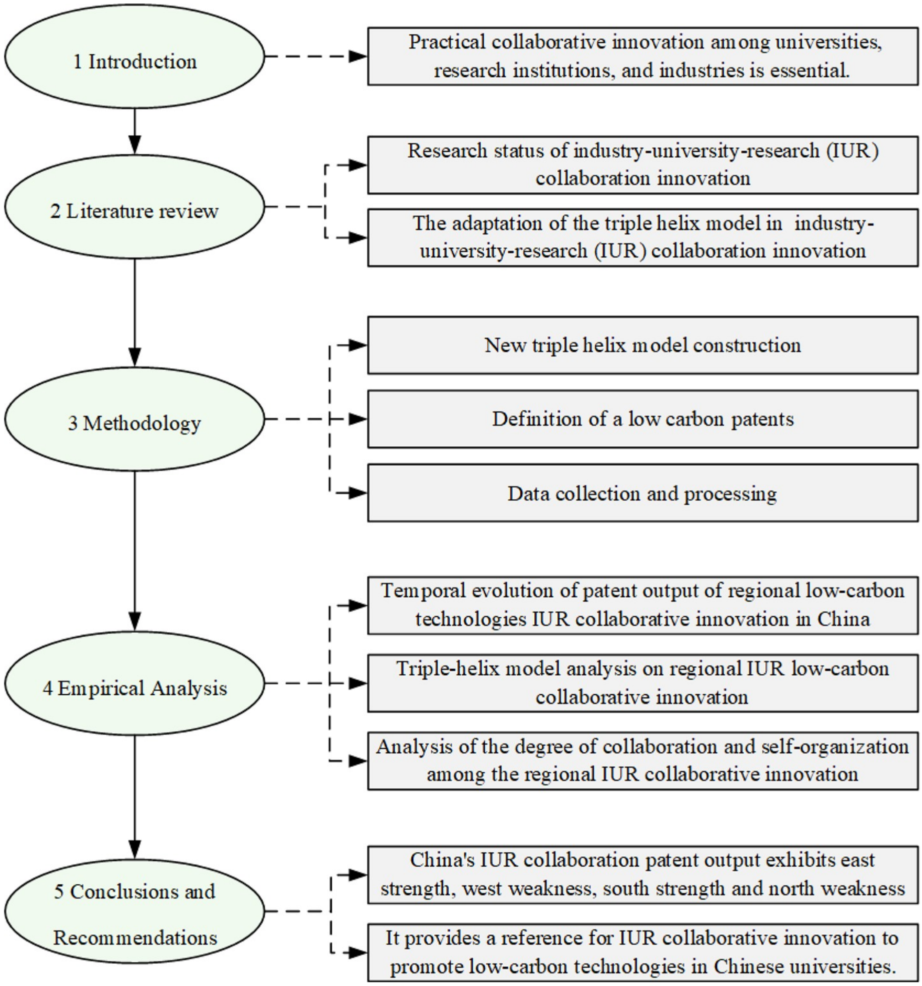
The technical roadmap of the study is shown in Figure 1. The remainder of this paper is organized as follows: Section 2 describes the literature review. Section 3 introduces methodology. Section 4 analyzes the coupling relationship and spatiotemporal evolution characteristics of regional low-carbon technology IUR collaborative innovation in China. Finally, conclusions and recommendations are proposed in Section 5.

2. Literature review

Peter (2006) defined collaborative innovation for the first time, which refers to a collaborative group with a common goal as a premise (Fan *et al.*, 2023). The group is also characterized by mutual motivation to promptly exchange knowledge, ideas and project progress. It is a dynamic and evolving process. IUR collaborative innovation refers to the transfer, absorption, digestion, sharing, integration, utilization and re-creation of knowledge among enterprises, universities and scientific research institutions with high-quality resources and capabilities (Song *et al.*, 2020; Zeng *et al.*, 2023). Evaluating IUR's collaborative innovation is essential in examining the development status and improving such collaboration. Table 1 summarizes some of the research outcomes of IUR's collaborative innovation.

The TH model criticizes the traditional innovation theory. Unlike the traditional model, it emphasizes the interaction between individual subjects and not just the role of a single-subject innovation (Guo *et al.*, 2023). This theory emphasizes that the industry-university-government triad can organize and lead innovation activities. It also highlights the importance of cross-organizational cooperation at different stages of innovation (Fan *et al.*, 2023). There is a growing importance of synergistic collaboration among stakeholders, that is, between the university and industry (Atta-Owusu *et al.*, 2021). Communication and coordination across institutional boundaries are essential to achieve improved performance and capacity of national and regional innovation systems (Moaniba *et al.*, 2019).

The TH concept first appeared in biology and was later introduced into the innovation system by Etzkowitz and Leydesdorff (1995). The theory suggests that the overlap between universities, industries and governments is at the heart of regional and national innovation systems. The closer the interaction and integration among two or three stakeholders, the more beneficial the innovative activities become. Industries are often the initiators of innovation activities, universities are the organizers and the government manages innovation activities (Pan *et al.*, 2023c). The three parties are independent and coordinated with each other, forming a dynamic TH structure (Xiao *et al.*, 2023). The theory systematically explains the changing roles of industries, universities and governments in knowledge-based innovation systems. This approach emphasizes the importance of cooperation between critical public and private institutions to develop innovation systems (Murillo-Luna and Hernández-Trasobares, 2023). The TH model has initiated extensive research on the collaborative innovation system among industries, universities and governments. Hernández-Trasobares and Murillo-Luna (2020)



Source: Authors' work

Figure 1. Technical roadmap of the study

studied the synergy among industries, universities and governments' collaboration on business innovation. The results indicated that an increased number of agents participating in the TH collaboration model leads to a significant expansion in opportunities for business innovation.

These also confirmed the synergy among the agents. Mêgnigbêto (2018) argued that the industry-university-government spiral is a three-player cooperative game with transferable utility. Research institutions are essential components, apart from the national innovation system, such as the governments (Zhang *et al.*, 2019). Both are the sources of knowledge, technology and talent that can provide intellectual support for economic and social development (Hou *et al.*, 2023). They developed the TH model to understand how the three key players in the IUR collaboration work together effectively. They revealed how these

Table 1. Literature review of the IUR's collaborative innovation

Article	Model	Contribution	Shortcoming
Santoro and Chakrabarti (2002)	Seven-point Likert-type scale	Examined the association between key firm-specific variables and the various I/U relationship alternatives used by firms and universities	Conducted temporal evolution analysis of IUR cooperative relationships, which lacked regional spatial comparative analysis
David *et al.* (2007)	Data envelopment analysis model	Analyzed the operation level of university-industry collaborative innovation in Europe	Conducted spatiotemporal analysis of IUR collaborative innovation, lacked a spatiotemporal analysis of the relationship among IUR entities
Schartinger *et al.* (2002)	Interaction models	Analyzed the interaction of various types of knowledge between IU	Conducted temporal evolution analysis of cooperative relationships between IU entities, lacked regional spatial comparative analysis
Zhang *et al.* (2019)	Triple helix (TH) model	Analyzed triple helix interactions of IUR collaboration entities	Analyzed the interaction relationship between IUR entities, lacked a spatiotemporal evolution analysis of the coupling relationship among IUR entities
Zhang *et al.* (2022)	Two-stage data envelopment analysis model	Analyzed the policy effects of innovative city pilot on the dual efficiency of IUR knowledge flow	Conducted an overall spatial comparative analysis of IUR collaborative innovation, which lacked a spatiotemporal analysis of the relationship among IUR entities
Song *et al.* (2022)	A stochastic evolutionary game model	Examined the strategic choices of actors who participate in IU collaborative innovation alliances	Analyzed the interaction relationship between IU entities lacked a spatiotemporal evolution analysis of the coupling relationship among IUR entities
Song *et al.* (2022)	A stochastic evolutionary game model	Examined the strategic choices of actors who participate in IU collaborative innovation alliances	Analyzed the interaction relationship between IU entities lacked a spatiotemporal evolution analysis of the coupling relationship among IUR entities
Fan *et al.* (2023)	Network data envelopment analysis model	Analyzed the urban industry-university-research collaborative innovation performance	Conducted a spatiotemporal analysis of IUR collaborative innovation, lacked a spatiotemporal analysis of the relationship among IUR entities

(*continued*)

Table 1. Continued

Article	Model	Contribution	Shortcoming
Zeng *et al.* (2023)	Social cooperation network and multi-phase DID model (T)	Analyzed pilot policy effects on improving the efficiency of IUR innovation	Conducted a spatiotemporal analysis of IUR collaborative innovation, lacked a spatiotemporal analysis of the relationship among IUR entities
Yan *et al.* (2023)	Social network analysis (SNA)	Studied the evolution of the regional IUR collaborative innovation network	Conducted a spatiotemporal analysis of IUR collaborative innovation, lacked a spatiotemporal analysis of the relationship among IUR entities
Guo *et al.* (2023)	Tobit regression	Analyzed the impact of IUR entities on low-carbon technology innovation of new energy enterprises	Analyzed the interaction relationship among IUR entities, lacked a spatiotemporal evolution analysis of the coupling relationship among IUR entities
Hou *et al.* (2023)	A three-evolutionary game model	Analyzed the role of IUR cooperation entities in the agricultural innovation system	Analyzed the interaction relationship among IUR entities, lacked a spatiotemporal evolution analysis of the coupling relationship among IUR entities
Jia and Wang (2023)	A differential game method	Analyzed the optimal decision-making problem of industry-university research cooperation entities	Analyzed the interaction relationship among IUR entities, lacked a spatiotemporal evolution analysis of the coupling relationship among IUR entities
Xiao *et al.* (2023)	Coupling coordination degree model	Analyzed the spatiotemporal convergence trend of provincial IUR collaborative innovation in China	Conducted a spatiotemporal analysis of IUR collaborative innovation, lacked a spatiotemporal analysis of the relationship among IUR entities
Wang *et al.* (2024)	Complex network analysis	Analyzed the IUR collaborative innovation network in China's new energy vehicle industry	Conducted temporal evolution analysis of cooperative relationships among IUR entities, lacked regional spatial comparative analysis

Source: Authors' work

entities interact and combine their efforts to ensure the best distribution and efficient utilization of resources for innovation. The synergistic effect generates momentum to enhance the innovation spiral, promoting scientific and technological progress and synergistic economic and social development (Zhang *et al.*, 2016).

The above literature lays the foundation for the study of this paper. As shown in Table 1, existing studies either focus on spatiotemporal analysis of IUR collaborative innovation or the interaction relationship between two IUR entities. Still, few studies focus on spatiotemporal analysis of the relationship among IUR entities.

3. Methodology

3.1 Triple helix model construction

The TH innovation system, consisting of universities, industries and scientific research institutions, is a typical complex system with uncertainty (Xiao *et al.*, 2023). Leydesdorff (1995) is one of the founders of the TH theory. In information theory, he outlined that entropy or average information could describe innovation systems' uncertainty and self-organization. TH algorithm is proposed to measure the synergy of the TH. The quantitative approach of the TH model is rooted in mutual information measures and has its roots in Shannon's information entropy (Shannon, 1948). The TH algorithm was developed to measure the synergistic relationship of the TH. Entropy represents the probability of occurrence of discrete random events. The lower the entropy, the more ordered the system, and vice versa. The information entropy of a one-dimensional variable x is expressed in formula (1):

$$H_x = -\sum_x P_x \log_2 P_x \tag{1}$$

H denotes the entropy, that is, the average of the amount of information. P_x is the probability that the x^{th} message will occur.

The two-dimensional information entropy or joint entropy of the probability distribution of the discrete random variable x and variable y is:

$$H_{xy} = -\sum_{xy} P_{xy} \log_2 P_{xy} \tag{2}$$

P_{xy} is the joint probability distribution of the random events x and y.

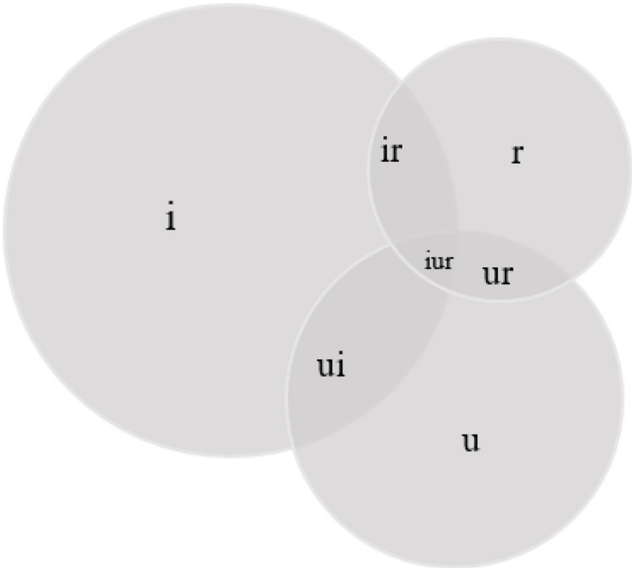
The mutual information in information theory, T, represents the uncertainty of a random event reduced by the information known by another random event.

In Figure 2, u, i and r indicate the invention patents containing only universities, industries or research institutions. ui, ur and ir denote the patented inventions by both the universities and industries, universities and research institutions and industries and research institutions. iur denotes the patented inventions developed by all three stakeholders: universities, industries and research institutions.

Take the university u as an example, when u contains two states: The invention patent contains information about the university with probability p_1. The invention patent does not contain information about the university with probability p_2.

Let $n = u + i + r + ui + ur + ir + iur$. a denotes a patent for any one invention, where p_1, p_2 *and* H_u are represented by formula (3) to formula (6):

$$p_1 = p(a \in \text{university}) = \mathrm{p}(a \in u \text{ or } a \in ui \text{ or } a \in ur \text{ or } a \in iur) = \log_2\left(\frac{u + ui + ur + iur}{n}\right) \tag{3}$$



Source: Authors' work

Figure 2. Application of information entropy and mutual information in IUR calculations

$$p_2 = p(a \notin \text{university}) = \mathrm{p}(a \in i \,\text{or}\, a \in r \,\text{or}\, a \in i\mathrm{r}) = \log_2\left(\frac{i+r+ir}{n}\right) \tag{4}$$

$$\begin{aligned} H_u &= -\sum_{i=1}^{2} p_i \bullet \log_2(p_i) = -p_1 \bullet \log_2(p_1) - p_2 \bullet \log_2(p_2) \\ &= -\frac{u+ui+ur+iur}{n} \times \log_2\left(\frac{u+ui+ur+iur}{n}\right) - \frac{i+r+ir}{n} \times \log_2\left(\frac{\mathrm{i}+r+\mathrm{i}r}{n}\right) \end{aligned} \tag{5}$$

Similarly, we can obtain H_i and H_r in formula (6):

$$\begin{aligned} H_{uc} &= -\sum_{i=1}^{4} p_i \bullet \log_2(p_i) = -p_1 \bullet \log_2(p_1) - p_2 \bullet \log_2(p_2) - p_3 \bullet \log_2(p_3) - p_4 \bullet \log_2(p_4) \\ &= -\frac{ui+iur}{n} \times \log_2\left(\frac{ui+iur}{n}\right) - \frac{u+ur}{n} \times \log_2\left(\frac{u+ur}{n}\right) - \frac{i+ir}{n} \times \log_2\left(\frac{i+ir}{n}\right) \\ &\quad - \frac{r}{n} \times \log_2\left(\frac{r}{n}\right) \end{aligned} \tag{6}$$

Similarly, we can obtain H_{ur} and H_{ir} in formula (7):

$$H_{ucr} = -\sum_{i=1}^{7} p_i \bullet \log_2(p_i) = -p_1 \bullet \log_2(p_1) - p_2 \bullet \log_2(p_2) - p_3 \bullet \log_2(p_3)$$
$$- p_4 \bullet \log_2(p_4) - p_5 \bullet \log_2(p_5) - p_6 \bullet \log_2(p_6) - p_7 \bullet \log_2(p_7)$$
$$= -\frac{u}{n} \times \log_2\left(\frac{u}{n}\right) - \frac{i}{n} \times \log_2\left(\frac{i}{n}\right) - \frac{r}{n} \times \log_2\left(\frac{r}{n}\right) - \frac{ui}{n} \times \log_2\left(\frac{ui}{n}\right)$$
$$- \frac{ur}{n} \times \log_2\left(\frac{ur}{n}\right) - \frac{ir}{n} \times \log_2\left(\frac{ir}{n}\right) - \frac{iur}{n} \times \log_2\left(\frac{iur}{n}\right) \quad (7)$$

The two-dimensional mutual information between the universities and the industries can be expressed in formula (8):

$$T_{ui} = H_u + H_i - H_{ui} \quad (8)$$

A higher value of the two-dimensional mutual information (e.g. between university and industry is expressed as T_{ui}) indicates a more significant reduction in uncertainty. This means there is a more harmonious relationship between the universities and industries.

The three-dimensional mutual information of IUR (T_{iur}) can be expressed in formula (9):

$$T_{iur} = H_u + H_i + H_r - H_{ui} - H_{ur} - H_{ir} + H_{iur} \quad (9)$$

The three-dimensional mutual information (T_{iur}) can reveal the significance of intra- and trans-regional cooperation dynamics in innovation systems. When T_{iur} is negative, it indicates that IUR cooperation is an intraregional collaboration; the larger the negative value, the stronger the intraregional collaboration effect. When T_{iur} is positive, it indicates that IUR cooperation is a cross-regional collaboration, and the larger the negative value, the stronger the cross-regional collaboration effect (Leydesdorff and Ivanova, 2013).

The mutual information T is used to measure the self-organization of a system network due to the lack of central coordination (Zhang *et al.*, 2019). The value of mutual information is related to the system configuration. The difference in mutual information between different systems cannot accurately reflect the degree of synergy and self-organization among the subjects of the innovation system. Mêgnigbêto (2014) measures the degree of synergy between organizations in an innovation system through system transfer effectiveness. Transfer effectiveness is the percentage of information to be shared in the system. It concerns the total amount of information transferred. This measure assesses the efficiency of mutual information, which can be interpreted as the dependence or synergy of the variables.

The transfer effectiveness τ_{ui} used in a two-dimensional system, such as between a university and an industry, is expressed as formula (10):

$$\tau_{ui} = T_{ui}/H_{ui} \quad (10)$$

A more considerable two-dimensional transfer effectiveness (τ) indicates more frequent interactions between two-dimensional subjects. It also signifies a closer synergistic relationship. The transfer effectiveness τ_{iur} between industries, universities and research institutions in a three-dimensional system is expressed in formula (11):

$$\tau_{iur} = \begin{cases} \dfrac{T_{iur}}{H_{iur} - H_u - H_i - H_r} & if \quad T_{iur} < 0 \\ \dfrac{T_{iur}}{H_{iur}} & if \quad T_{iur} > 0 \\ 0 & if \quad T_{iur} = 0 \end{cases} \tag{11}$$

Since H_{iur} - H_u - H_i -H_r < T_{iur} < H_{iur}, the range of τ values is within [0,1]. A higher value of the three-dimensional transfer effectiveness (τ) indicates a greater two-by-two synergy among the three subjects. It also signifies a greater self-organization level of the system, which includes universities, industries and research institutions. Due to the lack of central coordination, the three-dimensional relationships play a self-organizing role in the system. The system becomes self-driven and self-regulating in the mutual coordination between the innovation subjects. When more than one party or three parties collaborate, the weaker the self-organization of the system and the stronger the central coordination (Mêgnigbêto, 2014).

3.2 Definition of low-carbon technology patents

The three central patent systems define and classify low-carbon technology patents. The IPC Green List was issued by the World Intellectual Property Organization in 2010. ENV-TECH was issued by the Organization for Economic Cooperation and Development (OECD) in 2015. Both are based on the traditional IPC classification system for low-carbon technologies. They are suitable for studying specific low-carbon technologies and eco-innovations. The CPC-Y02 patent on climate change mitigation technologies or applications was jointly published by the EPO and USPTO in 2013. It has systematic and structured characteristics. This database enables the tracking and study of the overall innovation dynamics in low-carbon technologies. This paper applies the CPC-Y02 patent classification system published in October 2017 to define low-carbon technology patents (Table 2).

3.3 Data collection and processing

The patent application is an essential node for realizing the transformation of scientific research and innovation. It plays a crucial role in enhancing national and regional innovation capabilities. The joint patent application is a standard collaborative innovation mode between industry, academia and research institutes (Yan *et al.*, 2023). This study uses the incoPat technology and innovation intelligence platform from Beijing Hershey Intelligence Technology Co-developed. This platform is the first intelligence platform in the world that can search and browse global patent information in Chinese. It is highly integrated with

Table 2. CPC-Y02 patent classification system for defining low-carbon technology patents

Classification no.	Name
Y02B	Patented building-related technology
Y02C	Technologies for capturing, storing, sequestering or disposing of greenhouse gases
Y02E	Low-carbon technologies related to energy generation, transmission and distribution
Y02T	Low-carbon technologies related to transport
Y02W	Low-carbon technologies related to wastewater treatment or waste management
Y02P	Low-carbon technologies in the production or processing of goods

Source: Authors' work

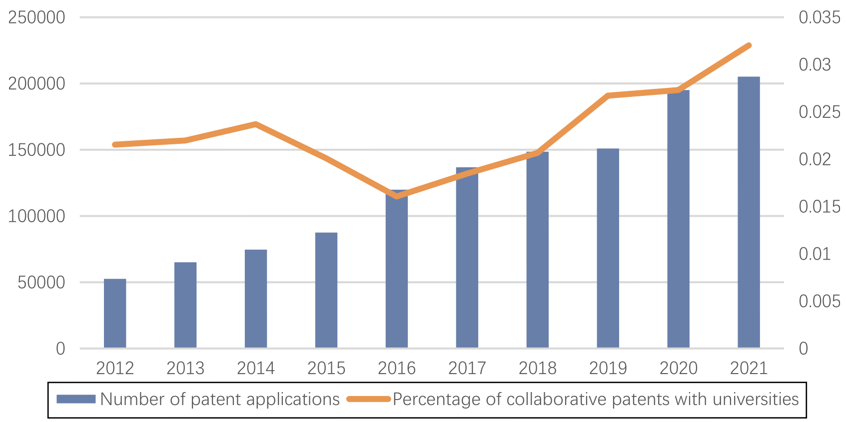
global science and technology innovation intelligence. It is one of China's few patent intelligence analysis platforms with rich data sources. It integrates several functional modules such as patent search, thematic library, 3D sandbox and clustering analysis and can complete multidimensional patent search and analysis.

The company ensures the accuracy, continuity and availability of data. The database covers characteristics for the development in Tibet Autonomous Region and Hong Kong, Macao and Taiwan. This study selected mainland China's 28 provincial administrative regions (excluding Tibet, Qinghai and Ningxia). Chinese invention patents have an examination period of 18–36 months; this paper uses the invention patents filed between 2012 and 2021 as research data. In the advanced search, patents can be classified as "I," "U" and "R" according to the keyword information of the patent applicant (patent right). Those containing both types of entities are further grouped into combined categories. These categories are "University-industry (UI)," "University-research (UR)," "Industry-research (IR)" and "Industry-university-research (IUR)." They are counted separately by year and provincial administrative region.

4. Coupling relationship and spatiotemporal evolution characteristics for China's regional IUR collaborative innovation in low-carbon technologies

4.1 Temporal evolution of patent output for China's regional IUR collaborative innovation in low-carbon technologies

In Figure 3, the number of patent applications for inventions in China's low-carbon field has increased yearly. It increased from 52,648 cases in 2012 to 205,081 cases in 2021. The average annual growth rate is 16.3%. It is higher than the growth rate of R&D expenditure, which indicates that China's science and technology innovation efficiency is improving yearly. The trend in patented invention applications shows that China has seen two leapfrog periods. These peaks occurred in the low-carbon sector in 2015–2016 and 2019–2020. The possible reason is that a series of policies to stimulate patent applications were introduced in the corresponding years. For example, in 2016, the Chinese government proposed extending the time limit to reduce annual patent fees. This effectively reduces the actual burden on most

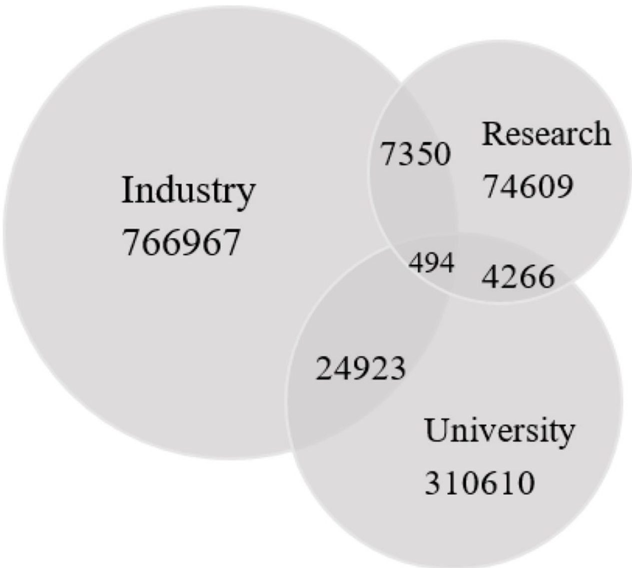


Source: Authors' work

Figure 3. The number of invention patents in China and the share of patents for IUR collaborative innovation in low-carbon technologies in Chinese universities, 2012–2021

innovation subjects. It aimed to stimulate social enthusiasm for invention and creation. The extension was from three years to six years after being granted. Despite the impact of the coronavirus disease in 2019, China achieved increased growth in the number of invention patent applications in 2020. This growth is closely linked to enhanced quality and efficiency of China's Intellectual Property Rights (IPR) examination. By 2020, the quality and efficiency of China's intellectual property examination have steadily improved. The examination cycle for high-value patents has been reduced to 14 months, and the average examination cycle for invention patents has been reduced to 20 months. Shortening the examination cycle further benefits the rapid acquisition of stable and reliable patent licenses for innovation subjects. Another benefit is the timely transfer and transformation of innovation achievements. All these measures were essential to the increased number of patent applications for inventions in China. The number of China's invention patents in the low-carbon field in 2019 remained almost the same as in 2018, the increase was essentially negligible. This indicates that China is changing from a major IPR importer country to a significant IPR creation country. IPR work is changing from pursuing quantity to improving quality. IPRs that are "more but not better" or "larger but not stronger" are not in line with China's new development concept. They do not align with the requirements of building a new development pattern and promoting high-quality development. Creating high-quality IPR products, including core patented technologies, copyrighted products and well-known brands, is necessary. This will help achieve a shift from "more to better" and from "more considerable to more robust" IPR creation. This paper only covers invention patents.

The TH distribution of invention patents in low-carbon technologies in China is shown in Figure 4. As one of the main players of IUR, the industry has the highest number of patent applications for inventions in the low-carbon sector. It is about twice that obtained by the



Source: Authors' work

Figure 4. TH distribution of China's invention patents in low-carbon technologies within 2012–2021

universities and ten times more than the research institutions. The number of invention patents applied by industry accounted for 66.57% of the total patents. Universities are mainly engaged in scientific research and are the primary source of knowledge for technological innovation. They play the role of a knowledge base and as an important subject participating in technology research, development and services. Next is universities, which account for 26.96% of the total number of patent applications, while research institutions produce a relatively small number of patents, only accounting for 6.48% of the total number of patents. As the source of low-carbon technology innovation, universities and research institutions have certain advantages in conducting scientific research and theoretical innovation in the low-carbon field. However, they lack motivation for low-carbon technology innovation and the transformation of scientific and technological achievements compared to the industry (Xiao *et al.*, 2023).

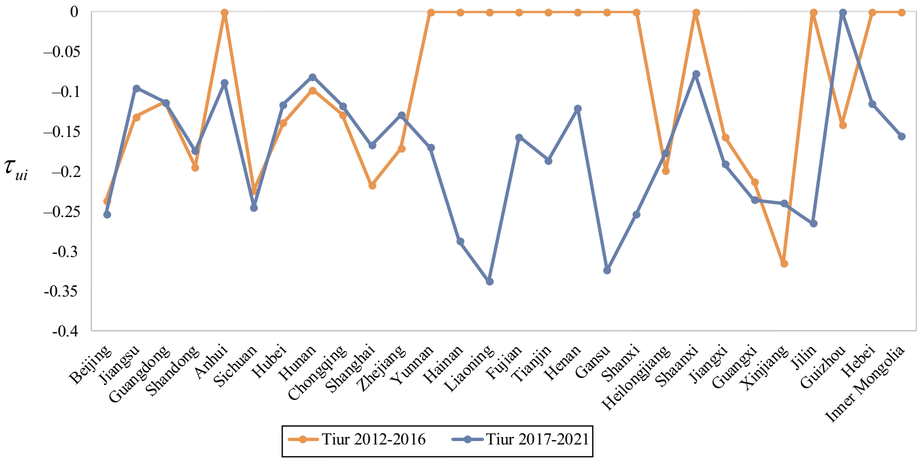
4.2 Triple-helix model analysis on regional IUR collaborative innovation in low-carbon technologies

To further explore the interaction between the tripartite subjects in the regional innovation system, each subject's degree of synergy and spatial association within and between regions were analyzed. This paper uses the TH algorithm and its extensions to calculate the information entropy H, mutual information T and transfer effectiveness τ values. The calculations are made in the regional collaborative innovation system using the collected patent data through formula (1) to formula (6), respectively. The three-dimensional mutual information T_{iur} reflects the scope of the synergy of the regional innovation system. The two-dimensional and three-dimensional transfer effectiveness τ reflects the degree of synergy between the innovation agents and the system's self-organization.

The three-dimensional mutual information (T_{iur}) modeled by the TH model can reflect the extent of collaborative innovation. It includes both the intra- and interregional analysis in each region. A smaller value of the 3D mutual information indicates a more potent intraregional synergy and vice versa. The T_{iur} for IUR collaborative innovation in the low-carbon technologies in Chinese universities is shown in Figure 5. The T_{iur} of all 28 provinces is negative. This result shows that China's regional IUR collaborative innovation in low-carbon Technologies is dominated by intraregional cooperation.

Provinces with high T_{iur}, including Jiangsu, Guangdong, Anhui, Hunan, Zhejiang and Chongqing, have a relatively high proportion of cross-regional cooperation. This is seen in collaborative innovation among the IUR. Jiangsu, Guangdong and Zhejiang have strong regional innovation capabilities, a wide range of science and technology drive and radiation. They are adjacent to other regions rich in science and technology resources, making it easier to carry out cross-regional collaborative innovation activities. Anhui, Hunan and Chongqing lack robust technology absorption capacity. Despite their surrounding areas having richer resources for science and technology innovation, the tripartite innovation resources of IUR are unbalanced. For example, Anhui and Jiangsu, Zhejiang and Shanghai, Hunan and Guangdong and Chongqing and Sichuan are geographically connected. Each pair has similar humanities, science and technology and complementary resources. These similarities make it easier to carry out cross-regional collaborative innovation among the IUR.

Provinces with small T_{iur}, including Hainan, Liaoning, Gansu and Xinjiang, indicate the predominance of collaborative innovation within these provinces. Three provincial administrative regions, Xinjiang, Gansu and Hainan are relatively backward in science and technology innovation development. These provinces are remote and far away from areas



Source: Author's work

Figure 5. Three-dimensional mutual information (t_{iur}) on low-carbon collaborative innovation in Chinese universities

rich in science and technology resources. Geographical distance hinders the development of cross-regional collaborative innovation activities. Liaoning is located across the sea from Shandong, Tianjin and Beijing. These areas are relatively advanced in science and technological innovation. The inconvenience of transportation has limited its collaborative interactions across the region, as shown in Figure 5, where the peak is low (−0.35, a low level).

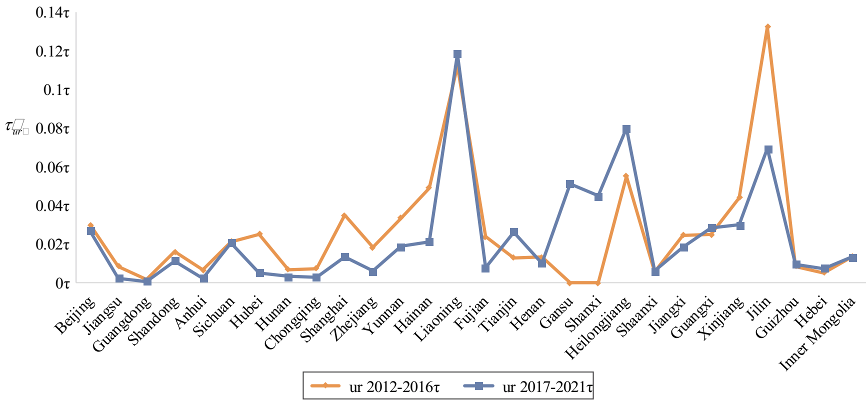
4.3 Analysis of the coupling degree among regional IUR collaborative innovation entities in low-carbon technologies

4.3.1 Analysis of the bilateral coupling degree among regional IUR collaborative innovation entities in low-carbon technologies. The two-dimensional transfer effectiveness reflects the bilateral coupling degree among the regional IUR collaborative innovation entities in low-carbon technologies. The transfer effectiveness between universities and industries (τ_{ui}) is shown in Figure 6. Among the ten provincial regions, only ten provinces (Chongqing, Tianjin, Henan, Gansu, Heilongjiang, Shaanxi, Jiangxi, Guangxi, Hebei and Inner Mongolia) show a decrease in their τ_{ui} values, indicating that in the past five years, the collaborative relationship between universities and enterprises in low-carbon technologies has become closer in most provinces. Provinces with high τ_{ui} values, including Jiangsu, Guangdong, Shandong, Anhui, Hubei, Hunan, Chongqing, Shanghai, Zhejiang, Fujian, Tianjin, Henan, Shaanxi and Hebei show more frequent cooperation in low-carbon technologies between universities and enterprises.

The transfer effectiveness between universities and research institutions (τ_{ur}) is shown in Figure 7. The τ_{ur} value is generally low, mostly below 0.1. Meanwhile, only six provinces (Tianjin, Gansu, Shanxi, Heilongjiang, Guangxi and Hebei) have increased their τ_{ur} values in the past five years. This indicates a weak interactive coupling relationship between universities and research institutions in low-carbon technologies.

Source: Author's workτ

Figure 6. Two-dimensional transmission effectiveness of UI in low-carbon technologies

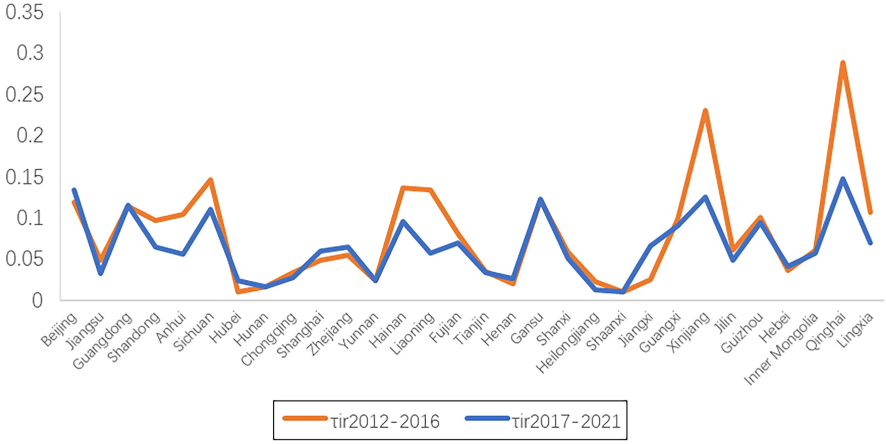


Source: Author's workτ

Figure 7. Two-dimensional transmission effectiveness of UR in low-carbon technologies

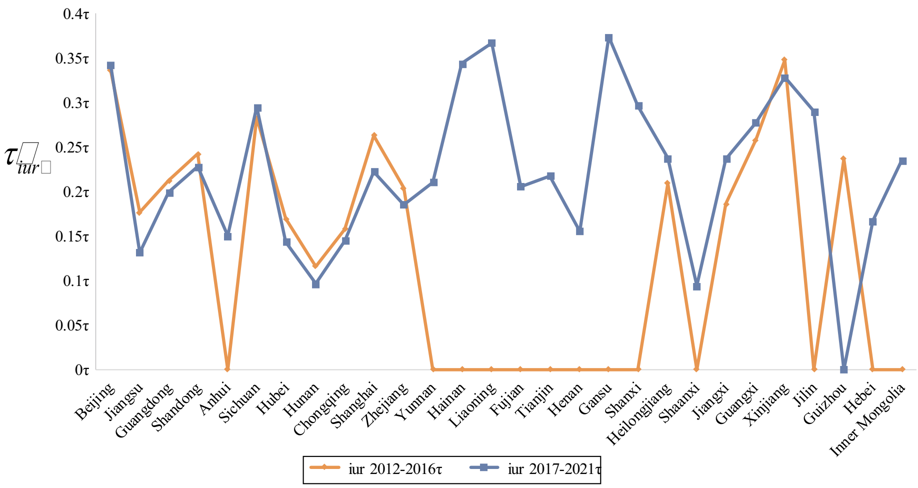
The transfer effectiveness between industries and research institutions (τ_{ir}) is shown in Figure 8. Among the 28 provincial regions, 19 provinces show a decrease in their τ_{ir} values, indicating that in the past five years, the collaborative relationship between industries and research institutions in low-carbon technologies tends to be loose in most provinces. Provinces with high τ_{ui} values include Beijing, Guangdong, Sichuan, Gansu, Xinjiang and Qinghai, indicating more frequent cooperation between industries and research institutions.

4.3.2 Analysis of the tripartite coupling degree among regional IUR collaborative innovation entities in low-carbon technologies. The three-dimensional transfer effectiveness reflects the tripartite coupling degree among the regional IUR collaborative innovation entities in low-carbon technologies. The transfer effectiveness among universities, industries and research institutions (τ_{iur}) is shown in Figure 9. Among the 28 provincial regions, only



Source: Author's work

Figure 8. Two-dimensional transmission effectiveness of IR in low-carbon technologies



Source: Author's workτ

Figure 9. Three-dimensional transmission effectiveness of low-carbon technologies IUR collaborative innovation in Chinese universities τ_{iur}

ten provinces (Jiangsu, Guangdong, Shandong, Hubei, Hunan, Chongqing, Shanghai, Zhejiang, Xinjiang and Guizhou) show a decrease in their τ_{iur} values, indicating that in the past five years, China's IUR collaborative innovation in low-carbon technologies has become closer in most provinces. The decrease in τ_{iur} value is not significant in all provinces except for Guizhou. During the two stages of 2012–2016 and 2017–2021, the provinces with high τ_{iur} values in these two periods include Beijing, Guangdong, Shandong, Sichuan, Shanghai, Zhejiang, Heilongjiang, Guangxi and Xinjiang, indicating more frequent cooperation in low-carbon technologies among universities, industries and research institutions.

4.4 Discussions

Low-carbon technology innovation is a key force in promoting the development of a low-carbon economy. Delineating the spatial-temporal disparities in IUR collaborative innovation within the same province and analyzing the evolution of such collaboration across different regions is a great challenge. This section aims to analyze and discuss China's regional IUR collaboration in low-carbon technologies from two dimensions: horizontal regional comparison and vertical temporal evolution. This two-dimensional analysis can provide a deeper understanding of the dynamics and influencing factors of regional IUR's collaborative innovation in China.

The findings reveal that industries are the most important source of invention patents. This indicates that industries are the main body of collaborative innovation among the IUR (Kamarkar, 1996). Industries are more directly involved in market competition. They can regulate the research direction of IUR collaborative innovation and integrate the innovation resources of different units such as universities, scientific research institutions and intermediaries. Industries can apply innovation resources to innovative products and innovative services with good market prospects to enhance the efficiency of collaborative innovation. However, as the source of low-carbon technology innovation, universities and research institutions have low patent output in the field of low-carbon technology. Therefore, universities and research institutions should increase their investment in the research and development of green low-carbon technology, carry out joint research and development of green low-carbon technology around the common needs and difficult problems in the field, promote the transfer and transformation of scientific and technological achievements and serve the high-quality development of the economy and society.

Meanwhile, China's regional IUR collaborative innovation in low-carbon technologies is dominated by intraregional cooperation. This indicates that China's IUR collaborative innovation in low-carbon technologies is still more limited to intraregional cooperation. Intraregional IUR cooperation may face limitations in its innovation subject capabilities, resulting in the inability to optimize the allocation of innovation resources and low efficiency of collaborative innovation. Cross-regional IUR cooperation can break through the geographical limitations of regional industry-university research cooperation, thereby achieving resource sharing and complementary advantages, accelerating the transformation and application of scientific and technological achievements. Therefore, it is necessary to strengthen cross-regional IUR collaborative innovation, integrate resources from all parties nationwide, form synergistic effects and promote cross-regional cooperation and development of low-carbon technology innovation.

From the two-dimensional cooperative relationship perspective, the collaborative relationship between universities and industries is the closest, followed by industries and research institutions, while the relationship between universities and research institutions is the looser. This indicates that universities mainly engage in original innovation, basic theoretical research and scientific research in low-carbon technologies. At the same time, industries are more engaged in applied research, technological innovation and technological achievement transformation in low-carbon technologies. The universities and industries complement each other in the innovation process, they could find innovation convergence points (Li and Zheng, 2024). The cooperation between research institutions and industries is similar to that between universities and industries. However, the cooperation between universities and research institutions should not be ignored. Universities as the main force in basic research and talent cultivation, while research institutions provide innovative practice venues and technological energy, jointly promoting the improvement of scientific and technological innovation capabilities, bringing better scientific research results and social benefits.

Beijing, Guangdong, Shandong, Sichuan, Shanghai, Zhejiang, Heilongjiang, Guangxi and Xinjiang have strong three-dimensional collaborative relationships and are in the deep integration of IUR. Among them, Beijing, Guangdong, Shandong, Sichuan, Shanghai and Zhejiang have strong low-carbon technology innovation capabilities and a high degree of marketization, mainly achieving deep integration of IUR through market mechanisms. Heilongjiang, Guangxi and Xinjiang have weaker low-carbon technology innovation capabilities, but close cooperation between IUR can also be achieved through government leadership. This indicates that promoting IUR collaborative innovation in low-carbon technologies relies on the power of the market and the government. The fundamental role of market mechanisms in allocating resources should be fully used to stimulate the vitality of IUR cooperation and improve the level and efficiency of IUR cooperation. The government can overcome the traditional institutional barriers in IUR cooperation through its own macroeconomic regulation and coordination capabilities, as well as unique advantages in funding, information and policies, thus building a platform for IUR cooperation.

The TH model provides a strong framework for understanding the spatiotemporal evolution of China's regional IUR collaborative innovation in low-carbon technology innovation (Zhang *et al.*, 2019). The analysis of patent cooperation output among various provinces in China reveals significant regional differences and provides insights into the cooperation dynamics between different innovation entities. By using these insights, stakeholders can strive to create a more balanced and effective collaborative innovation ecosystem, drive the development and adoption of low-carbon technologies and contribute toward the growth of a low-carbon economy.

5. Conclusions and recommendations

5.1 Conclusions

Based on the TH theory and its algorithm expansion, this paper analyzes Chinese invention patent data in low-carbon technologies for two intervals from 2012 to 2016 and 2017 to 2021. This study empirically investigates the regional differences in provincial collaborative innovation. It examines the interactive coupling relationship between intraregional and interregional IUR innovation entities and their dynamic evolution trends. The results are as follows: first, industries are the most important source of inventions accounting for 66.57% of the total. Second, China's regional IUR collaborative innovation in low-carbon technologies is dominated by intraregional cooperation. Hainan, Liaoning, Gansu and Xinjiang have relatively strong intraregional collaborative relationships, while Jiangsu, Guangdong, Anhui, Hunan, Zhejiang and Chongqing have relatively strong cross-regional collaborative relationships. Third, the bilateral synergy between industries and universities is more potent. Beijing, Guangdong, Shandong, Sichuan, Shanghai, Zhejiang, Heilongjiang, Guangxi and Xinjiang have strong three-dimensional collaborative relationships and are in the deep integration of IUR.

5.2 Recommendations

Collaboration platforms in low-carbon innovation between universities and research institutions should be strengthened to promote cutting-edge science and integrate core technology. Such platforms can build a full-chain system ranging from research and development technological innovation to industrialization, accelerating basic theoretical research in low-carbon technologies. More inter-regional IUR cooperation centers should be established by enabling policy to achieve technology transfer through transformation funds and talent cultivation. The industry should lead IUR's innovation network in low-carbon technology through market mechanisms, for example, by organizing industry-university research joint conferences and establishing information-sharing mechanisms.

References

Atta-Owusu, K., Fitjar, R.D. and Rodríguez-Pose, A. (2021), "What drives university-industry collaboration? Research excellence or firm collaboration strategy?", *Technological Forecasting and Social Change*, Vol. 173, p. 121084.

David, J.R., Duane, I. and Charles, C. (2007), "Strategic. Entrepreneurship, collaborative, innovation and wealth creation", *Strategic Entrepreneurship Journal*, Vol. 1 Nos 3/4, pp. 371-385.

Etzkowitz, H. and Leydesdorff, L. (1995), "The triple helix of university-industry-government relations: a laboratory for knowledge-based economic development", *EASST Review*, Vol. 14 No. 1, pp. 14-19.

Fan, F., Yang, B. and Wang, S. (2023), "The convergence mechanism and spatial spillover effects of urban industry-university-research collaborative innovation performance in China", *Technology Analysis and Strategic Management*, pp. 1-17.

Fujii, H. and Managi, S. (2016), "Research and development strategy for environmental technology in Japan: a comparative study of the private and public sectors", *Technological Forecasting and Social Change*, Vol. 112, pp. 293-302.

Guo, Y., Bruno, G., Zhang, D. and Han, K. (2023), "Analysis of low-carbon technology innovation efficiency and its influencing factors based on triple helix theory: evidence from new energy enterprises in China", *Heliyon*, Vol. 9 No. 10, p. e20308.

Hernández-Trasobares, A. and Murillo-Luna, J L. (2020), "The effect of triple helix cooperation on business innovation: the case of Spain", *Technological Forecasting and Social Change*, Vol. 161, p. 120296.

Hou, X., Gao, X., Yin, S. and Li, J. (2023), "A three evolutionary game model for driving mechanism of industry-university-research collaborative innovation in agricultural innovation ecosystems", *PloS One*, Vol. 18 No. 8, p. 0289408.

Jia, F. and Wang, D. D (2023), "Research on innovation decisions in industry-university-research cooperation based on differential games", *Technology Analysis and Strategic Management*, pp. 1-20.

Kamarkar, U. (1996), "Integrative research in marketing and operations management", *Journal of Marketing Research*, Vol. 33 No. 2, pp. 125-133.

Leydesdorff, L. and Ivanova, I.A. (2013), "Mutual redundancies in inter-human communication systems: steps towards a calculus of processing meaning", *Journal of the American Society for Information Science and Technology.*

Li, W. and Zheng, X. (2024), "Development mechanism and technological innovation of hydrogen energy: evaluating collaborative innovation based on hydrogen patent data", *International Journal of Hydrogen Energy*, Vol. 52, pp. 415-427.

Mêgnigbêto, E. (2014), "Efficiency, unused capacity and transmission power as indicators of the triple helix of university industry government relationships", *Journal of Informetrics*, Vol. 8 No. 1, pp. 284-294.

Mêgnigbêto, E. (2018), "Modelling the triple helix of university-industry-government relationships with game theory: core, Shapley value and nucleolus as indicators of synergy within an innovation system", *Journal of Informetrics*, Vol. 12 No. 4, pp. 1118-1132.

Moaniba, L.M., Su, H. and Lee, P. (2019), “On the drivers of innovation: does the co-evolution of technological diversification and international collaboration matter?”, *Technological Forecasting and Social Change*, Vol. 148, p. 119710.

Murillo-Luna, J.L. and Hernández-Trasobares, A. (2023), “Cooperation with the triple helix and corporate environmental innovation”, *Journal of Cleaner Production*, Vol. 384, p. 135479.

Pan, A., Zhang, W.N., Shi, X.P. and Dai, L. (2022), “Climate policy and low-carbon innovation: evidence from low-carbon city pilots in China”, *Energy Economics*, Vol. 112, p. 106129.

Pan, X. and Guo, S. (2023), “Dynamic decomposition and regional differences of urban emergy ecological footprint in the Yangtze river Delta”, *Journal of Environmental Management*, Vol. 326, p. 116698.

Pan, X., Li, J., Shen, Z. and Song, M. (2023a), “Life cycle identification of China’s regional innovation systems based on entropy weight disturbing attribute model”, *Habitat International*, Vol. 131, p. 102725.

Pan, X., Wang, Y., Tian, M., Feng, S. and Ai, B. (2023b), “Spatio-temporal impulse effect of foreign direct investment on intra-and inter-regional carbon emissions”, *Energy*, Vol. 262, p. 125438.

Pan, X., Wang, Y., Zhang, C., Shen, Z. and Song, M. (2023c), “The impact of platform economy on enterprise value mediated by technological innovation”, *Journal of Business Research*, Vol. 165, p. 114051.

Peter, G. (2006), “Swarm creativity: competitive advantage through collaborative innovation network”, *Innovation: Organization and Management*, Vol. 8 No. 4.

Santoro, M. and Chakrabarti, A. (2002), “Firm size and technology centrality in industry-university interactions”, *Research Policy*, Vol. 31 No. 7, pp. 1163-1180.

Schartinger, D., Rammer, C., Fischer, M. and Fröhlich, J. (2002), “Knowledge interactions between universities and industry in Austria: sectoral patterns and determinants”, *Research Policy*, Vol. 31 No. 3, pp. 303-328.

Shannon, C.E.A. (1948), “Mathematical theory of communication”, *Bell System Technical Journal*, Vol. 27 No. 4, pp. 623-656.

Song, Y., Berger, R., Rachamim, M., Johnston, A. and Fronzetti Colladon, A. (2022), “Modeling the industry perspective of university-industry collaborative innovation alliances: player behavior and stability issues”, *International Journal of Engineering Business Management*, Vol. 14, p. 18479790221097235.

Song, Y., Zhang, J., Song, Y., Fan, X., Zhu, Y. and Zhang, C. (2020), “Can industry-university-research collaborative innovation efficiency reduce carbon emissions?”, *Technological Forecasting and Social Change*, Vol. 157, p. 120094.

Wang, X., Qiu, L., Hu, F. and Hu, H. (2024), “Characteristics and influencing factors of the industry-university-research collaborative innovation network in China’s new energy vehicle industry”, *Energy Strategy Reviews*, Vol. 55, p. 101505.

Xiao, H., Cui, X., Sarker, M.N.I. and Firdaus, R.B.R. (2023), “Impact of industry-university-research collaboration and convergence on economic development: evidence from Chengdu Chongqing economic circle in China”, *Heliyon*, Vol. 9 No. 11, p. e21082.

Yan, W., Liu, H. and Han, B. (2023), “Industry–university–research knowledge flow in energy subjects: evolution of network structure in collaborative photovoltaic innovations”, *Frontiers in Energy Research*, Vol. 11, p. 1198998.

Zeng, J., Ning, Z., Lassala, C. and Ribeiro-Navarrete, S. (2023), “Effect of innovative-city pilot policy on industry-university-research collaborative innovation”, *Journal of Business Research*, Vol. 162, p. 113867.

Zhang, S., Wang, X. and Zhang, B. (2022), “The policy effects of innovative city pilot on the dual efficiency of industry–university–research knowledge flow”, *Technology Analysis and Strategic Management*, Vol. 34 No. 9, p. 1942446.

Zhang, Y., Chen, K. and Fu, X. (2019), "Scientific effects of triple helix interactions among research institutes, industries and universities", *Technovation*, Vols 86/87, pp. 33-47.

Zhang, Y., Chen, K., Zhu, G., Yam, R.C.M. and Guan, J. (2016), "Inter-organizational scientific collaborations and policy effects: an ego-network evolutionary perspective of the Chinese academy of sciences", *Scientometrics*, Vol. 108 No. 3, pp. 1383-1415.

Further reading

Alpkan, L. and Gemici, E. (2023), "The relation between high-performance work systems and product innovativeness: the mediating role of technological capabilities and the moderating role of university-industry collaboration", *Journal of Engineering and Technology Management*, Vol. 67, p. 101735.

Bai, X., Li, Z. and Zeng, J. (2020), "Performance evaluation of China's innovation during the industry-university-research collaboration process—an analysis basis on the dynamic network slacks-based measurement model", *Technology in Society*, Vol. 62, p. 101310.

Cai, Y. (2023), "Towards a new model of EU-China innovation cooperation: bridging missing links between international university collaboration and international industry collaboration", *Technovation*, Vol. 119, p. 102553.

Chen, Z., Zhang, Y., Wang, H., Ouyang, X. and Xie, Y. (2022), "Can green credit policy promote low-carbon technology innovation?", *Journal of Cleaner Production*, Vol. 359, p. 132061.

Evans, N., Miklosik, A. and Du, J.T. (2023), "University-industry collaboration as a driver of digital transformation: types, benefits and enablers", *Heliyon*, Vol. 9 No. 10, p. e21017.

Martínez-Ardila, H., Castro-Rodriguez, A. and Camacho-Pico, J. (2023), "Examining the impact of university-industry collaborations on spin-off creation: evidence from joint patents", *Heliyon*, Vol. 9 No. 9, p. e19533.

Xu, A., Qiu, K. and Zhu, Y. (2023), "The measurements and decomposition of innovation inequality: based on Industry-University-Research perspective", *Journal of Business Research*, Vol. 157, p. 113556.

Zhou, C., Huang, Y., Hu, S. and Huang, Z. (2023), "Government participation in low-carbon technology transfer: an evolutionary game study", *Technological Forecasting and Social Change*, Vol. 188, p. 122320.

Corresponding author
Tianchong Wang can be contacted at: wtianchong@126.com