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Multiple Pathways of Regional Innovation Ecosystem on Innovation Efficiency: An fsQCA Analysis

Juan Ouyang[a], Kaiyi Tang[a,*], Yi Su[b], Jiangfeng Ye[c]

[a] Business School, Yunnan University of Finance and Economics, Kunming 650221, China
[b] School of Economics and Management, Harbin Engineering University, Harbin 150001, China
[c] School of Business, Anhui University, Hefei 230601, China

Abstract

Enhancing regional innovation efficiency is of great significance for accelerating regional high-quality development and building an innovative country. Based on the perspective of innovation ecosystem, this study constructs a regional innovation ecosystem analytical framework by integrating six key regional innovation ecosystem elements from three aspects: innovation actor, innovation resource, and innovation environment. Using a sample of 30 provinces in China and adopting methods such as NCA and fsQCA, this paper analyzes the multiple pathways of regional innovation ecosystem on regional innovation efficiency in two stages from a configurational perspective. The study results in several findings. Firstly, a single element of the regional innovation ecosystem does not constitute the necessary condition either for high R&D efficiency or for high commercialization efficiency, though high innovation-actor-link generally plays a universal role in achieving high R&D efficiency. Secondly, there are three pathways to achieve high R&D efficiency and five pathways to achieve high commercialization efficiency. Great differences exist between these two types of regional innovation efficiency pathways: strong innovation-actor-link plays a more crucial role in achieving high R&D efficiency, while favorable innovation-supportive-environment is more important for achieving high commercialization efficiency. Besides, the distribution of the cases with high R&D efficiency exhibits distinct spatial distribution characteristic. Thirdly, based on the intersection operation of the two types of high innovation efficiency configurations, we find that three pathways can achieve both high R&D efficiencies and high commercialization efficiencies. Among the 6 typical cases, 4 provinces are in eastern China. Finally, based on further discussion and analysis, three meaningful research propositions for future exploration are proposed. Overall, this work refines the theoretical analysis framework of regional innovation ecosystem and deepens the analysis of the complex causal relationship between regional innovation ecosystem and innovation efficiency, and provides policy implications for regions to improve innovation efficiency from the perspective of innovation ecosystem.

Keywords

Regional innovation ecosystem; Innovation efficiency; Configurational perspective; Fuzzy-set qualitative comparative analysis

* Corresponding author. E-mail address: tangkaiyi@ynufe.edu.cn

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1. Introduction

Innovation is the primary driving force for development in countries around the world, and it is essential to maintain the core position of innovation in the process of national modernization. With the rapid development of digital and intelligent technologies, enhancing innovation efficiency through the construction of regional innovation ecosystem has become a significant approach for countries to improve overall innovation capabilities and build a globally competitive innovation ecology (Fernandes *et al*., 2021 ; Hu *et al*., 2023). Concerning the factors affecting regional innovation efficiency, existing research has conducted numerous analyses from the perspectives of innovation actors (Bai, 2013 ; Jiao *et al*., 2016), the innovation environment (Min *et al*., 2020 ; Wang *et al*., 2016), and regional innovation systems (Lau and Lo, 2015 ; Chen and Kou, 2014 ; Su and Chen, 2015). However, due to the complexity and uncertainty inherent in regional innovation activities, various factors interact with and influence each other in the process of driving regional innovation, resulting in inconsistencies in the research findings presented in the existing literature (Lecluyse *et al*., 2019 ; Beynon *et al*., 2024). Innovation often involves the recombination and collaborative synergy of multiple elements (Kaplan and Vakili, 2015 ; Shi *et al*., 2023), thus, it is necessary to further explain the enhancement of regional innovation efficiency from the perspective of the overall innovation ecosystem.

The innovation ecosystem aims to realize value co-creation among innovation actors, and emphasizes the self-organization of the innovation process and the collaborative interaction between actors and the external environment (Jacobides *et al*., 2018 ; Adner, 2017). Especially with the rapid development of big data elements and intelligent technologies like artificial intelligence, blockchain, and cloud computing, innovation ecosystem management has become a new paradigm in innovation management research (Bacon *et al*., 2020 ; Beltagui *et al*., 2020). Based on the innovation ecosystem perspective, scholars have used regression analysis to explore the impact of regional innovation ecosystem on innovation performance from the dimensions such as system structure (Doloreux and Gomez, 2017), system fitness (Xie *et al*., 2023), and symbiosis (Lecluyse *et al*., 2019). However, it is difficult to comprehensively investigate the effects of regional innovation ecosystem from the perspective of reductionism (Xie and Wang, 2020). Due to the limitations of traditional regression analysis in discussing complex issues such as the concurrent and substitutive complementarity of multiple elements (Fiss, 2011 ; Du and Kim, 2021), scholars have begun to introduce qualitative comparative analysis methods based on configurational perspectives to explore the synergistic mechanisms of regional innovation ecosystem in affecting innovation performance (Xie and Wang, 2020 ; Xie *et al*., 2021). These provides important reference for exploring the complex mechanism of regional innovation ecosystem on innovation efficiency.

Previous research is largely conducted from the perspective of "trichotomy" elements, constructing an analytical framework for regional innovation ecosystem from the aspects of innovation actors, innovation resources, and the innovation environment (Doloreux and Gomez, 2017 ; Xu and Yu, 2023). This lays the foundation for analyzing the structure of regional innovation ecosystem. However, there is still a lack of further in-depth exploration of these trichotomy elements, in terms of innovation actors. Previous studies have mainly investigated the scale of innovation actors which reflects the richness of entity nodes and their impact on regional innovation, while neglecting the significant role of connections between innovation actors in promoting the enhancement of regional innovation efficiency (Bai, 2013). Regarding innovation resources, previous research has focused on the impact of fundamental innovation resources such as R&D personnel, R&D funding, and physical resources, while paying relatively less attention to the impact of digital resources on regional innovation in the context of rapid digital technology development

(Zhang *et al.*, 2020). As for the innovation environment, existing studies have mainly explored the impact of supportive environmental elements such as economic development, labor quality, and market environment, while insufficient discussion has been conducted about the impact of the innovation agglomeration environment on regional innovation efficiency (Gkypali *et al.*, 2016). Meanwhile, previous research primarily discussed the impact of regional innovation ecosystem on innovation activities from the perspective of innovation outputs (Lau and Lo, 2015 ; Xu and Yu, 2023 ; Zhang *et al.*, 2020), or the overall innovation efficiency (Min *et al.*, 2020). However, the differences in the impact of regional innovation ecosystem on regional innovation efficiency during different innovation stages, such as technological R&D and commercial transformation, were overlooked.

In view of this, based on the innovation ecosystem perspective, this paper constructs a theoretical analysis framework by integrating six key regional innovation ecosystem elements and two types of innovation efficiency. Using a sample of 30 provinces in China and combining NCA and fsQCA methods, the paper analyzes the complex causal relationships between regional innovation ecosystem and innovation efficiency. The similarities and differences between the pathways of high R&D efficiency (RE) and high commercialization efficiency (CE) are revealed, and the pathways to achieving both high RE and CE are investigated. The main contributions of this paper are: (1) Based on the "innovation actor-innovation resource-innovation environment" trichotomy framework of the innovation ecosystem theory, the paper constructs an analytical framework for regional innovation ecosystem from six aspects: innovation-actor-scale, innovation-actor-link, innovation-basic-resource, digital resource, innovation-supportive-environment, and innovation-agglomeration-environment. Using R&D efficiency and commercialization efficiency as outcome variables, the paper examines the complex relationship between regional innovation ecosystem and innovation efficiency with a finer granularity (Liang and Ma, 2024). (2) Based on the analysis of necessity causality and sufficient causality, the paper investigates the multiple pathways of regional innovation ecosystem driving innovation efficiency from a configurational perspective, deepening the explanation of the complex mechanisms for enhancing regional innovation efficiency as provided by innovation ecosystem theory (Fernandes *et al.*, 2021). (3) Based on a configurational perspective and set theory, the paper analyzes the possible pathways for enhancing regional innovation efficiency from the aspects of innovation actors, innovation resources, and the innovation environments, including single-dominant, dual-linkage, and system-synergy type, as well as examining the pathways to achieving both high R&D and commercialization efficiencies based on the intersection operations of the two types of high innovation efficiency configurations, which enriches the research on the complex systemic problem of enhancing regional innovation efficiency (Min *et al.*, 2020).

2. Literature Review

2.1. Innovation ecosystem theory

The concept of innovation ecosystem was first derived from the “Innovate America” report released by the American President’s Council of Advisors on Science and Technology in 2004, which refers to a dynamic system formed by the interaction of organizations and individuals. Adner (2006) combining ecosystem theory with technological innovation, proposed that the innovation ecosystem is a synergistic mechanism that connects enterprises with other actors, and from the perspective of “innovation ecosystem strategy”, Adner and Kapoor (2010) further pointed out that a company's innovation success is closely related to the participation and efforts of other members in the environment. From the systems theory perspective, Jackson (2011) defined the innovation ecosystem as the complex relationships formed between participants or entities with the functional goal of technology development and innovation. The innovation ecosystem not only focuses on the complexity and dynamics of innovation activities, but also pays attention to the dynamic evolution and ecological nature of the system (Kapoor and Lee, 2013 ; Schroth and Haussermann, 2018), ultimately achieving value co-creation through symbiotic and coexisting innovation collaboration (Chae, 2019 ; Katz and Ronda-Pupo, 2019).

Aimed at their common goals, innovation actors in the innovation ecosystem synergistically integrate innovation resources within the ecosystem, and in an environment that promotes the realization of innovation, thereby ultimately foster value co-creation and maximize system effectiveness through complementary synergies among elements (Adner, 2017 ; Jacobides *et al*., 2018). Regarding the components of the innovation ecosystem, many scholars summarized it into three aspects: actors, resources, and environment, and based on the analytical framework of "innovation actors-innovation resources-innovation environment" to conduct related research on the construction (Tsai and Chang, 2016), evaluation (Xie *et al*., 2023), and synergy mechanisms (Xu and Yu, 2023) of the innovation ecosystem.

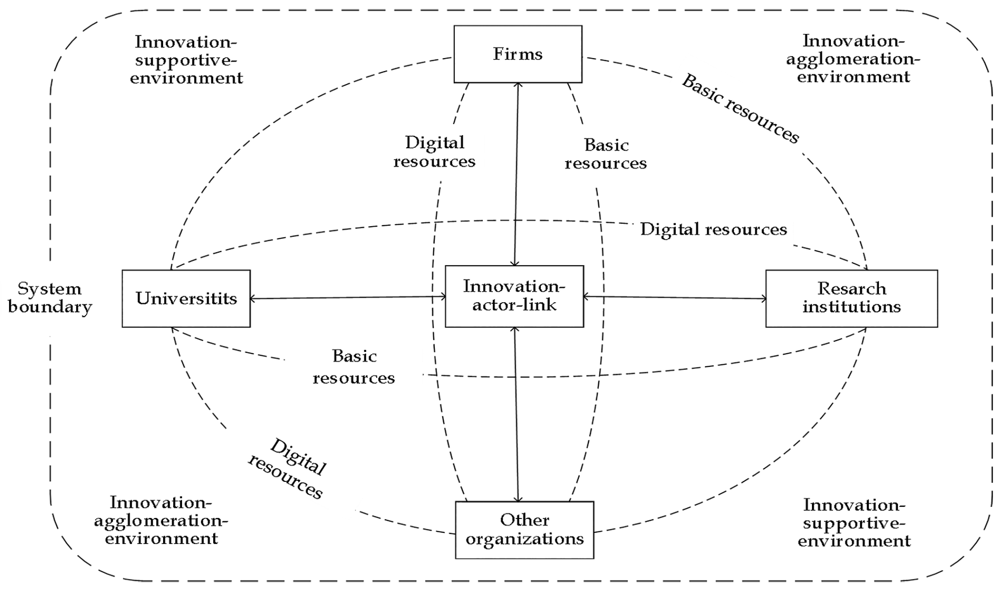
2.2. The connotation and structure of regional innovation ecosystem

Regional innovation ecosystem understands and analyzes regional innovation activities and processes from an ecological perspective, with its research originated from the study of the regional innovation system proposed by Cooke (1992), which emphasizes the interaction between actors within the system, and between actors and the environment (Xu *et al*., 2018 ; Doloreux, 2002). The innovation ecosystem perspective emphasizes the symbiotic coexistence of diverse innovation elements, the self-organizing growth of innovation actors, and the dynamic evolution between actors and their environment (Kapoor and Lee, 2013), which aligns closely with the characteristics of regional innovation, thus sparking research into regional innovation ecosystem (Doloreux and Gomez, 2017 ; Fernandes *et al*., 2021). For example, Rong *et al* (2021) empirically explore a 4C framework of regional innovation ecosystem through case studies, including the construct, cooperation, configuration, and capability of an RIE; Xu and Yu (2023) analyze the causal configurations of regional innovation ecosystem elements that drive regional innovation development by fsQCA; and Liang and Ma (2023) explore the pathways to realize patent commercialization based on the regional innovation ecosystem theory.

Concerning the structure of regional innovation ecosystem, a unified view has not yet been established due to different research perspectives. From the perspective of elements composition, the system structure analysis is generally carried out from three aspects: innovation actors, innovation resources, and innovation environment (Xie *et al*., 2023), or further incorporating the role of innovation carriers and the government (Xu and Yu, 2023). From a symbiosis perspective, the structure of the regional innovation ecosystem can be deconstructed into symbiotic model, symbiotic unit, and symbiotic environment (Li, 2009), or further considering the role of symbiotic platforms and symbiotic network (Su *et al*., 2024). From a process perspective, the regional innovation ecosystem is viewed as a dynamically equilibrium system that is achieved through the interaction of subsystems such as research, development, and application with various supportive subsystems (Estrin, 2009).

Based on different perspectives and dimensions, the structure of regional innovation ecosystem can be seen as a multi-dimensional structure. We started from the mainstream "actor-resource-environment" trichotomy view of the innovation ecosystem (Doloreux and Gomez, 2017 ; Xu and Yu, 2023), combining the connotations and characteristics of the systems perspective, that is, paying attention to the composition of elements within the system and the interconnections among elements (Schad and Bansal, 2018), to construct the framework of regional innovation ecosystem. Specifically, for innovation actors, the analysis is conducted from two aspects: the scale of innovation actors, which reflects the composition of the number of actors, and the linkages between innovation actors, which reflect the strength of connections among actors (Chen *et al*., 2022). For innovation resources, not only are the traditional innovation basic resources considered for their impact on regional innovation activities, but also the important role of digital resources in the digital age is taken into account, which accelerates the dissemination and sharing of resources and enhances the collaborative cooperation among innovation actors (Teece, 2018). For the innovation environment, while considering the impact of the basic innovation supporting environment on regional innovation activities, attention is also paid to the innovation agglomeration environment's role in promoting the formation of common value propositions and achieving value co-creation among innovation actors (Hu *et al*., 2023).

Therefore, based on the innovation ecosystem perspective, we define the regional innovation ecosystem as a complex system within a certain spatio-temporal range, where innovation actors and the external environment are interdependent and interconnected based on the flow and exchange of innovation resources, various elements and the connection between the elements jointly promote the development of the ecosystem. From the perspective of "trichotomy" innovation ecosystem, we construct the regional innovation ecosystem framework by integrating six key elements, namely, innovation-actor-scale, innovation-actor-link, innovation-basic-resource, digital resource, innovation-supportive-environment, and innovation-agglomeration-environment. The innovation actors interact with and collaborate with each other in response to the flow of innovation basic resources and digital resources, forming a strong innovation-actor-link. The government creates a favorable innovation-supportive-environment and innovation-agglomeration-environment aims to promote the development of innovation actors, ultimately forming a cooperative, symbiotic, and dynamically evolving complex system. The structural model of the regional innovation ecosystem is shown in Fig. 1.



Note: The outermost long-dashed line represents the spatio-temporal boundaries of the ecosystem, the short-dashed lines between actors represent the flow of innovation resources among the innovation actors, the bidirectional arrows between actors and the innovation-actor-link represent cooperation and collaboration among the innovation actors.

Fig.1. The structure model of regional innovation ecosystem.

2.3. Regional innovation ecosystem elements and innovation efficiency

2.3.1. Innovation actors and innovation efficiency

(1) Innovation-actor-scale (IAS) and innovation efficiency. The scale of innovation actors refers to the number of individuals and populations promoting the development and application of new technologies as well as the production and dissemination of knowledge (Jiao *et al*., 2016). Firms, universities, and research institutions play a significant role in enhancing regional innovation efficiency (Min *et al*., 2020), and large scale of innovation actors improve the practices of the knowledge combination and recombination (Martins and Singh, 2023). Some studies pointed out that, in the early stage of development, the larger the scale of innovation actors, the more beneficial it is for regional performance improvement. However, when the scale exceeds the regional capacity, it may inhibit the creation of new knowledge, which is not conducive to the improvement of performance. In other words, there exists a reasonable range for the scale of innovation actors (Lechner and Leyronas, 2007).

(2) Innovation-actor-link (IAL) and innovation efficiency. Linkages between innovation actors facilitate the flow and exchange of resources, information, and knowledge among nodes (Su *et al*., 2021), and represent the sum of the relationships and linkages among which actors interact with each other (Noni *et al*., 2018 ; Chen *et al*., 2022). These connections can significantly enhance regional innovation capacity and have a substantial positive impact on improving innovation efficiency (Bai, 2013 ; Guan *et al*., 2016). Interactions between firms, universities, and research institutions are effective in enhancing regional innovation efficiency (Jiao *et al*., 2016), mutualism relationships are established between universities and other eco-system actors in the regional innovation ecosystem (Schaeffer *et al*., 2021). However, some studies suggested that the positive impact of linkages between innovation actors on regional innovation efficiency is not significant (Bai and Li, 2011), mainly because the current regional innovation networks still face issues such as weak link density, suboptimal connections, and lagging relationship intensity.

2.3.2. Innovation resources and innovation efficiency

(1) Innovation-basic-resource (IBR) and innovation efficiency. Innovation basic resource refers to various types of resources invested to support innovation activities, such as human, financial, and material resources (Zhang *et al*., 2020). The aggregation and flow of innovation resource elements such as R&D personnel and capital significantly promote regional innovation efficiency (Bai, 2013). R&D personnel effectively promote the absorption and transformation of knowledge and the transfer and diffusion of technology in the regional innovation ecosystem (Asheim *et al*., 2011), and talent competitiveness has become the crucial indicator to measure the innovation development of countries and regions (Huang *et al*., 2023).

(2) Digital resource (DR) and innovation efficiency. Digital resources reflect a region's capabilities in digital access, construction, and application (Constantinides *et al*., 2018 ; Henfridsson and Bygstad, 2013). Abundant digital resources help innovation actors reduce various transaction costs such as assessment, decision-making, and regulation, and facilitate the efficient integration and cost-sharing of digital infrastructure (Czernich *et al*., 2011), thereby improving the efficiency of innovative production. Research shows that digital technology significantly promotes regional innovation efficiency by leveraging the effects of human capital accumulation, knowledge spillover, and optimization of innovation element allocation (Lyytinen *et al*., 2016). Besides, it is important to balance the issues of insufficient and excessive

investment in digital resources, given that excessive levels of digital resources beyond a moderate scale could be detrimental to regional innovation improvement.

2.3.3. Innovation environment and innovation efficiency

(1) Innovation-supportive-environment (ISE) and innovation efficiency. The innovation supportive environment mainly reflects the regional socio-economic and cultural development environment, encompassing elements such as economic level, workforce quality, cultural atmosphere, and market environment (Wang *et al*., 2016 ; Audretsch and Belitski, 2017). A favorable innovation supportive environment can guide the direction of innovation and facilitate the generation and transformation of innovative outcomes, thus enhancing regional innovation efficiency (Bai, 2013). Regional economic infrastructure, openness, and workforce quality all have significant positive impacts on regional innovation efficiency (Wang *et al*., 2016).

(2) Innovation-agglomeration-environment (IAE) and innovation efficiency. The innovation agglomeration environment reflects the aggregation level of spaces, places, and channels that facilitate material, information, and energy transmission as well as communication and collaboration among innovation actors (Liu *et al*., 2017 ; Wang *et al*., 2016). Important carriers of the innovation agglomeration environment include national high-tech zones, national university science parks, and national characteristic industrial bases. Empirical research shows that science parks have a significant positive impact on the innovation efficiency of the located regions (Gkypali *et al*., 2016), the cooperation among innovation entities in science parks is the main reason for the success of creating and developing the innovation ecosystem (Germain *et al*., 2023).

In summary, both the six regional innovation ecosystem elements have an important impact on regional innovation efficiency, but there is no consensus on the relationship between each element and regional innovation efficiency, and the impact of individual elements on different types of innovation efficiency are variable. Traditional regression analysis, which based on reductionism, focuses on the net effect of individual elements on regional innovation efficiency, making it difficult to deeply analyze the impact of the synergistic interactions among three or more innovation elements on innovation efficiency, which limits the explanatory power of innovation ecosystem theory on regional innovation. Therefore, it is necessary to introduce a new perspective to explore the complex causal mechanisms of regional innovation ecosystem synergistically driving innovation efficiency.

2.4. Theoretical model of regional innovation ecosystem on innovation efficiency from a configurational perspective

The configurational perspective is based on systemic and holistic analysis, focusing on the impact of the combination of multiple elements on the outcome (Fiss, 2011), which has been widely applied to studying complex management issues, such as innovation ecosystem (Xie and Wang, 2020), entrepreneurial ecosystem (Douglas *et al*., 2020), and business environment ecologies (Li *et al*., 2023). This helps to explain multiple concurrent causes and the interactive relationship between elements in the process of regional innovation ecosystem driving innovation efficiency. We analyze the possible pathways that a regional innovation ecosystem impacts on innovation efficiency by combining the configurational perspective with the interrelationships among three types of elements in the innovation ecosystem, including three main categories: single-dominant, dual-linkage, and system-synergy, as shown in Table 1.

Table 1
Possible pathways that regional innovation ecosystem impacts on innovation efficiency under the configurational perspective.

Pathways	Configuration types	Innovation actor	Innovation resource	Innovation environment	Theory logic
Single-dominant type	Innovation actor dominant type	1	0	0	The innovation-driven effect of innovation efficiency improvement is achieved by the dominant force of single-level elements of innovation actors, innovation resources, or innovation environment.
	Innovation resource dominant type	0	1	0	
	Innovation environment dominant type	0	0	1	
Dual-linkage type	Actor-resource linkage type	1	1	0	The innovation-driven effect of innovation efficiency improvement is achieved by the complementary effects of two dimensions among innovation actors, innovation resources, and innovation environment.
	Actor-environment linkage type	1	0	1	
	Resource-environment linkage type	0	1	1	
System-synergy type	Actor-resource-environment synergy Type	1	1	1	The innovation-driven effect of innovation efficiency improvement is achieved by the synergy effects of the three dimensions of innovation actors, innovation resources, and innovation environment.

Note: The number 0 represents the set where the condition at that dimension has no impact, and 1 represents the set where the condition at that dimension has an impact.

Firstly, from the perspective of single-dominant pathway, different regions may have varying emphases and inclinations in cultivating actors, allocating resources, and building environments. Although previous studies have confirmed that innovation actors, innovation resources, and innovation environments can all promote the improvement of regional innovation efficiency (Bai, 2013 ; Chen *et al*., 2018 ; Su and Chen, 2015), there are still significant differences in the richness of innovation actors, in resource endowments, and in the construction and optimization of environments among different regions. How to better leverage the innovation-driven effects of actors, resources, and environments according to local conditions and further promote the improvement of regional innovation efficiency remains to be further tested.

Secondly, from the perspective of dual-linkage pathway, there may exist different degrees of symbiosis and complementarity among actors, resources, and environments. A favorable innovation environment facilitates more efficient collaborative innovation and value co-creation among innovation actors (Corrocher *et al*., 2019 ; Han *et al*., 2021). Abundant innovation resources enhance the aggregation and connection among innovation actors (Pierrakis and Saridakis, 2019), and the borderless and reusable nature of data resources empower deeper and broader innovation cooperation among innovation actors (Lyytinen *et al*., 2016 ; Nambisan *et al*., 2017). Therefore, the mutual influence and interaction between dual elements may be an important mechanism for promoting the improvement of regional innovation efficiency.

Finally, from the perspective of system-synergy pathway, there may exist multiple synergistic pathways through which actors, resources, and environments jointly drive the improvement of innovation efficiency. Although previous research has integrated "trichotomy" elements to verify the significant promotion effect of the comprehensive level of regional innovation ecosystem on innovation efficiency, and has also explored the effectiveness of the traditional "actor-resource-environment" system equilibrium-driven path in the process of improving regional innovation performance (Xu and Yu, 2023), yet the mechanism of mutual influence and joint promotion on efficiency by new elements such as innovation-actor-link, digital resource, and innovation-agglomeration-environment is still unclear.

In summary, based on the perspective of innovation ecosystem, and focusing on the trichotomy view of "innovation actor - innovation resource - innovation environment", this paper integrates six regional innovation ecosystem elements, namely, innovation-actor-scale, innovation-actor-link, innovation-basic-resource, digital resource, innovation-supportive-environment, and innovation-agglomeration-environment as antecedent conditions. In addition, we pay attention to the synergistic interaction of these causal elements on the efficiency of different innovation processes, including technological research and development and commercial transformation, and takes R&D efficiency and commercialization efficiency as outcomes respectively. The configurational perspective is introduced to explore the multiple pathways of regional innovation ecosystem on innovation efficiency, the theoretical model is shown in Fig. 2.

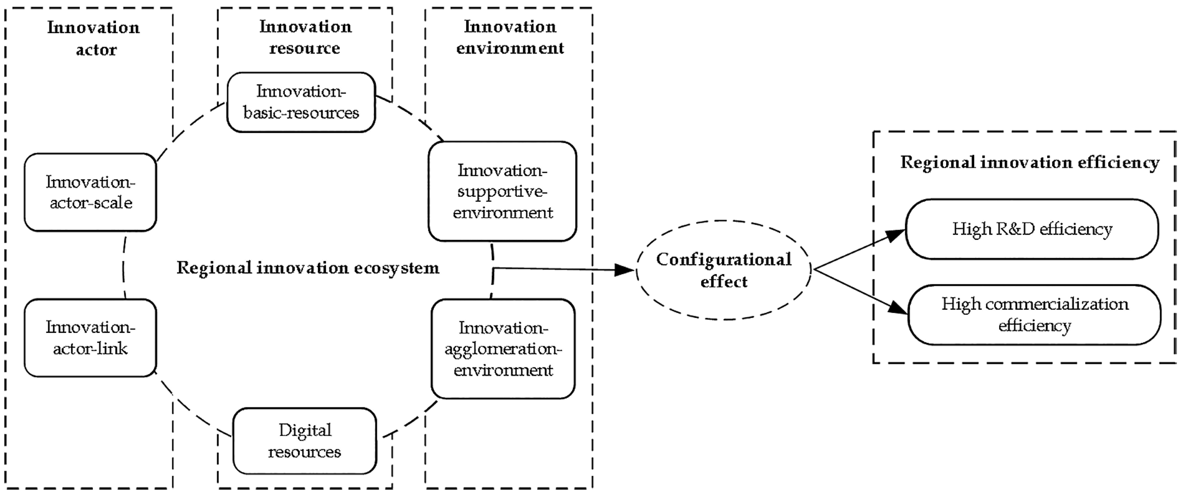


Fig. 2. Theoretical model that regional innovation ecosystem on innovation efficiency.

3. Data and Methodology

3.1. NCA and QCA methods

Necessary Condition Analysis (NCA) is a method specifically used to analyze necessary causal relationship, which not only qualitatively judges whether a certain condition is necessary to achieve an outcome from the category, but also quantitatively describes the level of conditions required to achieve a specific level of outcome from the degree (Dul, 2016 ; Dul *et al.*, 2020). We first use the NCA method to examine whether and at what level the six regional innovation ecosystem elements constitute a necessary condition for high RE or high CE, and then further verify the robustness of the NCA results through fsQCA single condition necessity tests.

Qualitative Comparative Analysis (QCA) uses Boolean algebra and set relations to achieve thoroughly comparison and analysis of the cases, aiming to explore the configurational effects of multiple antecedent conditions that are interdependent and interactive on the outcome. It can effectively analyze complex management problems such as concurrency conditions, equivalent pathways, and asymmetric relationships (Fiss, 2011), which are essential for discussing the multiple pathways of regional innovation ecosystem on innovation efficiency. Considering that both the conditions and outcomes concerned in this paper are continuous variables, fuzzy-set qualitative comparative analysis (fsQCA) is used to analyze the complex causal relationships between regional innovation ecosystem and R&D efficiency, as well as commercialization efficiency.

3.2. Data collection

The data mainly comes from the annual statistical yearbooks, such as *China Science and Technology Statistics Yearbook, China Statistical Yearbook, China Torch Statistics Yearbook, China Social Statistics Yearbook, China Foreign Economic Trade Statistics Yearbook, and China Population and Employment Statistics Yearbook, etc*. To ensure consistency in statistical calibers, the data range of all indicators is set from 2009 to 2020. Due to the obvious data gaps in Hong Kong and Macao Special Administrative Regions, Taiwan Province, and Tibet Autonomous Region, this paper takes 30 provinces in China as case samples.

To objectively and accurately evaluate the innovation level of each province, we use global principal component analysis (GPCA) and stochastic frontier analysis (SFA) to measure the innovation ecosystem elements level and innovation efficiency level of 30 provinces from 2009 to 2019. Based on this, the average value of the latest three years of data is used for NCA and QCA analysis to investigate the recent development characteristics of the regional innovation efficiency improvement pathways, and to avoid the impact of provincial data outliers in a given year (Zhang *et al*., 2020). Furthermore, considering the lag effect of regional innovation ecosystem on innovation efficiency, the lag period is set to one year. Finally, this paper selects the average value of the antecedent conditions from 2016 to 2018 and the average value of innovation efficiency from 2017 to 2019 for analysis.

3.3. Measurement

3.3.1. Outcome measurement

We categorize innovation efficiency into R&D efficiency (RE) and commercialization efficiency (CE) based on the different stages of innovation output (Chen and Kou, 2014). Innovation output includes technological innovation output and commercial transformation output, measured by the number of invention patent grants and new product sales revenue respectively (Zhang *et al*., 2020). Innovation input includes capital and personnel input, measured by internal expenditure on R&D funds and full-time equivalent of R&D personnel respectively (Sharma and Thomas, 2008). We set the lag period for input-output at one year (Zhang and Guan, 2018), selected the innovation input indicators from 2009 to 2019 and the innovation output indicators from 2010 to 2020, and used the SFA method (Su and Chen, 2015) to measure the R&D efficiency and commercialization efficiency of 30 province from 2009 to 2019 respectively, using Frontier 4.1 software.

3.3.2. Conditions measurement

Based on the integrative analytical framework of regional innovation ecosystem as analyzed before, the six innovation ecosystem elements, namely the 6 casual conditions in this paper, constitute the six first-level indicators that reflect the overall level of regional innovation ecosystem. We further refine the six first-level indicators into second-level indicators that can be measured, so as to construct the evaluation index system of regional innovation ecosystem. In the process of designing the evaluation index system, we followed the principles of scientifically, objectivity, systematically, independence, and operability, and refer to existing relevant studies, finally build the regional innovation ecosystem evaluation index system covering 6 first-level indicators and 29 second-level indicators, as shown in Table 2.

Table 2
The evaluation index system of regional innovation ecosystem.

First-level indicators	Second-level indicators	Indicator description	Reference
C1: Innovation-actor-scale	C11: Number of industrial enterprises above designated size (*Unit*)	Scale of enterprise clusters	Min *et al* (2020), Jiao *et al* (2016)
	C12: Number of research institutions (*Unit*)	Scale of research institution clusters	
	C13: Number of full-time teachers in higher education institutions (*Person*)	Scale of higher education clusters	
C2: Innovation-actor-link	C21: Transaction value in technical markets (*Ten thousand yuan*)	Linkages between enterprises	Su *et al*. (2021), Jiao *et al*. (2016)
	C22: Intramural expenditure on R&D of industrial enterprises above designated size that from government funds (*Ten thousand yuan*)	Linkages between enterprise and government	
	C23: External expenditure on R&D of universities and research institutions to other research institutions and universities (*Ten thousand yuan*)	Linkages between universities and research institutions	
	C24: Intramural expenditure on R&D of universities and research institutions that from enterprises funds (*Ten thousand yuan*)	Linkages among universities, research institutions and enterprises	
	C25: Intramural expenditure on R&D of universities and research institutions that from government funds (*Ten thousand yuan*)	Linkages among universities, research institutions and government	
C3: Innovation-basic-resource	C31: Full-Time equivalent of R&D personnel (*Man-year*)	Allocation of human resource	Zhang *et al*. (2020), Bai (2013)
	C32: Intramural expenditure on R&D (*Ten thousand yuan*)	Allocation of financial resource	
	C33: Total social investment in fixed asset (*Hundred million yuan*)	Allocation of fixed asset investment	
	C34: Investment of registered enterprises with foreign capital (*Ten thousand dollars*)	Allocation of foreign investment	
	C35: Expenditure on science and technology in the general budget (*Ten thousand yuan*)	Allocation of government support fund	
C4: Digital resource	C41: Number of broadband subscriber port of Internet (*Ten thousand ports*)	Digital infrastructure resources subscribed	Constantinides *et al*. (2018), Henfridsson and Bygstad (2013)
	C42: Number of IPv4 addresses (*Ten thousand units*)	Digital infrastructure resources accessed	
	C43: Number of domain names (*Ten thousand units*)	Digital platform resources accessed	
	C44: Number of web pages (*Ten thousand pages*)	Digital service resources accessed	
	C45: Business volume of telecommunication services (*Hundred million yuan*)	Digital service resources accessed	

Table 2. (continued)

First-level indicators	Second-level indicators	Indicator description	Reference
C5: Innovation-supportive-environment	C51: Per capita gross regional product (*Yuan*)	Economic environment	Audretsch and Belitski (2017), Wang *et al*. (2016)
	C52: Average years of schooling of the population (*Year*)	Labor force quality	
	C53: Book collection volume of public libraries (*Ten thousand volumes*)	Cultural atmosphere	
	C54: Retail sales of consumer goods (*Hundred million yuan*)	Market environment	
	C55: International trade in goods (*Ten thousand dollars*)	Open environment	
	C56: Added value of the financial industry (*Hundred million yuan*)	Financial environment	
C6: Innovation-agglomeration-environment	C61: Number of national science and technology business incubators (*Unit*)	Agglomeration level of science and technology business incubators	Liu *et al*. (2017), Wang *et al*. (2016)
	C62: Average income of high-tech zones (*Thousand yuan/household*)	Agglomeration development level of high-tech zones	
	C63: Average income of characteristic industrial bases (*Thousand yuan/household*)	Agglomeration development level of characteristic industrial bases	
	C64: Average income of national productivity promotion centers (*Thousand yuan/household*)	Agglomeration development level of productivity promotion centers	
	C65: Average income of incubated enterprises in national university science parks (*Thousand yuan/household*)	Agglomeration development level of university science parks	

Based on the panel data of the 30 provinces from 2009 to 2019, we use the GPCA method to measure the development level of the 6 first-level indicators. First of all, the original data is standardized globally using SPSS 19.0 software, followed by a partial correlation KMO test (KMO value= 0.899 > 0.7) and Bartlett's test of sphericity (Significance value= 0.000 < 0.01) on the standardized data, indicating that the data is suitable for GPCA. Then, the first 4 principal components are selected based on eigenvalues greater than 1 and a cumulative variance contribution rate of 80% (cumulative contribution rate = 81.20%). Next, the component score coefficient matrix, second-level indicator weights, second-level indicator scores, and first-level indicator scores are calculated sequentially. Finally, the first-level indicator scores are standardized to the [0,1] interval to obtain the development index of the 6 first-level indicators, namely the levels of each causal condition.

3.4. Calibration

Since there is still no clear theory or external standard as the calibration anchor, we use the direct calibration method to transform the original data into fuzzy set membership scores, and coded the data into fuzzy set based on the descriptive statistics of the cases (Du and Kim, 2021). Referring to previous research (Fiss, 2011), we set the calibration anchors for full membership, cross-over, and full non-membership of the causal conditions and outcomes at the upper quartile (75%), median, and lower quartile (25%) of the sample descriptive statistics, respectively. For the set with a calibrated membership score exactly equal to 0.5, we added a constant of 0.001 for all membership score less than 1(Fiss, 2011), to avoid cases that are difficult to classify and have not been analyzed. The calibration for non-high R&D efficiency and non-high commercialization efficiency is the non-set of high R&D efficiency and high commercialization efficiency. The calibration and descriptive statistics of casual conditions and outcomes are shown in Table 3.

Table 3
Set, calibration and descriptive statistics.

Set		Fuzzy set calibration			Descriptive statistics			
		Fully in	Crossover	Fully out	Mean	SD	Min	Max
Outcomes	R&D efficiency (RE)	0.633	0.577	0.473	0.569	0.142	0.279	0.850
	Commercialization efficiency (CE)	0.791	0.681	0.308	0.573	0.279	0.035	0.951
Innovation actor	Innovation-actor-scale (IAS)	0.511	0.413	0.242	0.415	0.245	0.009	0.988
	Innovation-actor-link (IAL)	0.135	0.050	0.022	0.111	0.157	0.003	0.816
Innovation resource	Innovation-basic-resource (IBR)	0.199	0.117	0.051	0.170	0.175	0.008	0.760
	Digital resource (DR)	0.226	0.091	0.053	0.164	0.176	0.008	0.803
Innovation environment	Innovation-supportive-environment (ISE)	0.383	0.279	0.209	0.343	0.209	0.093	0.876
	Innovation-agglomeration-environment (IAE)	0.210	0.121	0.087	0.181	0.179	0.013	0.879

4. Analysis and Results

4.1. Analysis of necessary conditions

First, the NCA method is used to test whether individual conditions constitute the necessary condition for the outcome. NCA provides two techniques, upper limit ceiling envelopment (CE) and upper limit ceiling regression (CR) for dealing with discrete and continuous variables respectively. Since both conditions and outcomes in this paper are continuous variables, we use the CR technique to generate the upper limit line (Dul, 2016). If the accuracy of the upper limit line is below 95%, the condition should not be considered as a necessary condition (Dul, 2016). The effect size range of the causal condition is [0,1], with larger values indicating greater importance, when the effect size is less than 0.1, the condition should not be considered as a necessary condition (Dul, 2016). To avoid the observed effect size being a result of random fluctuations, a Monte Carlo simulation permutation test is also used in the NCA analysis to examine the effect size; only when the effect size is significant ($p<0.05$), the condition can be considered as a necessary condition (Dul *et al.*, 2020).

Table 4 reports the NCA analysis results. For R&D efficiency, except for innovation-actor-link, the effect sizes of all other conditions are less than 0.1, indicating that they are not the necessary conditions for R&D efficiency. Although the effect size of innovation-actor-link reaches 0.119 with a significant p-value (0.000), however, its accuracy is 83.3%, which is below the general standard of 95%, thus, innovation-actor-link cannot be considered as a necessary condition for R&D efficiency. For commercialization efficiency, the effect sizes of innovation-actor-scale and innovation-agglomeration-environment are less than 0.1, indicating that they are not the necessary conditions for commercialization efficiency. Although the effect size of innovation-actor-link, innovation-basic-resource, digital resource, innovation-supportive-environment are all greater than 0.1, and the p-values are all significant, however, both of their accuracy is lower than 95%, so they can't be considered as a necessary condition for commercialization efficiency.

Table 4
Necessary condition analysis by NCA method.

Conditions ①	R&D efficiency					Commercialization efficiency				
	Accuracy/%	Upper zone	Scope	Effect size	Pvalue ②	Accuracy/%	Upper zone	Scope	Effect size	Pvalue ②
Innovation-actor-scale	86.7	0.060	0.999	0.060	0.004	100	0.010	0.989	0.010	0.127
Innovation-actor-link	83.3	0.118	0.990	0.119	0.000	86.7	0.173	0.980	0.177	0.000
Innovation-basic-resource	100	0.013	0.990	0.013	0.039	93.3	0.116	0.980	0.118	0.002
Digital resource	90.0	0.055	0.999	0.055	0.017	93.3	0.115	0.989	0.117	0.006
Innovation-supportive-environment	96.7	0.006	1.000	0.006	0.073	93.3	0.101	0.990	0.102	0.001
Innovation-agglomeration-environment	90.0	0.027	1.000	0.027	0.004	83.3	0.047	0.990	0.047	0.005

Note: ① The value of the condition is the membership value of the calibrated fuzzy set; ② In NCA, the permutation test (number of reshuffles = 10,000) is used.

Table 5 reports the bottleneck level analysis results for R&D efficiency and commercialization efficiency. The bottleneck level indicates the level of each antecedent condition (%), which needs to be met to achieve a certain level of outcome (%) (Dul *et al.*, 2020). For example, to achieve a 70% efficiency level, for R&D efficiency, an innovation-actor-scale level of 5.2%, an innovation-actor-link level of 9.6%, an innovation-basic-resources level of 2.2%, and a digital resource level of 8.9% are needed, there are no bottleneck levels for the innovation-supportive-environment and the innovation-agglomeration-environment, and for commercialization efficiency, levels of 1.4% for innovation-actor-scale, 28.2% for innovation-actor-link, 17.8% for innovation-basic-resources, 18.2% for digital resource, 17.1% for innovation-supportive-environment, and 7.3% for innovation-agglomeration-environment are needed.

Table 5
Bottleneck level analysis by NCA method ① .

Innovation efficiency	Innovation-actor-scale	Innovation-actor-link	Innovation-basic-resource	Digital resource	Innovation-supportive-environment	Innovation-agglomeration-environment
0	NN/NN ②	NN/NN	NN/NN	NN/NN	NN/NN	NN/NN
10	NN/0.2	NN/NN	NN/NN	NN/NN	NN/NN	NN/NN
20	NN/0.4	NN/NN	NN/2.4	NN/0.1	NN/NN	NN/0.2
30	NN/0.6	NN/3.2	NN/5.4	0.7/3.7	NN/NN	NN/1.6
40	NN/0.8	NN/9.4	0.3/8.5	2.7/7.4	NN/0.9	NN/3.0

Table 5. (continued)

Innovation efficiency	Innovation-actor-scale	Innovation-actor-link	Innovation-basic-resource	Digital resource	Innovation-supportive-environment	Innovation-agglomeration-environment
50	NN/1.0	NN/15.7	0.9/11.6	4.8/11.0	NN/6.3	NN/4.5
60	NN/1.2	NN/22	1.6/14.7	6.8/14.6	NN/11.7	NN/5.9
70	5.2/1.4	9.6/28.2	2.2/17.8	8.9/18.2	NN/17.1	NN/7.3
80	14.8/1.6	29.1/34.5	2.8/20.8	10.9/21.8	NN/22.4	NN/8.7
90	24.5/1.8	48.6/40.8	3.4/23.9	13.0/25.4	2.6/27.8	NN/10.2
100	34.2/2.0	68.1/47.1	4.0/27.0	15.0/29.0	6.9/33.2	57.9/11.6

Note: ① CR method; ② The left and right side of "/" represent the bottleneck level of R&D efficiency and commercialization efficiency respectively, and NN = not necessary.

The fsQCA method is further used to test the necessity of each condition, as shown in Table 6, the consistency levels of each causal conditions affecting high or non-high R&D efficiency as well as high or non-high commercialization efficiency are all below 0.9, which is consistent with the analysis results of the NCA method. That is, a single element of the regional innovation ecosystem does not constitute the necessary conditions for high R&D efficiency or high commercialization efficiency.

Table 6
Necessity tests of single conditions by fsQCA method.

Conditions	High RE		~ High RE		High CE		~ High CE	
	Consistency	Coverage	Consistency	Coverage	Consistency	Coverage	Consistency	Coverage
IAS	0.612	0.683	0.431	0.423	0.694	0.714	0.403	0.431
~IAS	0.483	0.491	0.677	0.605	0.447	0.419	0.732	0.713
IAL	0.707	0.752	0.377	0.353	0.740	0.726	0.376	0.383
~IAL	0.392	0.417	0.735	0.688	0.371	0.364	0.731	0.745
IBR	0.645	0.684	0.432	0.403	0.798	0.781	0.327	0.332
~IBR	0.437	0.467	0.661	0.621	0.317	0.312	0.784	0.801
DR	0.672	0.702	0.450	0.414	0.756	0.728	0.388	0.388
~DR	0.439	0.476	0.676	0.644	0.365	0.365	0.728	0.756
ISE	0.606	0.659	0.444	0.425	0.771	0.774	0.315	0.328
~ISE	0.472	0.491	0.644	0.590	0.330	0.317	0.783	0.780
IAE	0.596	0.662	0.394	0.385	0.687	0.704	0.330	0.351
~IAE	0.446	0.456	0.655	0.588	0.366	0.345	0.721	0.705

Note: the notation "~" means the absence of the condition.

4.2. Analysis of sufficient configurations

We use the fsQCA method to analyze the configurations that lead to high R&D efficiency and high commercialization efficiency, setting the case frequency threshold at 1, the consistency threshold at 0.8, and the PRI consistency threshold at 0.7 (Du and Kim, 2021; Fiss, 2011). During counterfactual analysis, due to the relationship between the six conditions and the R&D efficiency or commercialization efficiency has not yet reached a consensus, we assume that the presence or absence of each condition can contribute to high innovation efficiency (Schneider and Wagemann, 2012). Core conditions are identified based on the nested relationship between the intermediate solutions and parsimonious solutions, conditions that present in both solutions regarded as core conditions, and conditions that present only in the intermediate solutions regarded as peripheral conditions (Fiss, 2011). The configuration results are shown in Table 7. There are three configurations generating high R&D efficiency, that is, three pathways to achieve high R&D efficiency; and five configurations generating high commercialization efficiency, that is, five pathways to achieve high commercialization efficiency, indicating that regional innovation ecosystem has multiple pathways to achieve high R&D efficiency or high commercialization efficiency. Next, we will follow the process of configurational theorization, which should focus on the three points of concise expression, capturing the whole, and evoking the essence of the configuration (Furnari *et al.*, 2021), to name and analyze each configuration.

Table 7
Configurations with high RE and high CE.

Conditions	High RE			High CE				
	HRE1a	HRE1b	HRE2	HCE1a	HCE1b	HCE1c	HCE2a	HCE2b
IAS		•	●	•	•	⊗	⨂	⨂
IAL	●	●	●		•	•	•	⊗
IBR	●	●	⊗	●	●	●	⊗	•
DR	●	●	⊗	•	•		⊗	•
ISE	•	⊗	⊗	•		•	●	●
IAE	•		●	●	●	●	⊗	⊗
Consistency	0.818	0.870	0.859	0.800	0.816	0.951	0.811	0.932
Raw coverage	0.475	0.151	0.088	0.510	0.493	0.172	0.117	0.102
Unique coverage	0.375	0.048	0.034	0.036	0.020	0.035	0.035	0.032
Overall consistency	0.838			0.815				
Overall coverage	0.560			0.676				

Note: *●=core causal condition present; ⨂=core causal condition absent; •= peripheral condition present; and ⊗= peripheral condition absent.*

4.2.1. High R&D efficiency configurations

(1) HRE1a: Resource and environment synergy type supported by IAL. Configuration HRE1a indicates that the pathway with high innovation-actor-link, high innovation-basic-resource, and high digital resource as core conditions, and complemented by high innovation-supportive-environment and high innovation-agglomeration-environment as peripheral conditions, can generate high R&D efficiency. This configuration suggests that when a region has sufficient allocation of innovation basic resources such as human, financial, and material resources, as well as abundant allocation with digital resources, high R&D efficiency can be achieved by strengthening connections among innovation actors and optimizing innovation supportive environment and innovation agglomeration environment, regardless of whether the scale of innovation actors is large or not. Typical cases of this configuration include Beijing,

Guangdong, Jiangsu, Shanghai, Zhejiang, Hunan, and Sichuan, of which five are located in eastern China, one in central China and one in western China.

(2) HRE1b: Innovation actor and resource linkage type. Configuration HRE1b indicates that the pathway with high innovation-actor-link, high innovation-basic-resource, and high digital resource as core conditions, and complemented by high innovation-actor-scale and non-high innovation-supportive-environment as peripheral conditions, can generate high R&D efficiency. This configuration suggests that when innovation basic resources and digital resources of the region are adequately allocated, high R&D efficiency can be achieved by introducing rich innovation actors and enhancing the collaboration and cooperation among innovation actors, regardless of whether the innovation agglomeration environment is favorable or not, even if the innovation supportive environment is poor. Typical cases of this configuration are Anhui and Shaanxi, one in central China and one in western China.

(3) HRE2: Actor-driven type supported by IAE. Configuration HRE2 indicates that the pathway with high innovation-actor-scale, high innovation-actor-link, and high innovation-agglomeration-environment as core conditions, and complemented by non-high innovation-basic-resource, non-high innovation-supportive-environment, and non-high digital resource as peripheral conditions, can generate high R&D efficiency. This configuration suggests that when the allocation of innovation basic resources and digital resources in the region is insufficient and the innovation supportive environment is poor, high R&D efficiency can still be achieved by creating a favorable innovation agglomeration environment, gathering various actors to expand the scale of innovation actors, and strengthening the collaboration and cooperation of innovation actors. The typical case of this configuration is the China's central province of Heilongjiang; however, it is worth noting that combined with the original data of innovation activities in Heilongjiang, we found that the input of intramural expenditure on R&D funds and the full-time equivalent of R&D personnel are lower than the national median and average level. To some extent, Heilongjiang can be regarded as a case of high innovation efficiency but with low innovation input level.

From the horizontal perspective of individual conditions, high innovation-actor-link exists as the core presence condition in all configurations, indicating that good innovation actor linkages play a universal role in achieving high R&D efficiency. The collaboration and cooperation among innovation actors within the regional innovation ecosystem are important engines for promoting synergetic innovation, and empirical research has shown that linkages among actors such as enterprises, universities, and research institutions significantly promote the improvement of regional innovation efficiency (Jiao *et al*., 2016). Among the three configurations, the raw coverage and unique coverage of HRE1a are significantly higher than the other two configurations, indicating that the pathway "Resource and environment synergy type supported by IAL" is the main pathway for regional innovation ecosystem to drive R&D efficiency.

4.2.2. High commercialization efficiency configurations

Following the same configurational theoretical process, we name and conduct a detailed analysis of the five high commercialization efficiency configurations.

(1) HCE1a: Resource and environment synergy type supported by IAS. Configuration HCE1a indicates that the pathway with high innovation-basic-resource and high innovation-agglomeration-environment as core conditions, and complemented by high innovation-actor-scale, high digital resource, and high innovation-supportive-environment as peripheral conditions, can generate high commercialization efficiency. This configuration suggests that when a region has sufficient allocation of innovation basic resources and digital resources, high commercialization efficiency can be achieved by

introducing various types of innovation actors to increase the scale of innovation actors, and creating a favorable innovation supportive environment and agglomeration environment, regardless of the linkage level between innovation actors is high or not. Typical cases of this configuration include eight provinces, that is, Guangdong, Jiangsu, Shandong, Zhejiang, Henan, Hunan, Hubei, and Hebei, of which five in eastern China and three in central China.

(2) HCE1b: Actor and resource synergy type supported by IAE. Configuration HCE1b indicates that the pathway with high innovation-basic-resource and high innovation-agglomeration-environment as core conditions, and complemented by high innovation-actor-scale, high innovation-actor-link, and high digital resource as peripheral conditions, can generate high commercialization efficiency. This configuration suggests that when a region has sufficient innovation resources, high commercialization efficiency can be achieved by introducing a rich variety of innovation actors, enhancing the collaboration and cooperation among them, and optimizing the innovation agglomeration environment, regardless of the quality of the innovation supportive environment is good or not. Typical cases of this configuration include seven provinces, namely Guangdong, Jiangsu, Shandong, Zhejiang, Hunan, Hubei, and Anhui, of which four in eastern China and three in central China. Except for Anhui, the other six provinces are all the shared cases with configuration HCE1a.

(3) HCE1c: Environment-driven type supported by IAL and IBR. Configuration HCE1c indicates that the pathway with high innovation-basic-resource and high innovation-agglomeration-environment as core conditions, and complemented by high innovation-actor-link, high innovation-supportive-environment, and non-high innovation-actor-scale as peripheral conditions, can generate high commercialization efficiency. This configuration suggests that when the regional basic innovation resources are fully allocated and the innovation agglomeration environment is favorable, by enhancing the collaboration between innovation actors and creating a good innovation supportive environment, high commercialization efficiency can be achieved regardless of whether the digital resources allocation is sufficient or not and even if the scale of innovation actors is not high. The typical cases for this configuration are Tianjin and Shanghai in eastern China.

(4) HCE2a: Environment-driven type supported by IAL. Configuration HCE2a indicates that the pathway with high innovation-supportive-environment and non-high innovation-actor-scale as core conditions, and complemented by high innovation-actor-link, non-high innovation-basic-resource, non-high digital resource, and non-high innovation-agglomeration-environment as peripheral conditions, can still generate high commercialization efficiency. This configuration suggests that when the regional supportive environment such as economic, cultural, and market is highly developed, high commercialization efficiency can be achieved by enhancing the level of collaboration between innovation actors, even if the scale of innovation actors is not large, the allocation of innovation resources is insufficient, and the agglomeration environment is suboptimal. The typical case for this configuration is Chongqing in western China. However, combining the original data of innovation input in Chongqing, we find that, similar to the typical case of Heilongjiang under HRE2, its R&D expenditure and R&D personnel input are below the national median and average level, so to a certain extent, Chongqing can also be regarded as a case of high innovation efficiency but with low innovation input level.

(5) HCE2b: Resource-driven type supported by ISE. Configuration HCE2b indicates that the pathway with high innovation-supportive-environment and non-high innovation-actor-scale as core conditions, and complemented by high innovation-basic-resource, high digital resource, non-high innovation-actor-link, and non-high innovation-agglomeration-environment as peripheral conditions, can still generate high

commercialization efficiency. This configuration suggests that when the region already possesses a favorable innovation supportive environment, by enhancing the allocation level of innovation basic resources and digital resources, high commercialization efficiency can be achieved even if the scale of innovation actors is not large, the linkages between innovation actors are not strong, and the agglomeration environment is suboptimal. The typical case for this configuration is Fujian in eastern China.

Based on the comparative analysis of configuration, we found that there is a substitutive relationship between the high innovation-supportive-environment in HCE1a and the high innovation-actor-link in HCE1b. This means that when a region has a rich and large scale of innovation actors, the allocation of innovation basic resources and the access of digital resources are sufficient, and the innovation agglomeration environment is favorable, high regional commercialization efficiency can be effectively promoted as long as the region possess either a favorable innovation supportive environment or a high level of linkages among innovation actors. In addition, the coverage parameters of the configurations indicate that HCE1a (Resource and environment synergy type supported by IAS) and HCE1b (Actor and resource synergy type supported by IAE) are the main pathways for regions to achieve high commercialization efficiency.

4.3. Further discussion and analysis

Here we further discuss the results of the configurational analysis from the following three aspects. Comparing the similarities and differences between the two types of high innovation efficiency pathways, analyzing the spatial distribution characteristics of high innovation efficiency cases, and exploring the configurations that generating dual high innovation efficiency, we propose research propositions to be further explored in the future. The configurations, pathways, and typical cases of the two types of high innovation efficiency are shown in Table 8.

Table 8
Configurations, pathways and typical cases of the HRE and HCE.

	High RE			**High CE**				
Configurations ①	HRE1a: **IAL*****IBR*****DR***ISE*IAE	HRE1b: IAS***IAL*****IBR*****DR***~ISE	HRE2: **IAS*****IAL***~IBR*~DR*~ISE***IAE**	HCE1a: IAS***IBR***DR*ISE***IAE**	HCE1b: IAS*IAL***IBR***DR***IAE**	HCE1c: ~IAS*IAL***IBR***ISE***IAE**	HCE2a: ~**IAS***IAL*~IBR*~DR***ISE***~IAE	HCE2b: ~**IAS***~IAL*IBR*DR***ISE***~IAE
Pathways	Resource and environment synergy type supported by IAL	Innovation actor and resource linkage type	Actor-driven type supported by IAE	Resource and environment synergy type supported by IAS	Actor and resource synergy type supported by IAE	Environment-driven type supported by IAL and IBR	Environment-driven type supported by IAL	Resource-driven type supported by ISE
Typical cases ②	Beijing, **Guangdong**, **Jiangsu**, **Shanghai**, **Zhejiang**, **Hunan**, Sichuan	**Anhui**, Shaanxi	Heilongjiang	**Guangdong**, **Jiangsu**, Shandong, **Zhejiang**, Henan, **Hunan**, Hubei, Hebei	**Guangdong**, **Jiangsu**, Shandong, **Zhejiang**, **Hunan**, Hubei, **Anhui**	Tianjin, **Shanghai**	Chongqing	Fujian

Note: ① *the notation "*" means and, conditions in bold indicates that they are the core condition;* ② *Case examples in bold represent that these cases are both high R&D efficiency and high commercialization efficiency cases.*

4.3.1. Comparison of high R&D efficiency and commercialization efficiency pathways

The similarities and differences between the two types of high innovation efficiency pathways are mainly reflected in the following three aspects.

(1) The pathways of regional innovation ecosystem driving the improvement of innovation efficiency shows the characteristics of multiple concurrency and the same destination. On the one hand, there are multiple configurations to achieve both high R&D efficiency and high commercialization efficiency, but there is no subset relationship between these two types of high innovation efficiency configurations, which indicate that there is a significant difference between the implementation mechanism of regional innovation ecosystem to drive the improvement of innovation efficiency in the two stages (Chen and Kou, 2014 ; Wan *et al*., 2023). On the other hand, no matter to achieve high R&D efficiency or high commercialization efficiency, each pathway is the result of the joint action of multiple elements of the regional innovation ecosystem. Meanwhile, the configuration solution can't be formed by the elements of the individual innovation actor layer, innovation resource layer, or innovation environment layer, and there has not yet been a case of achieving high innovation efficiency through a single dominant pathway in practice. The above indicates that the improvement of innovation efficiency driven by regional innovation ecosystem is a complex process of multi-elements synergy (Tsujimoto *et al*., 2018).

(2) Well-established innovation-actor-link plays a more important role in improving R&D efficiency. In all high R&D efficiency configurations, the innovation-actor-link is always the core present condition, and other regional innovation ecosystem elements need to synergize with high innovation-actor-link to promote the improvement of R&D efficiency. However, in the high commercialization efficiency configurations, innovation-actor-link is either a peripheral condition or absent, indicating that even if the linkage and collaboration among regional innovation actors are not strong, commercialization efficiency can still be promoted by improving the level of other innovation elements. Research shows that innovation-actor-link has a significant positive impact on regional R&D efficiency (Min *et al*., 2020 ; Zhuang *et al*., 2021), and is an important engine to promote the improvement of R&D efficiency.

(3) Favorable innovation-supportive-environment plays a more important role in improving commercialization efficiency. Among the five high commercialization efficiency configurations, except for the blank innovation-supportive-environment in HCE1b, both the other four configurations contain the high innovation-supportive-environment. However, in the high R&D efficiency configurations, high R&D efficiency can still be achieved by enhancing other elements even if the innovation-supportive-environment is suboptimal (HRE1b, HRE2). A favorable innovation supportive environment is an important guarantee to promote the transformation of commercial outcomes, which is different from the view that the impact of open innovation environment on commercialization efficiency is not significant (Bai, 2013), this is because previous studies used traditional regression methods to explore the net effect of a single element on the results, overlooking the interaction effects of innovation-supportive-environment with other elements in the process of improving innovation efficiency.

Based on the above discussion and analysis, we give the proposition 1: Innovation-actor-link plays a more important role in driving R&D efficiency, and innovation-supportive-environment plays a more important role in driving commercialization efficiency.

4.3.2. Comparison of spatial distribution characteristics between high R&D efficiency cases and high commercialization efficiency cases

By sorting out typical cases covered by high R&D efficiency and high commercialization efficiency configurations, we further analyze the distribution characteristics of the cases with high innovation efficiency in the eastern and central-western regions in China.

Among all the typical cases covered by high R&D efficiency configurations, there are 5 in eastern China, 3 in central China, and 2 in western China. All the 5 eastern provinces achieved high R&D efficiency through the pathway that "Resource and environment synergy type supported by IAL" (HRE1a), indicating that compared with the central-western provinces, the regional innovation ecosystem construction in the eastern China showed a more balanced feature in driving R&D efficiency improvement. In addition, these regions have achieved relatively advanced development in innovation-actor-link, digital resource, and innovation-agglomeration-environment. For the five central-western provinces, all three high R&D efficiency pathways are distributed.

Among all the typical cases covered by high commercialization efficiency configurations, there are 8 in eastern China, 4 in central China, and 1 in western China. The number of high commercialization efficiency cases in the eastern China far exceeds that in the central-western, showing that the commercialization efficiency level in the eastern regions is ahead of the central-western regions, which is generally consistent with the view of the existing studies that the commercialization efficiency level in China is ahead in the eastern region, followed by the central region and lowest in the western region (Bai, 2013). Different from the spatial distribution characteristics of high R&D efficiency cases, both eastern and central-western provinces show diversity in the pathways to achieve high commercialization efficiency.

Based on the above discussion and analysis, we give the proposition 2: The cases with high R&D efficiency show spatial distribution characteristics, while commercialization efficiency cases do not show obvious spatial distribution characteristics. In terms of technology research and development, the regional innovation ecosystem in the eastern China shows more balanced development characteristics.

4.3.3. Configurations generating dual high innovation efficiency

By observing the typical cases that simultaneously belong to high R&D efficiency and high commercialization efficiency, we find that they include 4 eastern provincial entities, namely Guangdong, Jiangsu, Shanghai, Zhejiang, as well as 2 central provinces, Hunan and Anhui. We perform an intersection calculation on the configurations of high R&D efficiency and high commercialization efficiency of the 6 cases respectively, the intersection results are the configurations that simultaneously produce high R&D efficiency and high commercialization efficiency. The results are shown in Table 9. There are 3 configurations that can generate dual high innovation efficiency, that is, three pathways that can achieve both high R&D efficiency and high commercialization efficiency.

Table 9
Configurations with dual high innovation efficiency.

Conditions	HIE1: HRE1a∩HCE1a; HRE1a∩HCE1b	HIE2: HRE1a∩HCE1c	HIE3: HRE1b∩HCE1b
Innovation-actor-scale	•	⊗	•
Innovation-actor-link	●	●	●
Innovation-basic-resource	●	●	●
digital resource	●	●	●
Innovation-supportive-environment	•	•	⊗
Innovation-agglomeration-environment	●	●	●
Typical cases	Guangdong, Jiangsu, Zhejiang, Hunan	Shanghai	Anhui

(1) HIE1: System synergy type under the assistance of both IAS and ISE. In configuration HIE1, all six elements of the regional innovation ecosystem are present. Besides the innovation-actor-scale and the innovation-supportive-environment are peripheral conditions, the innovation-actor-link, innovation-basic-resource, digital resource, and innovation-agglomeration-environment are all core conditions. The representative cases of this configuration include Guangdong, Jiangsu, Zhejiang and Hunan provinces, of which 3 are eastern provinces and 1 central province. The number of cases covered by this configuration is the largest, which means that constructing a regional innovation ecosystem with balanced development of 6 elements is the main pathway to achieve dual high innovation efficiency.

(2) HIE2: System synergy type coordination with the absence of IAS and the assistance of ISE. Configuration HIE2 differs from HIE1 in that the innovation-actor-scale is a peripheral absent condition, and the representative case is Shanghai. Compared to the average level of innovation-actor-scale across the provincial entities nationwide, Shanghai does not have an advantage in the number of both industrial enterprises that above designated size and full-time teachers at higher education institutions, but due to the outstanding development level of its other five elements, Shanghai still achieves dual high innovation efficiency.

(3) HIE3: System synergy type coordination with the absence of ISE and the assistance of IAS. Configuration HIE3 differs from HIE1 in that the innovation-supportive-environment is a peripheral absent condition, and the representative case is Anhui. Compared to the average level of the innovation-supportive-environment across the provinces nationwide, Anhui's economic environment (Per capita gross regional product) and open environment (international trade in goods) are relatively insufficient, but the other five elements show balanced development characteristics, therefore still achieve dual high innovation efficiency.

Overall, the innovation-actor-link, innovation-basic-resource, digital resource, and innovation-agglomeration-environment are the core existing conditions in all dual high innovation efficiency configurations, and the four conditions have complementary effects in the process of regional innovation ecosystem driving dual high innovation efficiency. Studies show that adequate innovation resources play a foundational role in driving high innovation performance in regional innovation ecosystem (Carayannis *et al*., 2018), and regional collaborative innovation can be enhanced by improving the linkages among innovation actors, which is an important mechanism to promote regional innovation efficiency (Zhuang *et al*., 2021 ; Noni *et al*., 2018).

Based on the above discussion and analysis, we give the proposition 3: High innovation-actor-link, high innovation-basic-resource, high digital resource, and high innovation-agglomeration-environment play a universal role in the process of regional innovation ecosystem simultaneously driving high R&D efficiency and high commercialization efficiency.

4.4. Robustness test

We used the method of adjusting the PRI consistency threshold to conduct robustness test on the configuration of high R&D efficiency and high commercialization efficiency respectively (Du and Kim, 2021 ; Fiss, 2011), and further calculated the intersection of the obtained configurations of high R&D efficiency and high commercialization efficiency to examine the robustness of the dual high innovation efficiency configurations. Results are shown in Table 10 and Table 11. After raising the PRI consistency from 0.7 to 0.75, for high R&D efficiency, the configuration number of new model is still 3, which are the perfect subset of the original model configuration; for high commercialization efficiency, the configuration number of new model is 4, which are basically consistent with the original model configuration; and for dual high innovation efficiency, the configuration number of new model is 2, which are also the perfect subset of the original model configuration. The above analysis indicates that the research results of this paper are robust (Schneider and Wagemann, 2012).

Table 10
Robustness test of the configurations with high RE and high CE.

Conditions	High RE			High CE			
	HRE1	HRE2	HRE3	HCE1a	HCE1b	HCE1c	HCE2
IAS		•	●	•	•	⊗	⊗
IAL	●	●	●		•	•	⊗
IBR	●	●	⊗	●	●	●	●
DR	●	•	⨂	•	•		•
ISE	●	⊗	⊗	•		•	●
IAE	•	⨂	●	●	●	●	⊗
Consistency	0.818	0.905	0.859	0.800	0.816	0.951	0.932
Raw coverage	0.475	0.034	0.088	0.510	0.493	0.172	0.102
Unique coverage	0.408	0.092	0.036	0.036	0.020	0.054	0.050
Overall consistency	0.835			0.826			
Overall coverage	0.546			0.642			

Table 11
Robustness test of the configurations with dual high innovation efficiency.

Conditions	HIE1	HIE2
IAS	•	⊗
IAL	●	●
IBR	●	●
DR	●	●
ISE	●	●
IAE	●	●

5. Conclusions and Implications

5.1. Research findings

Based on the perspective of innovation ecosystem, we take 30 provincial entities in China as case samples, and adopt NCA and fsQCA methods to analyze the multiple pathways of regional innovation ecosystem, in order to drive the improvement of R&D efficiency and commercialization efficiency from a configurational perspective. The main conclusions are as follows.

(1) A single regional innovation ecosystem element does not constitute the necessary condition either for high R&D efficiency or for high commercialization efficiency, but enhancing the strength of innovation-actor-link plays a universal role in achieving high R&D efficiency.

(2) There are multiple pathways for regional innovation ecosystem to drive high R&D efficiency and high commercialization efficiency, and there is no single-dominant pathway. There are 3 pathways to achieve high R&D efficiency, among which the “Resource and environment synergy type supported by IAL” is the main pathway. There are 5 pathways to achieve high commercialization efficiency, and under certain conditions, there is a substitutive relationship between high innovation-supportive-environment and high innovation-actor-link in driving high commercialization efficiency.

(3) There are significant differences between the pathways of high R&D efficiency and high commercialization efficiency. On the whole, good innovation-actor-link plays a more important role in improving R&D efficiency, while favorable innovation-supportive-environment plays a more important role in improving commercialization efficiency.

(4) For the cases of high R&D efficiency, eastern and central-western China each have 5 provinces that all achieve high R&D efficiency through the pathway “Resource and environment synergy type supported by IAL”; whereas for the 5 central-western provinces, all three pathways have been distributed. Among the cases of high commercialization efficiency, 8 are eastern provinces and 5 are central-western provinces, and the pathways for both eastern and central-western provinces show diversity.

(5) There are 3 pathways to achieve dual high innovation efficiency, among which the “System synergy type under the assistance of both IAS and ISE” is the main pathway, with the representative cases of dual high innovation efficiency covering 4 eastern provinces and 2 central provinces.

(6) Based on further discussion and analysis, three meaningful research propositions are given regarding the improvement of innovation efficiency driven by regional innovation ecosystem, which await deeper exploration in the future.

5.2. Theoretical contributions

(1) Based on the "trichotomy" framework of innovation ecosystem theory, we construct the analysis framework of regional innovation ecosystem by integrating six elements: innovation-actor-scale, innovation-actor-link, innovation-basic-resource, digital resource, innovation-supportive-environment, and innovation-agglomeration-environment, to explore the complex relationship between six regional innovation ecosystem elements and two regional innovation efficiency of R&D efficiency and commercialization efficiency. On the one hand, different from previous studies, which mainly focused on the impact of traditional innovation ecosystem elements such as innovation-actor-scale, innovation-basic-resources, and innovation-supportive-environment on regional innovation (Xu and Yu, 2023 ; Zhang *et al*., 2020), we look at the new trend of regional innovation development in the digital era to further incorporate three major elements into this causal condition system, namely innovation-actor-link, digital resource, and innovation-agglomeration-environment, to enrich and improve the theoretical connotation of regional innovation ecosystem, and make up for the insufficiency discussion of the regional innovation ecosystem analytical framework in previous studies (Cai, 2023 ; Chen *et al*., 2017). Based on this, we further reveal the universal role of innovation-actor-link in promoting the improvement of regional R&D efficiency, hence provide an important theoretical reference for a more fine-grained explanation of the complex relationship between regional innovation ecosystem and innovation efficiency (Liang and Ma, 2024 ; Chen *et al*., 2018). On the other hand, we deepen the research on the elements influencing regional innovation efficiency from the perspective of the overall innovation ecosystem (Min *et al*., 2020), and further refine the improvement pathways of regional innovation efficiency from the perspective of both R&D efficiency and commercialization efficiency.

(2) Based on the necessity causality analysis, we use NCA and fsQCA methods to analyze the necessity relationship between six regional innovation ecosystem elements and R&D efficiency, as well as commercialization efficiency (Dul, 2016 ; Dul *et al*., 2020). We find that individual innovation ecosystem elements do not constitute necessary conditions for the two types of innovation efficiency, not only in terms of category but also in the sense of degree, to provide a more granular necessity causal analysis for in-depth understanding of the relationship between regional innovation ecosystem and innovation efficiency (Xu and Yu, 2023 ; Zhang *et al*., 2020). Based on sufficient causality analysis, we reveal the multiple pathways of regional innovation ecosystem driving R&D efficiency and commercialization efficiency, and identify the similarities and differences between the two type of pathways, to make up for the setback of previous studies that mainly focused on the net effects of individual elements such as innovation actors (Carayannis *et al*., 2018), innovation resources (Huang *et al*., 2023), innovation environment (Min *et al*., 2020), and digitalization (Nambisan *et al*., 2017 ; Helfat and Raubitschek, 2018) on regional innovation efficiency, while ignoring the configurational effects of the synergistic linkage among these elements, and to deepen the explanation of the complex mechanism of regional innovation efficiency improvement given by innovation ecosystem theory.

(3) The configuration perspective and set theory are introduced into the study of regional innovation efficiency, and NCA, QCA, SFA, and GPCA methods are combined to systematically analyze the complex causal relationship between regional innovation ecosystem on innovation efficiency, to respond to the call of innovation ecosystem view for combinatorial methodology (Li *et al*., 2023), and to provide new ideas and perspectives for studying the complex mechanism of improving regional innovation efficiency. Firstly, based on the configurational perspective, we analyze the possible pathways of improving regional innovation efficiency, including single-dominant type, dual-linkage type, and system-synergy type. Secondly, we integrate a variety of methods to explore whether there is a certain regional innovation ecosystem element that is the necessary condition for achieving high regional innovation efficiency, and how the combination of multiple innovation ecosystem elements can synergistically promote the improvement of regional innovation efficiency. Finally, based on the Boolean algebra logic of QCA method, we further investigate the pathways to achieve dual high innovation efficiency through the intersection operation of high R&D efficiency configuration and high commercialization efficiency configuration.

5.3. Policy implications

Our research provides valuable policy recommendations for regions to improve innovation efficiency. Firstly, a region should formulate innovation policies tailored to its local conditions, and pay attention to the coordinated improvement of various elements at different levels of innovation actors, innovation resources, and innovation environments. There are 3 pathways that drive high R&D efficiency and 5 pathways that drive high commercialization efficiency within regional innovation ecosystems; each region should comprehensively consider the differentiation characteristics of these pathways, and combine the actual development level of the regions in these six innovation ecosystem elements to identify the benchmark provinces, so as to formulate the innovation policies that are in line with their own actual situations and have differentiated competitive advantages. What should be noted is that via the pathway of single-dominant type a region is difficult to achieve high regional innovation efficiency.

Secondly, a region should give priority to improving the linkages between innovation actors, so as to achieve high R&D efficiency. High innovation-actor-link plays a universal role in driving R&D

efficiency, which means that no matter which pathway is adopted to improve R&D efficiency, the region should prioritize the improvement of the coordination and cooperation among regional innovation actors. Specifically, a region can guide in-depth cooperation between industry-universities-research institutes, establish strategic alliances for technological innovation, and promote the construction of information service platforms, so as to achieve a sound innovation-actor-link that is conducive to the formation of complementary resource advantages, risk sharing, and benefit sharing among enterprises, universities, research institutions, and governments. Taking the typical cases of Shaanxi Province in the western China as an example, it is advisable to give full play to the cluster advantages of universities and research institutions, by creating the Qin-Chuang-Yuan innovation driven platform, the Xi'an intelligent manufacturing industry-university-research cooperation alliance, and the Xi'an high-tech zone "enclave" parks in universities and research institutes, to promote in-depth cooperation between enterprises, universities and research institutes, and continuously enhancing the endogenous driving force and innovation vitality of enterprises.

Thirdly, a region should pay attention to the substitution effect between the high innovation-supportive-environment and high innovation-actor-link, so as to create differentiated pathways for high commercialization efficiency. When a region has abundant innovation actors, sufficient innovation basic resources, well-established innovation agglomeration environment, and ample digital resources, there is a substitution relationship between high innovation supportive environment and high innovation actor link in driving high commercialization efficiency. At this time, a region can accelerate the realization of high commercialization efficiency by optimizing the innovation supportive environment or improving the innovation actor linkage, according to the actual situation of the region. Taking Hubei Province in the central China as an example, in 2023, Hubei's business environment ranked 10th among the involved 31 provinces in China. Achieving consecutive progress for three years, its number of national major scientific infrastructure projects built or under construction has reached 8 to rank the fifth in China, and the number of national-level innovation platforms has reached 163 to rank the fourth in China. All of those help creating a favorable innovation environment to promote enterprises to achieve the transformation of scientific and technological achievements.

Fourthly, a region should actively promote the balanced development of regional innovation ecosystem, so as to achieve dual high innovation efficiency. Among the three pathways to achieve dual high innovation efficiency, the “System synergy type under the assistance of both IAS and ISE” shows the strongest empirical relevance, which emphasizes the balanced development of the six regional innovation ecosystem elements. For the regions that have already achieved high R&D efficiency or high commercialization efficiency, it is necessary to scientifically benchmark the current situation and development goals, and formulate innovative policies that are more targeted and practical, so as to promote the coordinated improvement of the R&D efficiency and commercialization efficiency.

5.4. Limitations and future research

This research has several limitations that should be considered in future research. One limitation concerns the selection of antecedent conditions. Based on the "trichotomy" framework of innovation ecosystem theory, we construct the regional innovation ecosystem framework that covers six major factors. Considering the complexity of regional innovation, we encourage researchers to include more antecedent conditions into the research framework in the future work, such as policy support (Kou *et al*., 2023), knowledge flow (Su *et al*., 2021), etc., and expand the coverage and scale of samples in the meanwhile, so as to further refine our understanding on regional innovation. Another limitation concerns the consideration of the dynamics of time, based on the static configuration perspective, we discussed the complex relationship between regional innovation ecosystem and innovation efficiency. With the development of dynamic QCA methods, future research can consider further expand the time range of data samples, and introduce the growth pattern QCA (GPQCA) method (Du *et al*., 2024), to explore the complex dynamic mechanisms of regional innovation ecosystem on innovation efficiency, and analyze the complex growth pathways that driving the improvement of regional innovation efficiency.

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