

The Path of Digital Ecosystem Empowering Regional Scientific and Technological Innovation under the Dual Temporal-Spatial Dimensions: A Dynamic QCA Analysis Based on Panel Data

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ABSTRACT

Regional innovation serves as the cornerstone of a country's innovation development.

In the digital era, identifying the pathways and spatiotemporal effects through which the digital ecosystem drives regional scientific and technological innovation has become critical to breaking through bottlenecks in regional scientific and technological innovation and enhancing innovation performance. Drawing upon the TOE framework, and grounded in the resource-based view and the co-evolutionary theory, this study uses a dynamic QCA approach to analyze panel data from 31 Chinese provinces over the period 2019–2023. From a configurational perspective, this paper investigates the pathways and effects through which the digital ecosystem enables regional scientific and technological innovation. The findings are as follows: High digital talent and low digital innovation serve as necessary conditions for high and non-high regional scientific and technological innovation, respectively. Four configurational pathways are identified for high regional scientific and technological innovation, namely: technology-dominated, technology-organization-dominated, technology-environment-dominated, organization-environment-dominated. In contrast, five configurational pathways are found to lead to non-high regional scientific and technological innovation. In the temporal dimension, the evolutionary trajectories of various configurations for high scientific and technological innovation differ, with 2021 serving as a critical turning point, and the development levels among these configurations are heterogeneous. In the spatial dimension, configurations of high-tech innovation exhibit differential spatial effects and region-specific adaptability. This study provides both theoretical support and policy implications for understanding how digital ecosystems empower regional scientific and technological innovation from a spatiotemporal perspective.

区域创新是国家创新发展的基石。在数字时代，明确数字生态系统驱动区域科技创新的路径及其时空效应，对于突破区域科技创新中的瓶颈、提升创新绩效至关重要。本研究借鉴TOE框架，并植根于资源基础观与协同进化理论，采用动态QCA方法对2019–2023年间中国31个省份的面板数据进行了分析。从配置视角出发，本文探究了数字生态系统赋能区域科技创新的路径与作用机制。研究结果如下：高素质的数字人才与低水平的数字创新分别是实现高和地区非高区域科技创新的必要条件；针对高区域科技创新，本文识别出四种配置路径，即：技术主导型、技术-组织主导型、技术-环境主导型以及组织-环境主导型；相比之下，研究发现五种配置路径会导致非高区域科技创新。在时间维度上，各类高科技创新配置的演化轨迹各不相同；2021年成为这一演变过程中的关键转折点，且这些配置之间的发展水平存在差异。在空间维度上，高科技创新的配置呈现出差异化的空间效应及区域适应性特征。本研究为从时空视角理解数字生态系统如何赋能区域科技创新提供了理论支撑与政策启示。

1. Introduction

Technological innovation serves as the core driving force for high-quality economic development. As a crucial spatial carrier of the national innovation system, enhancing regional levels of scientific and technological innovation holds significant strategic importance for advancing China's high-quality economic growth and shaping its competitive edge. While implementing an innovation-driven development strategy, the Outline of the 14th Five-Year Plan for National Economic and Social Development of the People's Republic of China and the Long-Range Objectives Through the Year 2035 has identified "accelerating digital development and building a Digital China" as a key strategic objective, with systematic measures put in

place to promote rapid growth of the digital economy. The "14th Five-Year Plan for Digital Economy Development" indicates that the added value of core digital industries accounted for 7.8% of GDP in 2020, and is projected to rise to 10% by 2025, highlighting its broad reach, rapid growth rate, and profound impact [1]. The "Key Tasks for Digital Economy Development by 2025" further proposes "strengthening the foundation of digital infrastructure" "accelerating the realization of data's value as a factor of production" "promoting the standardized and healthy development of the platform economy" and "stimulating innovation vitality in the digital sector" outlining pathways and goals for building a robust digital ecosystem through deep integration of technological and industrial innovation. Currently, regions across China are accelerating the convergence of the digital economy with the real economy by fostering digital ecosystems, thereby injecting new momentum into scientific and technological innovation. Beyond China's domestic context, the construction of digital ecosystems has also become an important

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policy instrument for numerous economies around the world to advance regional scientific and technological innovation. Developed economies such as the European Union and the United States have widely implemented regional digital- ecosystem- oriented policies centered on digital infrastructure, open- data platforms and digital talent cultivation. These policies aim to narrow inter- regional innovation gaps and facilitate local industry- university- research collaboration. Against this global backdrop, investigating how digital ecosystems function to shape regional innovation under China's institutional and resource conditions carries both local policy value and comparative theoretical significance. However, regional innovation activities exhibit high complexity and systemic nature; their outcomes depend not only on digitalization alone but also vary significantly due to differences in resource endowments and developmental stages, leading to distinct challenges such as the "digital divide" and "innovation bottlenecks". Regarding the aforementioned issues, most existing studies adopt a static and horizontal perspective, focusing on the impact of individual or partial digital elements on regional technological innovation [2–4], while lacking research from a dynamic and longitudinal standpoint that examines the influence of digital ecosystems on regional technological innovation. In light of this, this paper adopts the TOE framework, drawing on resource-based theory and co-evolution theory, and utilizes the dynamic QCA method to analyze panel data from 31 provinces in China during 2019–2023. The study aims to explore the configurational pathways and spatiotemporal effects through which digital ecosystems drive regional technological innovation, thereby providing theoretical foundations and policy recommendations for leveraging digital ecosystems to empower regional technological advancement.

2. Literature Review and Theoretical Model

2.1. Literature Review

Regional scientific and technological innovation refers to the process by which innovation entities within a specific region integrate and utilize various resources to conduct technological research and development and achieve commercial application [2]. It has undergone a paradigm

evolution from mechanization, automation, and informatization to the Intelligent 4.0 stage, during which the boundaries, methods, and processes of innovation have been profoundly reshaped [3].

As a multidimensional concept, the digital ecosystem encompasses the development and enhancement of elements such as digital infrastructure, digital technology innovation, digital talent, data resources, policy frameworks, and digital security, collectively forming a new ecological environment for regional scientific and technological innovation. In the context of the digital economy, the digital ecosystem, as a key strategic resource, is increasingly serving as a systemic driver for empowering regional scientific and technological innovation.

The academic community has conducted extensive discussions on the relationship between digital ecosystems and regional technological innovation. Firstly, from an overall or systemic perspective, it is argued that various elements of digitalization are interdependent, forming a complex ecosystem that significantly enhances regional innovation efficiency [4], particularly through the synergistic effects of digital technologies, infrastructure, and digital industrialization on improving regional innovation performance [5]. In terms of mechanisms, digitalization exerts significant influence on regional innovation efficiency by optimizing industrial structures and enhancing human capital [6], effectively fostering disruptive innovations [7]; however, its impact exhibits a dual-threshold effect that accelerates the convergence of regional innovation patterns [8]. Secondly, analyses from a singular or localized perspective examine the impact of digital elements on regional innovation. Digital infrastructure serves as the cornerstone of regional innovation, markedly boosting technological advancement [9], with mechanisms including elevated marketization levels [10], improved allocation efficiency of innovation resources [11], increased corporate patent holdings and revenues [12], and industrial structure optimization

[13]. These effects show regional disparities [14], being more pronounced in central and northeastern regions [12], though some studies indicate stronger empowerment effects in central and western regions [15]. Digital technological innovation is crucial for high-quality urban and regional development [16], significantly enhancing regional innovation capacity [17] through mechanisms such as expanding knowledge horizons [18], promoting industrial upgrading [19], increasing R&D investment [20], and fostering innovation polarization patterns [21]; simultaneously, digital innovation ecosystems strengthen regional innovation capabilities [22]. Digital talent refers to individuals equipped with digital technological capabilities, data analysis skills, and innovative thinking [23], serving as the core driving force for high-quality development of the digital economy [24] and the key competitive advantage in scientific innovation [25]. They have become pivotal actors and the "core engine" of regional scientific innovation, significantly enhancing regional innovation capacity [26]. As a "new production factor" under the context of new-quality productive forces [27], data elements reshape the regional innovation factor system [28], with mechanisms including market-oriented allocation of data elements [29]. For instance, the establishment of national big data pilot zones has markedly improved urban innovation efficiency [30], by optimizing factor allocation efficiency, promoting industrial structure upgrading, and boosting entrepreneurial activity [31], thereby enhancing urban R&D efficiency and advancing urban innovation [32]. Digital policies exert a decisive influence on regional innovation directions; initiatives such as the "Broadband China" strategy [33] and big data pilot zone policies [34] have been proven effective in boosting regional scientific innovation capabilities. Currently, research on the relationship between digital security and regional scientific innovation remains insufficient.

Despite significant achievements, existing research still faces several limitations: Firstly, most studies focus primarily on the "net effects" of digital factors, failing to elucidate the equivalent pathways and substitution effects formed by multi-factor combinations; Secondly, static QCA methodologies based on cross-sectional data exhibit a "time lag," making it impossible to capture the dynamic evolution of driving mechanisms [35]; Lastly, there is insufficient attention to regional contextual differences and pathway applicability across China, with inadequate exploration of spatial heterogeneity. To address these gaps, this study uses a dynamic QCA approach using provincial panel data to systematically reveal the complex causal mechanisms through which digital ecosystems drive regional technological innovation. The research encompasses four key aspects: first, identifying essential conditions for fostering high versus low levels of technological innovation within digital ecosystems; second, delineating configuration pathways and substitution effects comprising six core elements—digital infrastructure, digital innovation, digital talent, data resources, policy frameworks, and digital security; third, analyzing the dynamic evolution patterns of digital configuration pathways driving high-tech innovation across regions over time; fourth, comparing distribution disparities and adaptation characteristics of high-tech innovation configurations across different geographical areas.

2.2. Theoretical Model

The "Technology-Organization-Environment" (TOE) framework proposed by Tornatzky and Fleischer (1990) emphasizes that technological innovation adoption and implementation are jointly influenced by three dimensions: technology, organization, and environment. Currently, the TOE framework has been widely applied in research on digital transformation and technological innovation, with a solid theoretical foundation and empirical evidence. It provides a comprehensive and systematic perspective for analyzing the relationship between digital ecosystems and regional technological innovation, facilitating the elucidation of complex mechanisms driving regional innovation and interpreting multidimensional interactions. Building upon the TOE theoretical framework and incorporating reviews of studies examining how digital elements and digital

ecosystems impact regional innovation, this paper categorizes key components of digital ecosystems — including infrastructure, digital innovation, digital talent, data resources, policy frameworks, and digital security — into three dimensions: the Technology Dimension (T), encompassing advanced digital infrastructure and technological innovations [36], serves as the foundational support for regional innovation; the Organization Dimension (O), comprising digital talent [37] and data resources [38], reflects the core capabilities of micro-level innovation actors; the Environment Dimension (E), involving digital policies [36] and digital security [39], determines the direction and sustainability of regional innovation. It should be noted that the 'Organization (O)' dimension in our TOE framework, while conceptually anchored in micro-level innovation actors, is operationalized at the provincial level. The rationale lies in viewing regional organizational capabilities as emergent properties arising from the density, interconnectivity, and collective endowments of local firms, universities, and research institutes. Variables such as digital talent and data resources, though rooted in micro-level activities, are measurable and meaningful at the regional scale, constituting critical organizational endowments of a province. Regional technological innovation is not driven by a single factor but results from the synergistic interaction among technology, organizational structures, and environmental conditions within a digital ecosystem context.

Does the digital ecosystem exert spatiotemporal effects in empowering regional technological innovation? On one hand, according to resource-based theory, an organization's unique competitive advantage stems from its possession of intangible and tangible resources that are difficult to transfer or replicate, which can be

transformed into exclusive organizational capabilities. Similarly, different regions in China exhibit varying levels of digital ecosystems due to inherent disparities in digital resource endowments. These distinctive digital resources and their combinations serve as differentiated drivers for regional technological innovation, demonstrating spatial effects. On the other hand, based on co-evolution theory, elements within a system do not simply accumulate but rather exhibit organic integration, mutual penetration, and interdependent relationships through co-evolution, with their interactions continuously adjusting over time and in response to external changes. This co-evolutionary perspective is crucial because it moves beyond static resource-based explanations and directly underpins our dynamic QCA approach. It implies that the driving pathways of digital ecosystems are not fixed but evolve over time, as elements mutually adjust in response to technological shifts and policy changes. Without acknowledging co-evolution, empirical configurations would be misinterpreted as time-invariant, obscuring the temporal turning points and heterogeneous trajectories we observe. Thus, co-evolution theory provides the theoretical bedrock for treating time as an integral dimension of causal configurations, rather than merely a background factor. The impact of digital ecosystems on regional technological innovation likewise exhibits co-evolutionary characteristics over time, demonstrating temporal effects. In conclusion, this study constructs a research model for digital ecosystem-driven regional technological innovation (Figure 1) to explore the configurational pathways and spatiotemporal effects of digital ecosystem empowerment.

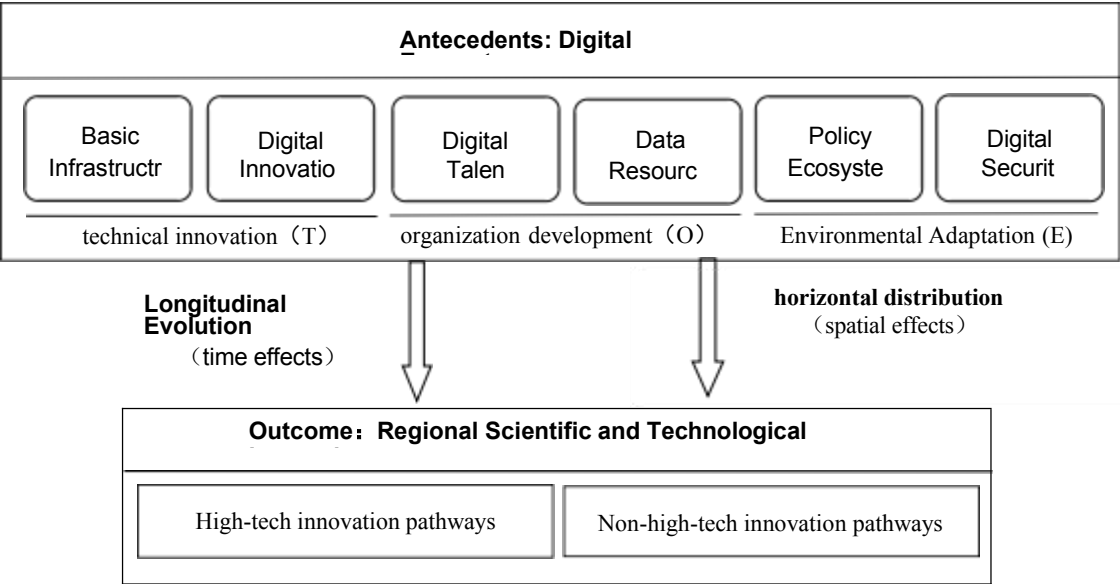


Figure 1. Research Model

As illustrated in Figure 1, this research model consists of three core components: antecedent conditions, an outcome variable, and dual analytical dimensions of space and time. First, the antecedent is the digital ecosystem, which is further decomposed into three TOE-based dimensions: technology (T), organization (O), and environment (E). The technology dimension includes basic infrastructure and digital innovation, providing material and technical foundations for regional innovation activities. The organization dimension covers digital talent and data resources, representing core micro-level innovation carriers and key production factors. The environment dimension contains the policy

ecosystem and digital security, shaping the institutional guarantee and risk-control conditions for innovation. Second, the outcome variable is regional scientific and technological innovation, which generates two sets of configurational results: high-tech innovation pathways and non-high-tech innovation pathways. Multiple combinations of the six antecedent elements jointly produce high or non-high regional innovation outcomes, reflecting the equifinality and causal asymmetry emphasized by QCA. Third, the model incorporates dual temporal-spatial dimensions. The horizontal distribution denotes spatial effects, which capture how identical digital ecosystem configurations exert differentiated innovation

performance across geographically heterogeneous provincial regions. The longitudinal evolution denotes time effects, which reflect how the driving configurations dynamically change and evolve across successive years. By integrating configurational antecedents, innovation outcomes and spatiotemporal dimensions, the model systematically depicts how combined digital - ecosystem elements shape regional scientific and technological innovation and further reveals their evolutionary trajectories and regional adaptability.

3. Research Design

3.1. Research Methods

Adopting the dynamic Qualitative Comparative Analysis (dynamic QCA) approach, this study explores the complex causal mechanisms through which the digital ecosystem drives regional scientific and technological innovation. Compared with the traditional static QCA approach, dynamic QCA introduces the temporal dimension into configurational analysis, enabling the capture of dynamic evolutionary characteristics of causal relationships between antecedent conditions and outcome variables, thereby overcoming the "time blind spot" of static QCA, which can only analyze cross-sectional data. More importantly, dynamic QCA utilizes panel data structure by treating "region-year" as analytical cases, which substantially expands the sample size and allows for the identification of robust configurational pathways under a greater number of antecedent conditions. In recent years, the dynamic QCA method has been applied in various research fields. At the methodological level, Du Yunzhou et al. (2021) systematically reviewed the progress and limitations of configurational theory and QCA methods from a dynamic perspective in *Management World*, pointing out that developing dynamic QCA methods is an important direction for deepening dynamic configurational theory research [35]. At the empirical level, the dynamic QCA method has been widely applied and has been gradually adopted in configurational studies across fields such as regional innovation, digital economy, ecological efficiency, and industrial governance, and has become a crucial methodological tool for analyzing the multi-factor concurrent causal relationships in complex dynamic social phenomena.

3.2. Data Sources

The independent variable, digital ecosystem data, is sourced from the "Digital Ecology Index Report" (2019–2023) released by the National Engineering Laboratory for Big Data Analysis and Application Technology at Peking University, which systematically presents the development of digital ecosystems across 31 provinces in China over a five-year period and possesses considerable authority. The dependent variable, regional scientific innovation data, is derived from the "China Regional Scientific Innovation Evaluation Report" (2019–2023) compiled by the China Academy of Science and Technology Development Strategy, objectively reflecting the level and evolution of scientific innovation across provinces during the same period. Additionally, to enhance data accuracy, necessary supplements and corrections were made to certain indicators by referencing the China Statistical Yearbook, local statistical yearbooks, and national statistical bulletins.

3.3. Measurement and Calibration

3.3.1. Outcome Variable

The dependent variable for regional scientific and technological innovation comprises five primary indicators and twelve secondary indicators. The five primary indicators are: scientific and technological innovation environment, investment in scientific and technological activities, output of scientific and technological activities, industrialization of high-tech industries, and the role of science and technology in promoting economic and social development. Their corresponding secondary indicators are as follows: the scientific and technological innovation environment encompasses human resources for science and technology and material conditions for science and technology; investment in scientific and technological activities includes investment in S&T funds and investment in S&T personnel; output of scientific and

technological activities covers scientific and technological achievements and the technology market; industrialization of high-tech industries consists of the scale of high-tech industries, the efficiency of high-tech industries, and the development of high-tech enterprises; and the role of science and technology in promoting economic and social development comprises the transformation of the economic development mode, environmental improvement, and informatization of social life. This entire indicator system comprehensively covers the core dimensions of the full process of regional scientific and technological innovation development [40].

3.3.2. Antecedent Conditions

The antecedent conditions encompass digital infrastructure, digital innovation, digital talent, data resources, policy ecosystem, and digital security, which are summarized into three dimensions: technological innovation (T), organizational development (O), and environmental compatibility (E). (1) The technology innovation dimension encompasses infrastructure and digital innovation. Infrastructure refers to digital facilities such as data centers, computing power centers, and 5G networks, measured by the New Infrastructure Competitiveness Index and the Cloud Computing Index; digital innovation reflects the level of patent development and innovation leadership in frontier fields such as big data, artificial intelligence, and integrated circuits, quantified by the Digital Patent Index. (2) Organizational development covers digital talent and data resources. Digital Talent refers to professionals equipped with digital technology capabilities, data analysis skills, and innovative thinking. It serves as the core driving force for the development of the digital economy and a key competitive advantage for scientific and technological innovation, and is measured by the Digital Workforce Index, AI Developer Index, and Artificial Intelligence Research Index. Data Resources, as a "new production factor" in the context of new-quality productive forces, can reshape the regional innovation factor system and enhance innovation efficiency through market-oriented allocation. They are measured by the Open Data Index and Data Circulation Index. (3) Environmental compatibility includes policy frameworks and digital security. igital policy refers to the strategic plans, pilot policies, and institutional arrangements formulated by the government to promote the development of the digital economy and scientific and technological innovation. It exerts a decisive influence on the direction of regional innovation and is measured by the Digital Policy Index. Digital security refers to the protection capabilities for core data, information networks, and systems, including the construction of a cybersecurity ecosystem. It aims to safeguard R&D data and intellectual property, providing a trustworthy environment for cross-organizational cooperation and sustained innovation activities, and is measured by the Cybersecurity Ecosystem Index [41]. High-quality regional innovation is not driven by a single factor but results from the synergistic interaction of technological, organizational, and environmental dimensions.

3.3.3. Data Calibration

Using the direct calibration method, 95%,50%, and 5% of the sample data were designated as calibration anchors representing complete membership, crossover points, and complete non-membership respectively, to calibrate each variable; the results are shown in Table 1.

Variable Classification	Variable Name	Full Membership	Crossover Point	Full Non-Membership
Outcome Variable	Technology Innovation (TI)	54.673	26.320	18.175

Antecedent	Basic	78.561	28.475	12.273
Conditions	Infrastructure (	71.293	17.938	10.300
	BI) Digital	85.770	29.221	11.650
	Innovation (DI)	90.492	36.361	10.000
	Digital Talent	93.078	41.337	12.524
	(DT)	57.267	21.881	11.492
	Data Resource			
	(DR)			
	Policy			
	Ecosystem (PE)			
	Digital			
	Security(DS)			

In the dynamic QCA analysis, when the aggregated consistency level exceeds 0.9 and the coverage exceeds 0.5, it indicates that the causal variable is a necessary condition for the outcome variable. Table 2 shows that high digital talent (DT) and low digital innovation (~DI) exhibit both an aggregated consistency above 0.9 and a coverage exceeding 0.5, serving as necessary conditions for regional high-and non-high-tech innovation respectively, highlighting the pivotal role of digital talent and digital innovation in regional technological advancement. In the digital era, if a region lacks sufficient digital innovation capability, it is difficult to achieve high overall innovation performance. This theoretical inference is consistent with China's regional development reality: less-developed provinces, especially those in the central and western regions, typically have weak digital infrastructure, limited R&D investment in digital technologies, and scarce patent outputs in fields such as artificial intelligence and big data, resulting in relatively low levels of scientific and technological innovation.

4. Data Analysis and Empirical Results

4.1. Analysis of the necessity of individual conditions

Table 2. Necessary conditions analysis

Antecedent Conditions		Regional High-Tech Innovation (TI)				Regional Non-High-Tech Innovation (~TI)			
		Aggregated Consistency	Aggregated Coverage	Inter-group Consistency Adjustment Distance	intra-group Consistency Adjustment Distance	Aggregated Consistency	Aggregated Coverage	Inter-group Consistency Adjustment Distance	intra-group Consistency Adjustment Distance
	BI	0.893	0.828	0.104	0.239	0.489	0.589	0.180	0.590
Technical	~BI	0.557	0.456	0.212	0.461	0.857	0.912	0.191	0.175
Innovation	DI	0.853	0.898	0.090	0.303	0.430	0.587	0.267	0.677
	~DI	0.608	0.451	0.052	0.414	0.926	0.891	0.148	0.117
Organizati	DR	0.834	0.774	0.081	0.263	0.472	0.569	0.110	0.630
on	~DR	0.536	0.439	0.087	0.502	0.813	0.864	0.064	0.356
Developm	DT	0.908	0.871	0.052	0.216	0.467	0.581	0.217	0.613
ent	~DT	0.563	0.449	0.110	0.449	0.896	0.927	0.107	0.140
	PE	0.783	0.718	0.336	0.163	0.512	0.610	0.432	0.496
Environme	~PE	0.574	0.475	0.299	0.409	0.763	0.820	0.214	0.257
ntal	DS	0.871	0.843	0.064	0.216	0.486	0.611	0.165	0.566
Adaptation	~DS	0.598	0.472	0.055	0.420	0.875	0.898	0.072	0.222

Table 2 shows that the adjustment distance for inter-group and intra-group consistency exceeded 0.2 in several conditional variable groups,

indicating significant temporal differences and case heterogeneity. For causal combinations with an inter-group consistency adjustment distance greater than 0.2, following relevant studies [22], further in-depth analysis is required (Table 3).

Table 3. Causal combinations with inter-group consistency adjustment distances greater than 0.2

Causal Configurations	Index	Year	2019	2020	2021	2022	2023
Situation 1	$\sim BI/TI$	Inter-group Consistency	0.387	0.525	0.631	0.630	0.579
		intra-group Coverage	0.382	0.441	0.519	0.483	0.428
Situation 2	$DI/\sim TI$	Inter-group Consistency	0.600	0.359	0.395	0.387	0.390
		intra-group Coverage	0.686	0.563	0.528	0.547	0.573
Situation 3	$DT/\sim TI$	Inter-group Consistency	0.369	0.423	0.485	0.606	0.469
		intra-group Coverage	0.606	0.581	0.549	0.577	0.598
Situation 4	PE/T	Inter-group Consistency	0.901	0.905	0.396	0.963	0.807
		intra-group Coverage	0.650	0.706	0.905	0.670	0.799

Situation 5	$PE/\sim TI$	Inter-group Consistency	0.559	0.580	0.204	0.709	0.480
		intra-group coverage	0.638	0.627	0.483	0.581	0.660
Situation 6	$\sim PE/TI$	Inter-group Consistency	0.498	0.523	0.774	0.397	0.657
		intra-group coverage	0.416	0.473	0.484	0.538	0.476
Situation 7	$\sim PE/\sim TI$	Inter-group Consistency	0.694	0.728	0.960	0.597	0.854
		intra-group coverage	0.917	0.914	0.622	0.950	0.860

Table 3 demonstrates that in the process of regional high-tech innovation, none of situation 1, 2, 3, 5, or 6 exhibited inter-group consistency exceeding 0.9 or intra-group coverage surpassing 0.5, thus eliminating the need for further necessity analysis. However, situation 4 (high policy intensity [PE] and high technological innovation [TI] in 2019,2020, and 2022) and situation 7 (low policy intensity ($\sim PE$) and low technological innovation ($\sim TI$) in 2021) showed inter-group consistency exceeding 0.9 and intra-group coverage above 0.5, necessitating

verification through X-Y scatter plots of conditional variables versus outcome variables. Figure 2 reveals that in situation 4 (2019 and 2020), fewer than one-third of case points lie above the diagonal of the scatter plot, while cases from situation 4 (2022) and situation 7 (2021) predominantly cluster near the right Y-axis. Referring to studies by Schneider and Wagemann [42] as well as Tan Haibo et al. [43], although the consistency of these conditional variables passed the test, they still fail to constitute necessary conditions for regional high-tech innovation.

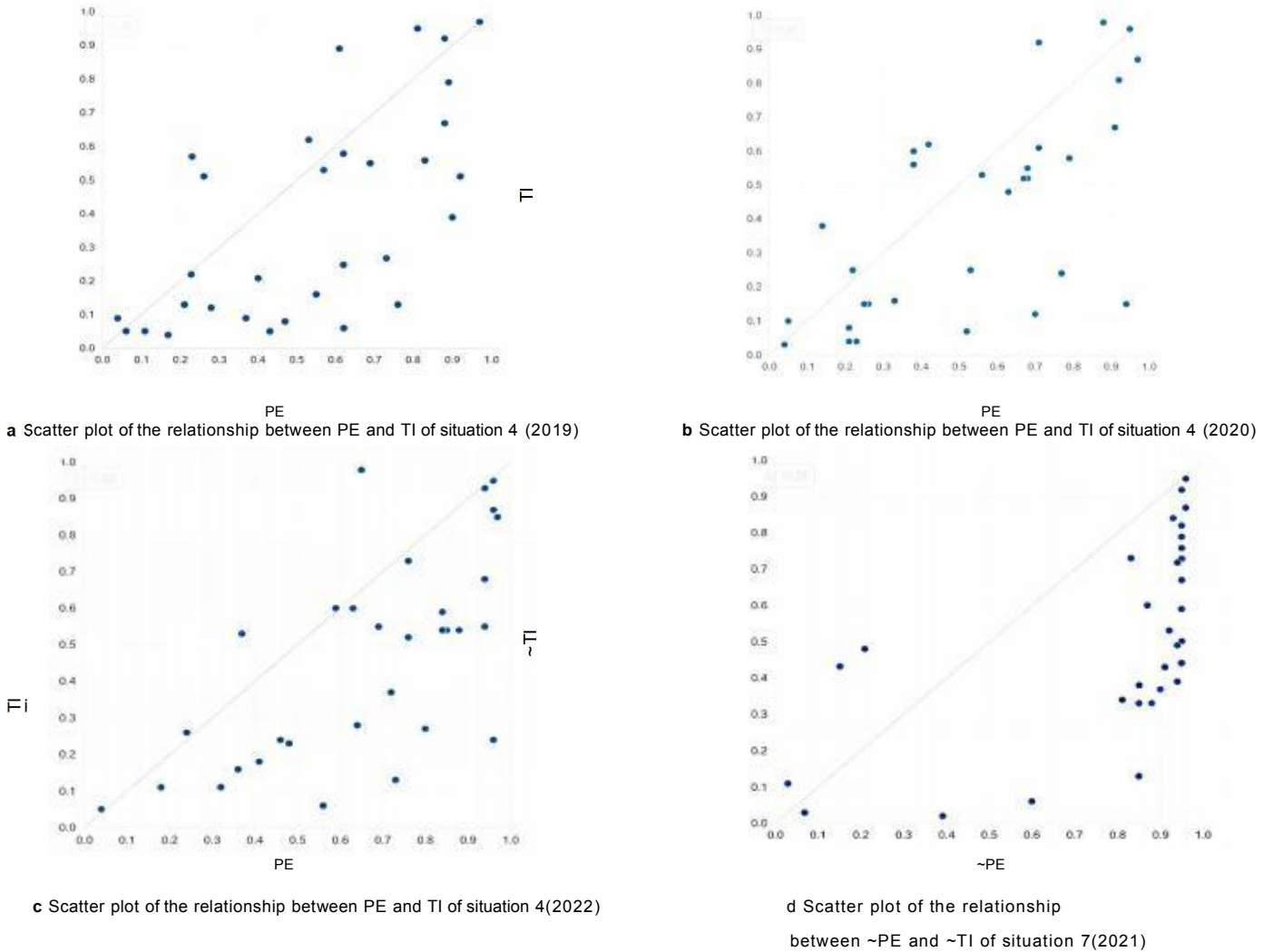


Figure 2. Scatter plot of necessity condition tests

4.2 Analysis of Condition Configuration Adequacy

4.2.1. Analysis of Summary Results

During the sufficiency analysis of condition configurations for regional technological innovation, the original consistency threshold was set at 0.8, the PRI threshold at 0.6, and the case frequency threshold at 1. Using R software, a truth table was constructed to analyze complex solutions, simple solutions, and intermediate solutions. Following established practice, the shared digital

ecosystem elements among simple and intermediate solutions were identified as core conditions, enabling configuration analyses for both

high-and low-tech innovation in the region; the results are presented in Table 4.

Table 4. Results of regional science and technology innovation configuration

Antecedent Conditions	High-Tech Innovation (TI)				Non-high-tech innovation (~TI)			
	Configuration H1	Configuration H2	Configuration H3	Configuration H4	Configuration L1	Configuration L2	Configuration L3	Configuration L4
Basic Infrastructure (BI)	■	▲		△	□	△		
Digital Innovation (DI)	■	■	■		□		□	
Digital Talent (DT)	■		▲	△				□
Data Resource (DR)	■	■	■			□		
Policy Ecosystem(PE)	▲	■	■					
Digital security (DS)	■		■			△		□
Consistency	0.979	0.983	0.986	0.986	0.954	0.933	0.938	0.941
PRI	0.953	0.959	0.967	0.968	0.917	0.881	0.886	0.897
Raw Coverage	0.770	0.618	0.618	0.611	0.799	0.840	0.789	0.772
Total Coverage	0.165	0.013	0.014	0.006	0.002	0.009	0.001	0.025
Inter-group Consistency	0.017	0.015	0.009	0.009	0.041	0.061	0.055	0.041
Adjustment Distance								
Intra-group Consistency	0.076	0.076	0.070	0.076	0.105	0.123	0.158	0.111
Adjustment Distance								
Overall Consistency		0.974				0.908		
Overall PRI		0.942				0.843		
Overall Coverage		0.803				0.950		

Note: ■ indicates the presence of core conditions, ▲ indicates the presence of peripheral conditions, □ indicates absence of core conditions, △ indicates absence of peripheral conditions.

(1) Configuration of Regional High-Tech Innovation. Table 4 shows that the overall consistency of digital ecosystem-driven regional high-tech innovation configurations is 0.974, exceeding the threshold of 0.8, indicating these configurations serve as sufficient conditions for regional high-tech innovation. The overall coverage rate reaches 0.803, demonstrating that four configuration pathways account for 80.3% of the sample cases, reflecting high validity. Consistent with Xu Shibo's [44] study, 36 cases fully meet all four configuration criteria across regions, exhibiting robust performance and serving as core case studies: Beijing, Shanghai, and Guangdong (2019–2023); Shandong (2020–2023); Zhejiang (2019,2020,2022,2023); Jiangsu and Fujian (2020,2022,2023); Hubei (2019,2022); Sichuan (2022,2023); Anhui (2020,2022); and Henan (2023). These regions possess strong digital ecosystems, where diverse and comprehensive configuration pathways have significantly enhanced their technological innovation capabilities.

Configuration H1: Technology-Dominated Type. This pathway is constituted by four peripheral conditions: basic infrastructure, digital innovation, digital talent, and digital security, with a configuration consistency score of 0.979, raw coverage rate of 77.0%, and unique coverage rate of 16.5%. Typical cases illustrating this pathway include Jiangsu Province in 2019; Shaanxi and Hunan Provinces in 2020; Henan Province from 2020 to 2022; Hubei Province during 2020–2021 and 2023; Sichuan Province in 2020 and 2021; and Anhui, Fujian, Jiangsu, Shandong, and Zhejiang Provinces in 2021. The mechanism underlying H1 lies in the provision of foundational digital capacities—infrastructure, innovation, talent, and security—which collectively establish a self-reinforcing cycle of technological capability accumulation. Infrastructure supplies the material basis for data generation and processing; digital innovation generates proprietary technologies that differentiate regional industries; digital talent ensures the effective deployment of these technologies; and digital security safeguards the trust environment necessary for sustained R&D activities. Together, these four elements

lower the marginal cost of knowledge production and enable rapid experimentation and iteration, making H1 a viable pathway even in regions with weaker organizational and environmental conditions.

Configuration H2: Technology-Organization-Dominated Type. This pathway comprises basic infrastructure, digital innovation, digital talent, data resources, and policy ecosystem. With the exception of peripheral policy elements, all components serve as core requirements, achieving a configuration consistency score of 0.983, raw coverage rate of 61.80%, and unique coverage rate of 1.3%. Typical cases illustrating this pathway include Henan Province in 2019. H2 operates through the synergy between technological assets and organizational absorptive capacity. While infrastructure and digital innovation provide the technological frontier, digital talent and data resources ensure that this frontier can be effectively absorbed, adapted, and commercialized within local firms and research institutions. The policy ecosystem, though peripheral, plays a coordinating role by aligning innovation incentives with regional development priorities. This configuration is particularly effective in regions where technological supply and organizational demand are well-matched, allowing for seamless translation of digital potential into innovation outcomes.

Configuration H3: Technology-Environment-Dominated Type. This pathway comprises basic infrastructure, digital innovation, policy ecosystem, digital security, and data resources. Apart from edge condition infrastructure, all other elements serve as core components, with configuration consistency reaching 0.986, raw coverage at 61.80%, and unique coverage at 1.4%. Typical cases illustrating this pathway include includes Fujian, Sichuan, Anhui in 2019, and Tianjin in 2020. H3 leverages the complementarity between technological advancement and institutional support. Digital innovation and infrastructure provide the technical means, while the policy ecosystem and digital security create a favorable institutional environment that reduces uncertainty and encourages long-term

investment in innovation. Data resources, as an edge condition, further amplify this effect by enabling evidence-based decision-making and knowledge spillovers across sectors. This pathway is especially relevant in regions where strong government commitment and institutional stability compensate for weaker organizational endowments.

Configuration H4: Organization-Environment-Dominated Type. This pathway comprises digital talent, data resources, policy ecosystem, digital security, and digital innovation. Apart from the peripheral factor of digital talent, all other elements serve as core components, with a configuration consistency score of 0.986, raw coverage rate of 61.10%, and unique coverage rate of 0.6%. Typical cases illustrating this pathway include Hunan Province in 2022 and Chongqing Municipality in 2023. H4 demonstrates that strong technological foundations are not the only route to high innovation; organizational and environmental factors can substitute for technological shortcomings. Digital talent and data resources furnish the human capital and informational inputs necessary for innovation, while the policy ecosystem and digital security provide the institutional infrastructure that protects and incentivizes innovation activities. This configuration validates the observation that regions with moderate technological endowments can still achieve high innovation performance by cultivating robust organizational capabilities and favorable institutional environments.

For the sake of brevity, the main text above reports only representative provinces for each configurational pathway. A comprehensive summary of all representative cases, along with the corresponding provincial policy initiatives and years, is provided in Appendix A, Table A1.

(2) Regional Non-high-Tech Innovation Configuration. Given the asymmetry in QCA configuration analysis results, it is essential to further identify five distinct configuration pathways for regional non-high-tech innovation, with an overall consistency score of 0.908 and coverage rate of 0.950. **Configuration L1:** Basic Infrastructure – Digital Talent Restriction. This configuration is characterized by inadequate infrastructure and a shortage of digital talent, with a consistency score of 0.954 and coverage of 79.9% of cases. Outdated digital infrastructure creates data silos, constrains real-time computing capacity, and impedes data flow and the effective circulation of innovation-critical information. Meanwhile, the scarcity of digitally skilled personnel weakens technological R&D and iteration capabilities, while also diminishing the region's absorptive capacity and knowledge-creation ability. Together, these factors restrict the region's capacity to attract and sustain high-end innovation resources, forming systemic constraints that hinder long-term innovation upgrading. **Configuration L2:** Digital Technology Restriction. Marked by deficient core infrastructure and a lack of digital innovation, this configuration shows a consistency score of 0.933 and covers 84.0% of cases. The absence of proprietary digital innovation locks the region into low-value-added activities, stifles breakthrough momentum, and prevents the emergence of disruptive technologies and competitive emerging industries. Coupled with weak core infrastructure, which further limits the scale and scope of pilot applications, these deficiencies together severely decelerate the overall pace of regional innovation. **Configuration L3:** Basic Infrastructure – Digital Security Restriction. Featuring insufficient infrastructure and gaps in digital security, this configuration achieves a consistency score of 0.938 and covers 78.9% of cases. Inadequate digital security heightens the perceived risk of data leakage and intellectual property infringement, discouraging firms from engaging in open collaboration and knowledge sharing, thus threatening R&D data and intellectual property protection. Outdated infrastructure simultaneously constrains the potential for innovation. Together, these factors form a "systemic risk" and a vicious cycle that undermine both the foundation and the potential of regional innovation, severely hampering its development. **Configuration L4:** Digital Innovation–Data Resource Restriction. Defined by the dual scarcity of digital innovation capabilities and data resources, this configuration exhibits a consistency score of 0.941 and encompasses 77.2% of cases. The absence of digital innovation outputs and accessible data resources deprives the region of the essential inputs for evidence-based R&D and iterative experimentation. Without novel technologies or reliable data, innovation activities become arbitrary and inefficient, making it difficult to achieve

precise decision-making and rapid iteration, thereby constraining innovation quality and efficiency and consistently yielding low innovation performance. **Configuration L5:** Digital Talent – Digital Security Restriction. The core conditions of this configuration are deficiencies in digital talent and digital security, with a consistency of 0.950 and coverage of 82.2% of cases. The shortage of digital talent leads to a critical void in R&D manpower, while weak cybersecurity undermines the trust environment necessary for cross-organizational cooperation. This dual deficiency creates an "innovation suffocation" effect, where the departure of skilled workers and the collapse of collaborative networks together stifle the regional innovation ecosystem, leaving R&D entities absent and the innovation ecology continuously deteriorating.

4.2.2. Inter-group analysis of high-tech innovation configurations – Time effect

To overcome the limitations of traditional QCA in temporal analysis, dynamic QCA was employed to analyze changes in inter-group consistency levels across regional high-tech innovation configurations driven by digital ecosystems (Figure 3), thereby revealing the evolutionary trajectory of these configurations.

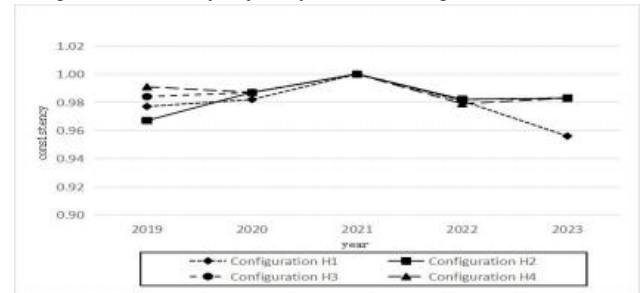


Figure 3. Level of inter-group consistency in regional high-tech innovation configurations

Figure 3 illustrates the evolutionary trajectory of configuration consistency levels across regional high-tech innovation clusters, demonstrating pronounced dynamic characteristics.

From the perspective of configuration evolution, four distinct phases can be identified: (1) 2019–2020: Consistency levels among Configuration H1, H2, and H3 improved, while those for H4 declined; (2) 2020–2021: Consistency levels across all configurations showed an overall upward trend; (3) 2021–2022: Consistency levels generally decreased across all configurations; (4) 2022–2023: Consistency levels for H2, H3, and H4 gradually recovered, whereas H1 continued to decline. The year 2021 marked a pivotal turning point in this evolutionary process. To further examine whether 2021 constitutes a genuine turning point, this study conducted a placebo test by removing the 2020 data and re-analyzing the evolutionary trajectories of the four configurational pathways using the remaining data from 2019, 2021, 2022, and 2023. The results show that all four pathways exhibited the same turning pattern—a rise followed by a decline in 2021—thereby confirming the robustness of 2021 as a critical turning point in configurational consistency.

From the perspective of co-evolution theory, the differentiated responses of each path to the 2021 shock fundamentally reflect differences in the strength of synergistic coupling among the technological, organizational, and environmental factors within each configuration, as well as differences in their evolutionary inertia. When an external shock disrupts the existing co-evolutionary equilibrium, if there is strong complementarity and redundancy between core and peripheral conditions, the system can mitigate the shock through dynamic reconfiguration among elements. Conversely, if core elements are heavily dependent on a single technological dimension and are only weakly coupled with other dimensions, the co-evolutionary path is more prone to disruption. The core conditions of H1 are entirely anchored in technological factors, with relatively weak co-evolutionary relationships with organizational and environmental factors; thus, external disturbances are rapidly

amplified through the technological chain, triggering a sharp decline. H2 and H3, by incorporating organisational or environmental buffering factors that exhibit complementary co- evolution with the technological core, can partially absorb the disturbance and maintain path continuity. H4, dominated by organisation- environment co- evolution, experiences only limited impact from technological fluctuations on its core co- evolutionary relationships, displaying greater evolutionary stability. Therefore, the co- evolutionary perspective reveals that a path's resilience to external shocks depends not only on the vulnerability of its core conditions, but also on the depth of co- evolutionary interdependence between core and peripheral conditions and the capacity for substitutive reconfiguration—a mechanism that can provide theoretical support for understanding the divergent trajectories of different configurations after a turning point.

In terms of configuration development levels, only Configuration H2 demonstrated an improvement in consistency over the five-year period (from 0.967 to 0.983), while the consistency levels of all other configurations declined. Specifically, Configuration H1 saw the largest decrease (from 0.977 to 0.956), whereas Configurations H3 and H4 experienced minor declines (from 0.984 and 0.991 to 0.983 and 0.983, respectively). The robust performance of Configuration H2 can be attributed to its four core pillars — digital innovation, digital talent, infrastructure, and data resources—all of which serve as key focal points for regional scientific and technological innovation at present. Combined with marginal supportive policy and institutional arrangements, these elements collectively foster a sound sci-tech innovation ecosystem, enhancing the stability and explanatory power of this development pathway. Configuration H2 is expected to emerge as a core enabling pathway in the next phase.

We acknowledge that alternative explanations — such as measurement standard changes in the two evaluation reports or potential outlier effects—could, in principle, influence our findings.

However, we argue that these factors are unlikely to undermine the identified turning point. First, according to the annual methodological

documentation of both reports, the indicator frameworks of the Digital Ecosystem Index Report and the China Regional Scientific and Technological Innovation Evaluation Report have remained largely consistent throughout the study period, minimizing the risk of artificial breaks in the time series. Second, the turning pattern consistently appears across all four configurational pathways, making it improbable that a single outlier or minor measurement adjustment could artificially generate such a systematic structural shift. Moreover, in QCA analysis, extreme cases do not exert the same leverage as in regression- based models, as the truth table algorithm minimizes their influence through set- theoretic aggregation. Therefore, while we cannot entirely rule out these possibilities, the collective evidence supports the robustness of our core conclusion.

4.2.3 Intra-group analysis of high-tech innovation configurations – spatial effects

From a spatial perspective, a intra-group analysis was conducted on the configurations driving regional high-tech innovation from 2019 to 2023. By examining their aggregated consistency (Figure 4) and coverage extent (Table 5), the study identified the spatial utility and regional suitability of these driving pathways.

(1) Configuration consistency. At the overall configuration level, the consistency scores of all four configurations across provincial regions exceeded 0.75, indicating strong explanatory power for high-tech innovation. Regarding regional variations, Configuration H1 and H3 demonstrated consistency above 1.0 in 21 provinces, H2 in 20 provinces, and H4 in 22 provinces, revealing differences in their effectiveness and applicability in empowering regional technological innovation. Western and less-developed provinces exhibited lower configuration consistency levels, primarily due to constraints such as weak digital infrastructure, limited digital talent, and insufficient data resources, which restrict the impact of digital ecosystems on innovation and highlight areas requiring improvement.

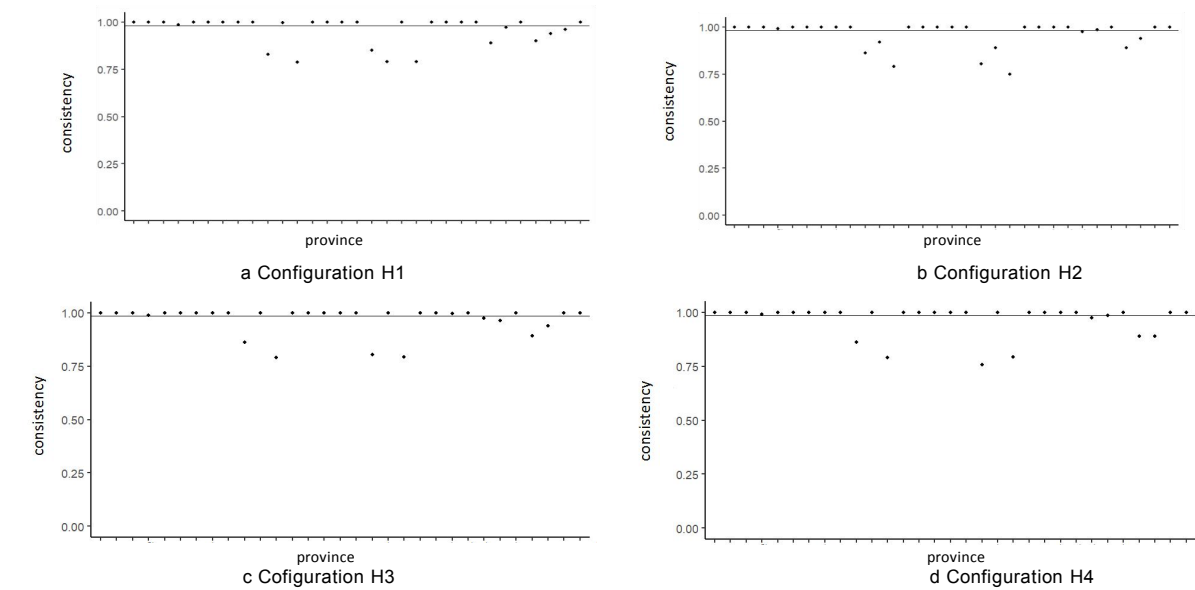


Figure 4. intra-group consistency of configurations H1 through H4

(2) Configuration coverage. Referring to relevant standards, sample cases were categorized into eastern (11), central (9), and western (11) regions, and a five-year configuration coverage analysis was conducted across these three regions.

Table 5. Coverage of high-tech innovation configuration regions

Eastern Region	0.814	0.654	0.654	0.641
Central Region	0.715	0.537	0.542	0.536
Western Region	0.547	0.495	0.483	0.488

In terms of coverage levels, Configuration H1 ("Technology-Dominated Type") exhibits the widest reach across eastern, central, and western regions, with coverage rates of 0.814, 0.715, and 0.547 respectively, indicating its broadest applicability; Configurations H2 ("Technology-Organization-Dominated Type") and H3 ("Technology-Environment-Dominated Type"), which represent regional innovation pathways driven by digital technology combined with organizational and environmental factors, demonstrate moderate coverage in eastern and central regions and relatively wide applicability; Configuration H4 ("Organization-Environment-Dominated Type"), by diminishing the direct driving role of digital technology, shows the lowest coverage in eastern and central regions and ranks third in western regions. The observed regional heterogeneity can be attributed to three mechanisms. First, the starting-point disparity mechanism: eastern regions possess well-developed digital infrastructure and mature innovation ecosystems, forming a virtuous cycle that translates digital endowments into innovation performance, whereas central and western regions lack the critical mass required for high-level innovation. Second, the factor circulation mechanism: eastern regions benefit from more efficient innovation factor markets, enabling seamless integration of capital, talent, and data, while central and western regions face constraints in computing power and data application scenarios that limit resource transformation. Third, the institutional environment mechanism: eastern regions exhibit higher marketization, stronger intellectual property protection, and greater enterprise digitalization, amplifying the innovation-enabling effects of digital policies—conditions less prevalent in central and western regions. These mechanisms explain why H1 (Technology-Dominated) has the widest regional coverage, while H4 (Organization-Environment-Dominated) performs poorly outside the east, as it relies on organizational and environmental factors that are less developed elsewhere.

In terms of configuration coverage, the eastern region exhibits the highest coverage rates at 0.814, 0.654, 0.654, and 0.641 respectively, with typical cases including Beijing, Shanghai, Shandong, Fujian, Guangdong, and Zhejiang, which aligns with research findings that digital-driven innovation effects are primarily concentrated in the eastern region [45]. The central region shows moderate coverage rates, with representative examples being Inner Mongolia, Hubei, Anhui, Henan, and Heilongjiang. The western region has the lowest coverage rates, exemplified by Xizang, Sichuan, Xinjiang, Shanxi, and Chongqing. This regional gradient distribution pattern of configurations corroborates the research conclusion that "the impact of digital transformation on technological innovation is not significant in central and western regions" [46].

4.3. Robustness Test

Referring to relevant studies, we conducted robustness tests on the configuration of regional high-tech innovation across three aspects: First, increasing the original consistency threshold from 0.8 to 0.85 yielded four configuration results identical to the original four; second, raising the PRI threshold from 0.6 to 0.65 produced four configuration results identical to the original four; third, adjusting the case frequency from 1 to 2 for testing revealed a clear subset relationship between the results after threshold adjustment and the original results. All these tests confirmed the stability of the original configuration structure, demonstrating strong robustness of the research conclusions.

5. Conclusion and Recommendations

5.1. Research Conclusion

Building upon the TOE theoretical framework and integrating co-evolution theory with resource-based theory, this study uses dynamic QCA methodology to analyze provincial panel data from 2019 to 2023. It systematically investigates the complex causal mechanisms through which digital ecosystems drive regional technological innovation, including the essential conditions for high- and low-tech innovation from a digital ecosystem perspective, four configurational pathways through which digital ecosystems empower high-tech innovation across regions in China (Technology-Dominated, Technology-Organization-Dominated

Technology-Environment-Dominated, and Organization-Environment-Dominated Type), five configurational pathways fostering non-high-tech innovation, the developmental levels, evolutionary trajectories, and key turning points of various innovation configurations over time, as well as their spatial utility and regional adaptability. These findings provide new theoretical foundations and policy insights for leveraging digital ecosystems to enhance regional technological innovation in China.

5.2. Theoretical Contributions

First, the dynamic QCA method was introduced into research on the relationship between digital ecosystems and regional technological innovation, expanding its application scope in innovation studies. By examining the co-evolution mechanisms of multiple factors across time dimensions, this approach overcomes the "static blind spots" inherent in cross-sectional data and traditional QCA methods [35], providing new methodological support for analyzing the complex processes through which digital ecosystems drive regional technological innovation, thereby enriching longitudinal research on regional innovation mechanisms under digital economic development. Second, based on the TOE framework, an integrated theoretical analysis framework for digital ecosystems was developed, systematically categorizing six key elements—basic infrastructure, digital innovation, digital talent, data resources, policy ecosystems, and digital security—into technical, organizational, and environmental dimensions. This enhances the systematicness and hierarchy of digital ecosystem theory construction, offering a solid theoretical foundation for subsequent research on decomposing and measuring regional digital ecosystem levels. Third, configurational comparison revealed the synergistic driving pathways of digital ecosystem elements from spatiotemporal perspectives, deepening the theoretical understanding that different approaches within digital ecosystems ultimately converge toward driving regional technological innovation.

5.3. Policy Recommendations

First, based on the necessary conditions identified in our analysis, we propose strengthening digital talent cultivation to secure high-tech innovation, while enhancing digital innovation capabilities to avoid non-high-tech innovation. Digital talent serves as the indispensable foundation for high-level regional innovation, and its strategic importance should be consistently prioritized in regional development planning. Concurrently, as low digital innovation is a necessary condition for non-high-tech innovation, regions must accelerate independent R&D and breakthroughs in core digital technologies to raise their overall digital innovation proficiency. This dual focus ensures that regions not only build the human capital essential for cutting-edge innovation but also prevent technological stagnation that traps them in low-level innovation trajectories.

Second, with respect to the four distinct configurational pathways for high-tech innovation, we propose differentiated policy strategies tailored to the digital ecosystem characteristics and innovation endowments of specific provinces. The four configurations exhibit varying applicability across regions, and policy design should align with local conditions. Configuration H1 (Technology-Dominated Type) is broadly applicable and exhibits the widest coverage across all regions (eastern: 0.814, central: 0.715, western: 0.547), making it a suitable core pathway for cross-regional promotion. This configuration has been observed in typical cases including Jiangsu (2019), Shaanxi and Hunan (2020), and Anhui, Fujian, Shandong, Zhejiang, Sichuan, and Henan (2021–2022). For these provinces, policy efforts should prioritize the coordinated development of digital infrastructure, digital innovation, digital talent, and digital security to establish a self-reinforcing cycle of technological capability accumulation. Configuration H2 (Technology-Organization-Dominated Type), which relies on the synergy between technological assets and organisational absorptive capacity (digital talent and data resources), shows high potential for driving future regional innovation, as its consistency has continuously increased throughout the study

period (from 0.967 in 2019 to 0.983 in 2023). Representative cases include Henan (2019). For provinces sharing similar characteristics, policies should focus on strengthening the interplay between digital talent pools, data resource sharing, and technological innovation, while optimising the policy ecosystem to align innovation incentives with regional development priorities. Configuration H3 (Technology - Environment - Dominated Type) leverages the complementarity between technological advancement and institutional support, with typical cases including Fujian, Sichuan, Anhui (2019), and Tianjin (2020). For these regions, policy measures should emphasise the construction of digital infrastructure and digital innovation capabilities, complemented by a robust policy ecosystem and digital security framework that reduce uncertainty and encourage long-term innovation investment. Configuration H4 (Organization - Environment - Dominated Type), centred on digital talent, data resources, policy ecosystems, and digital security, demonstrates that strong technological foundations are not the only route to high innovation. This pathway is particularly relevant for provinces where technological endowments are moderate but organisational and environmental factors are well-developed, with representative cases including Hunan (2022) and Chongqing (2023). Policy strategies for these regions should focus on cultivating digital talent, promoting open data sharing, refining digital policies, and strengthening digital security governance to create a favourable institutional environment that compensates for weaker technological foundations.

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H1	2021	Anhui, Fujian, Jiangsu, Shandong, Zhejiang, Sichuan	Digital computing center; talent programs; computing power networks
H2	2019	Henan	Digital economy key tasks; National Supercomputing Center; data sharing
H3	2019	Fujian, Sichuan, Anhui	5G industry opinions; AI key tasks; big data clusters
H3	2020	Tianjin	National AI innovation pilot zone; Ziguang Cloud; Huawei Cloud
H4	2022	Hunan	"Three Capabilities" support plan; digital talent cultivation
H4	2023	Chongqing	Talent aggregation; data element market reform



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Appendix A. Representative Cases and Provincial Policies for Each Configuration
(2019–2023)

Configuration	Year	Provinces	Key Policy Initiatives
H1	2019	Jiangsu	5G commercialization; information infrastructure; digital twins
H1	2020	Shaanxi, Hunan, Henan	5G base station planning; IC breakthroughs; 5G industry action plan