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Research on the Radiation Effect and Collaborative Path of Xi'an as a Central City's Innovation Function against the Background of High-Quality Development

Huan Liu

Institute for Tourism Studies, Xian International Studies University, Xian 710128, China

Abstract: Against the backdrop of high-quality development, this paper focuses on the radiation effect and collaborative paths of innovation function of Xi'an as a national central city. The study systematically summarizes the four-stage evolutionary characteristics of Xi'an's innovation function from single-core polarization to networked collaboration, and identifies three major collaborative obstacles: administrative barriers, industrial isomorphism and innovation chain rupture, as well as gradient gaps in the innovation ecosystem. On this basis, a three-dimensional mechanism framework of "space-industry-institution" is constructed to reveal the spatial friction caused by topographic barriers and transportation infrastructure, the bonding effect formed by industrial complementarity, and the barrier-breaking role of institutional coordination. In response to the above obstacles and mechanisms, this paper proposes a collaborative path system that optimizes spatial carriers through the "米"-shaped transportation network and zonal layout, promotes the in-depth integration of innovation chain and industrial chain with the Qinchuangyuan platform, and breaks down administrative barriers via cross-regional governance mechanism innovation. The results show that the systematic promotion of spatial restructuring, industrial collaboration and institutional innovation can effectively improve the innovation radiation efficiency of Xi'an, and provide theoretical support and practical paradigm for the high-quality development of urban agglomerations in western China.

Keywords: High-quality development, national central city, innovation radiation, regional coordination.

1. Introduction

High-quality development, as a core strategy for China to build a great modern socialist country in all respects [1], is essentially a fundamental transformation of the economic development model [2]. Its core momentum comes from innovation-driven growth, and its key pathway relies on regional coordination [3]. National central cities play a vital role in this strategic landscape: they are not only bearers of national strategies but also core growth poles that lead regional innovation, drive industrial upgrading, and radiate development to surrounding areas [4]. As the only national central city in northwest China, Xi'an is endowed with strategic roles including an economic center in western China and a sci-tech innovation center for the Silk Road [5].

However, a striking contradiction persists: Xi'an's strong endogenous innovation capacity has not been effectively transformed into spillover and radiation power over the Guanzhong Plain Urban Agglomeration [6]. The region features a distinct core–periphery structure, where innovation factors are highly polarized in Xi'an's main urban area, while neighboring cities such as Xianyang, Weinan, and Baoji present obvious characteristics of innovation depressions. As a result, scientific and technological achievements largely remain confined locally, with numerous technological outcomes "developed in Xi'an but commercialized in Shanghai, Jiangsu, Zhejiang and Guangdong". Although Shaanxi Province has launched the Qinchuangyuan Innovation-Driven Platform to tackle transformation bottlenecks through models such as enclave innovation and off-site incubation, it still faces deep-seated challenges including difficult cross-administrative coordination, weak industrial chain synergy, and large gradient gaps in the innovation ecosystem.

These practical dilemmas raise a series of core academic issues that urgently require solutions: First, what evolutionary logic does Xi'an's innovation function follow in the spatiotemporal dimension, and what key factors shape its current pattern? Second, how does Xi'an's innovation radiation effect differ in intensity and spatial regularity across spatial scales such as metropolitan area and urban agglomeration? Third, what are the major obstacles restricting cross-regional flow and efficient collaboration of innovation factors, and what is their relative importance? Fourth, how do spatial, industrial, and institutional factors behind these obstacles intertwine and function jointly? Fifth, facing the multidimensional goals of high-quality development, how to construct a systematic, precise and operable collaborative path system to substantially improve Xi'an's innovation radiation efficiency and promote higher-quality integrated development of the Guanzhong Plain Urban Agglomeration? In-depth exploration of these questions carries important theoretical innovation value and practical guiding significance.

Elevant foreign studies have formed a relatively mature theoretical system. Regarding innovation radiation [7], research is rooted in growth pole theory, spatial interaction theory and new economic geography. Early studies focused on the distance-decay diffusion of knowledge and technology. In recent years, research has delved into micro-mechanisms, emphasizing the complex impacts of multidimensional proximity (geographical, cognitive, institutional, social, etc.) on knowledge spillovers [8], and dialectically recognizing that radiation from core cities produces both diffusion effects that boost peripheral development and siphon effects that drain resources [9]. Studies on interactions between global innovation networks and local innovation systems have revealed pathways through which core cities embed into

global knowledge chains and radiate locally to drive regional upgrading [10]. On regional collaboration, research concentrates on cross-regional governance [11], exploring ways to overcome market segmentation and industrial isomorphism caused by administrative regional economies [12], highlighting the importance of effective coordination mechanisms, benefit-sharing and compensation schemes, and unified planning standards. Diverse collaborative models have emerged, including market-led [13] and government-guided approaches. Although there is no direct equivalent to the concept of high-quality development in foreign literature, its philosophy is fully reflected in studies on sustainable development, inclusive growth and green innovation, which emphasize innovation as the key to coordinating economic, social and environmental goals [14], with particular attention to green technological innovation and reducing regional inequality through knowledge diffusion. Domestic research has closely responded to national strategic needs [15]. Regarding innovation radiation from national central cities, numerous empirical studies using gravity models [16] and spatial econometric models have verified the existence of radiation effects, distance-decay regularities and circle-layer differences [17]. However, insufficient in-depth mechanistic analyses from an integrated perspective exist for insufficient radiation efficiency in western central cities such as Xi'an [18]. Research on regional innovation collaboration and cross-regional governance [19] is extensive, covering dynamic mechanisms, model classification and obstacle factors, with abundant summaries of collaborative models in developed regions such as the Yangtze River Delta and the Guangdong-Hong Kong-Macao Greater Bay Area [20], while studies in central and western regions focus more on breaking administrative barriers. The Qinchuangyuan Platform has attracted scholarly attention as a typical case, yet its in-depth operational mechanism and effectiveness evaluation of cross-regional collaboration still require further exploration. Regional collaborative innovation oriented toward high-quality development has become a cutting-edge topic, emphasizing that collaborative innovation should integrate quality improvement, structural optimization, green transition and common prosperity.

Overall, despite fruitful achievements, existing literature still leaves obvious room for expansion. First, the integration of research perspectives is insufficient. Most studies focus separately on spatial geography, industrial economy or institutional policy, with few systematically interpreting the interactive mechanism among spatial carrier, industrial content and institutional guarantee within a unified framework. Second, in-depth case studies on specific types of cities are lacking.

2. Research Methods and Study Area

2.1. Research Methods

2.1.1. Literature Research Method

This method runs through the whole process of initial theoretical construction and subsequent analysis of the research. It is mainly used to systematically sort out and review theoretical achievements and policy documents at home and abroad in the fields of innovation radiation, regional coordination, national central cities and high-quality development, so as to clarify the theoretical basis and analytical framework of the research, identify the deficiencies of existing studies, and provide a basis for the perspective innovation of this study.

2.1.2. Entropy Weight Method

The entropy weight method is employed to measure the urban innovation level of Xi'an. First, the original data are standardized. Then, the weight of each indicator is determined. Finally, the comprehensive innovation score is calculated using the linear weighting method. The specific steps are as follows. The original data are standardized according to indicator attributes to eliminate the influence of inconsistent dimensions on the results.

Positive indicators:

$$Z_{ij} = \frac{x_{ij} - x_{ij}^{\min}}{x_{ij}^{\max} - x_{ij}^{\min}} \ (i = 1,2,\cdots,m; j = 1,2,\cdots,n) \quad (1)$$

Negative indicators:

$$Z_{ij} = \frac{x_{ij}^{\max} - x_{ij}^{\min}}{x_{ij}^{\max} - x_{ij}^{\min}} \ (i = 1,2,\cdots,m; j = 1,2,\cdots,n) \quad (2)$$

2.2. Study Area

Xi'an is the only national central city in northwest China. In the national strategy for regional coordinated development in the new era, it undertakes multiple missions, including leading high-quality development in western China, promoting opening-up in inland areas, and advancing ecological conservation in the Yellow River Basin. This special status makes it a typical case for observing how national strategies are implemented in specific regions, how core urban functions evolve, and how cross-administrative coordination mechanisms are established.

3. Results and Analysis

3.1. Spatiotemporal Evolution Analysis of Xi'an's Innovation Function

Based on three dimensions: innovation resource agglomeration, innovation output efficiency, and innovation carrier density, this study selects core indicators including R&D investment.

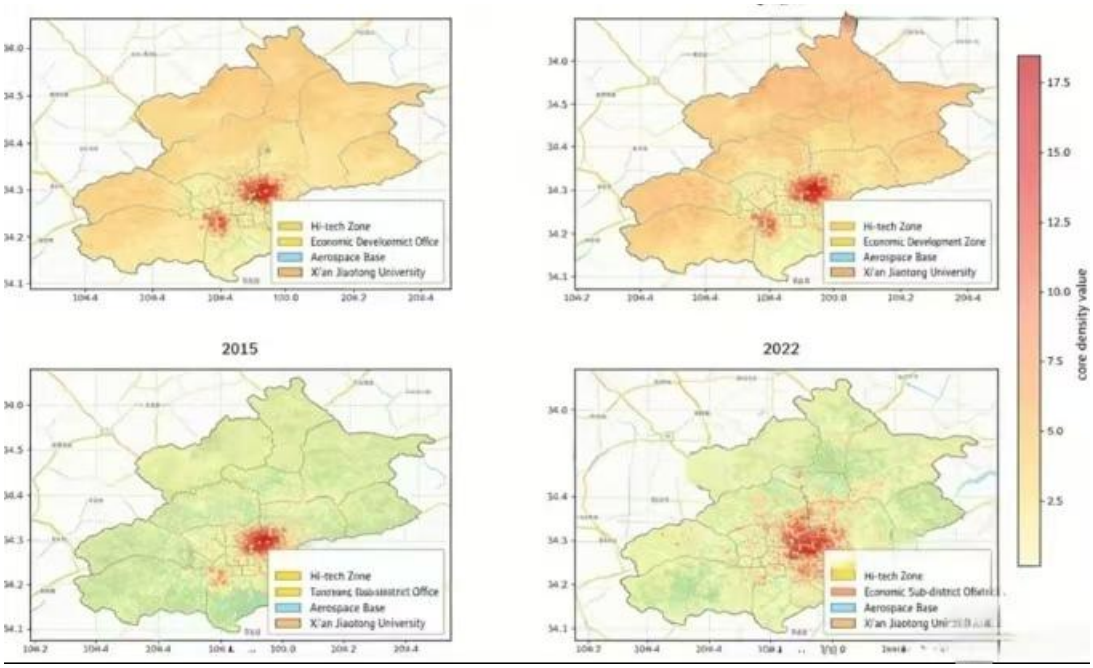

Figure 1. Spatial distribution map of kernel density of Xi'an's innovation function, 2010–2022

(1) 2015: Dual-Core Axial Extension

Two high-density zones (red) took shape: Yanta-Changan High-tech Zone and Weiyang-Economic Development Zone, with kernel density peaks of 7.9 and 5.3 respectively, indicating the initial formation of a dual-core structure. Medium-density zones (orange to red) extended in strips along Metro Line 2 and Line 3. Changan University Town and International Port Area became new innovation nodes, and innovation diffusion featured the "transportation corridor-guided" pattern.

(2) 2020: Multi-Core Diffusion Pattern

A new high-density zone (deep red) emerged in Xixian New Area, forming a "tripartite balance" with the original two cores. The coverage of high-density zones expanded by 127% compared with 2015, showing a significant policy-driven effect of the Qinchuangyuan Platform. Medium-density zones were continuously distributed in Yanta, Changan, Weiyang and Xixian New Area. Lintong Industrial Zone and Huyi High-tech Zone became suburban innovation agglomeration nodes, and the innovation space transformed from "point-based agglomeration" to "area-based expansion".

(3) 2022: Networked Collaborative Pattern

Four high-density zones (Yanta, Changan, Xixian New Area, Economic Development Zone) merged into a contiguous whole, forming a networked agglomeration pattern of "one main core and three sub-cores", with significantly improved spatial continuity of kernel density. Medium-density zones extended to Lintong, Yanliang and Linwei District of Weinan along the Beijing-Kunming Expressway and Lianyungang-Huozhou Expressway, forming a cross-city innovation agglomeration belt. The density values of low-density zones in remote suburban counties (Lantian, Zhouzhi) increased notably, and a full coverage of innovation across the region took shape.

3.2. Driving Forces of Evolution

As an institutional catalyst for the spatial evolution of innovation, policies guide the optimal allocation and spatial restructuring of innovation resources through strategic positioning, institutional innovation, and targeted carrier layout. The national strategy for developing central cities has defined Xi'an's core role as a science and technology innovation center in western China, integrating innovation radiation and regional coordination into the national strategic framework, thus providing institutional support for Xi'an to gather national-level innovation platforms and secure major scientific and technological projects. As a landmark regional policy platform, the Qinchuangyuan Innovation-Driven Platform focuses on the deep integration of the innovation chain, industrial chain, capital chain, and talent chain, addressing the "last-mile" problem in the commercialization of scientific and technological achievements.

Factor agglomeration constitutes the core foundation of Xi'an's innovation resource endowment. The continuous accumulation of innovation factors provides a solid source for the upgrading of Xi'an's innovation function, forming a supporting system centered on knowledge, capital, and talent. The intensity of R&D investment is significantly higher than the national average, with total R&D expenditure accounting for 5.23% of GDP, and the rising share of basic research funding ensures stable financial support for original innovation. The capital allocation mechanism has been continuously improved: the Xi'an Innovation Investment Fund adopts a strategy of "investing in early-stage, small-scale, and tech-oriented enterprises", leveraging social capital to flow into strategic emerging industries and establishing a multi-level sci-tech finance system of "parent fund – sub-fund – special direct investment". Xi'an also enjoys outstanding advantages in knowledge and talent resources, with 63 institutions of higher education and more than 460 research institutes, including 47 high-level research universities such as Xi'an Jiaotong University and Northwestern Polytechnical University. These institutions have accumulated profound expertise in aerospace, electronic information, new materials, and other fields, forming a core source of original innovation.

Market orientation serves as the core driver for the industrial transformation of innovation functions. Market demand guides the allocation of innovation resources through signal transmission, and the role of market mechanisms is reflected in three dimensions. First, demand-oriented technological breakthroughs: leading enterprises put forward technical demands for key industrial links and conduct

targeted R&D with universities and research institutes. Eight industries in Xi'an High-tech Zone have been selected into the national new-track cultivation plan, and the scale of the digital economy core sector has exceeded 280 billion yuan, demonstrating the effectiveness of market-led innovation. Second, market-based validation of innovation achievements: the Qinchuangyuan online platform integrates more than 13.5 million data entries, promotes the opening and sharing of 647 provincial-level R&D platforms, helps enterprises solve over 1,000 R&D needs through market-oriented matching, and accelerates the industrial application of scientific and technological achievements. Third, industrial ecosystem optimization and agglomeration: carriers such as the Medical Device Industrial Cluster in Xixian New Area have built a full-industry-chain service system through the "one zone, three centers" layout, attracting more than 100 medical device-related enterprises and forming a market-oriented industrial innovation cluster.

4. Obstacle Diagnosis and Mechanism of Collaborative Innovation

4.1. Obstacle Factor Diagnosis of Coordinated Development

Administrative Barriers: This factor has an average obstacle degree of 35.2%, ranking first, characterized by inter-provincial interest segmentation plus municipal administrative authority barriers. In terms of talent mobility, Xi'an accounted for 91.3% of newly added innovative talents in the Guanzhong Plain Urban Agglomeration in 2024, while cities such as Xianyang and Baoji showed weak net outflows. Mutual recognition of professional titles across Shaanxi, Shanxi and Gansu covers only 32 technical positions, and the approval time for part-time work by university research talents across regions is more than 50% higher than that for local positions. Regarding innovation resource sharing, technological achievement data from Xi'an's universities and pilot platform resources of Qinchuangyuan are restricted by administrative divisions, resulting in "data islands" with resource-based cities such as Yulin and Qingyang. The Xi'an Science and Technology Bureau has also explicitly noted problems of limited policy coverage and an underdeveloped cross-regional cooperation ecosystem.

Industrial Isomorphism and Innovation Chain Rupture: As a structural obstacle to collaborative transformation, this factor has an average obstacle degree of 28.7%, reflecting the dual contradiction of traditional industrial isomorphism and disconnected hard-tech industrial chains. In terms of industrial isomorphism, the overlap of equipment manufacturing and new energy battery industries among Xi'an, Xianyang and Baoji reaches 63%, and 40% of newly added new energy battery capacity in the three cities in 2023 was idle, leading to low-level competition. Innovation chain rupture directly exposes the weakness of Xi'an's hard-tech radiation: in 2024, only 41% of R&D achievements in Xi'an's semiconductor and aerospace industries were transformed within the Guanzhong Plain Urban Agglomeration, far lower than that of core cities in the Yangtze River Delta; the local matching rate of key components is less than 38%. For example, semiconductor materials used by Xi'an Yicai must be purchased from Jiangsu, while manufacturing bases in Tongchuan and Weinan struggle to undertake production due to mismatched technical standards. Although Qinchuangyuan's model of "R&D in Xi'an, transformation in prefecture-level cities" has been implemented, the linkage mechanism between the industrial chain and innovation chain remains imperfect, weakening the radiation effect.

Gradient Gap in Innovation Ecosystem: As a capability gap restricting the reception of innovation radiation, this factor has an average obstacle degree of 25.0%, forming an unbalanced pattern of strong agglomeration in Xi'an's core and weak ecosystems in surrounding areas. In innovation input, Xi'an's R&D expenditure accounted for 5.1% of GDP in 2024, while that of Weinan and Shangluo was less than 1.5%, and cities such as Yan'an and Qingyang still had R&D intensity below 1%. In terms of innovation carriers, 85% of Qinchuangyuan's high-end laboratories and incubators are concentrated in Xi'an High-tech Zone, and surrounding cities only undertake resources through enclave incubation. For instance, the core R&D team of Zhixin Epitaxial Semiconductor, an enterprise incubated in Tongchuan's enclave park, still needs to be permanently based in Xi'an.

5. Path Construction of Collaborative Innovation Oriented to High-Quality Development

Spatial Dimension: Space serves as the fundamental carrier for regional coordination. It is necessary to break topographic barriers through an intensified transportation network, optimize the innovation radiation pattern via tiered spatial layout, and form a spatial development structure of "core-led, multi-point supported, and regionally integrated". With Xi'an as the hub, transportation network construction will implement the "米"-shaped high-speed rail plan for the Guanzhong Plain Urban Agglomeration, focusing on the full completion of the Xi'an-Yan'an High-speed Railway, the capacity expansion of the Xi'an-Hancheng High-speed Railway, and the construction of intercity railways from Xi'an to Tianshui and Yuncheng, so as to achieve full high-speed rail coverage among all prefecture-level cities in the agglomeration by 2025. Meanwhile, branch lines of the Guanzhong intercity railway will be expanded to establish a "half-hour commuting circle" linking Xi'an with Xianyang, Baoji and Weinan, and an "one-hour economic circle" connecting Xi'an with Yan'an, Yulin and Qingyang, reducing the mobility cost of innovation factors through spatiotemporal compression. In response to topographic barriers in northern and southern Shaanxi, high-speed freight special lines from Xi'an to Ankang and Hanzhong will be planned and constructed, supported by logistics distribution centers in node cities including Tongchuan and Shangluo, aiming to improve regional logistics efficiency by more than 30% compared with 2024.

Industrial Dimension: Industrial coordination constitutes the core focus of innovation radiation. Guided by the Qinchuangyuan Platform, efforts should be made to address industrial isomorphism and chain disruption through industrial chain integration, innovation chain extension, and value chain upgrading, so as to build a modern industrial system with rational division of labor. In accordance with the resource endowments of each city, differentiated industrial division and strategies for chain supplementation and strengthening will be implemented. Xi'an will focus on high-end R&D sectors such as aerospace and integrated circuits; Baoji will specialize in manufacturing links including CNC machine tools and advanced structural materials; Yulin and Yuncheng will advance the high-end transformation of energy

and chemical industries; Weinan and Tongchuan will undertake supporting production of basic components. For key industrial chains such as semiconductors and new energy, Xi'an will take the lead in establishing industrial alliances and compiling industrial chain maps to clarify the division of labor among cities. The "chain leader system" will be adopted to promote the coordinated layout of leading enterprises. For example, BYD will be guided to set up its R&D headquarters in Xi'an, build battery component factories in Baoji, and arrange parts supporting bases in Weinan, with the goal of raising the local matching rate of the industrial chain to more than 60%.

Institutional Dimension: Institutional coordination is the key to breaking administrative barriers. Long-term guarantees for regional coordination will be established through governance mechanism innovation, coordinated policy implementation, and integrated factor markets, realizing the transformation from "territorial governance" to "collaborative co-governance".Based on the principle of "provincial overall planning and municipal implementation", the cross-regional collaborative governance mechanism will be upgraded. A substantive Executive Committee for the Coordinated Development of the Guanzhong Plain Urban Agglomeration will be established, led by Xi'an with the participation of relevant cities in Shaanxi, Shanxi and Gansu, to coordinate major issues including industrial layout, factor mobility and ecological protection. The "one office, eight groups" working mechanism of the Xi'an Metropolitan Area will be deepened, and a monthly consultation system among "four cities and one district" (Xi'an, Xianyang, Tongchuan, Weinan and Yangling) will be established to promote coordination in policy formulation, project approval and planning implementation. A special cross-regional working group will be set up in the field of scientific and technological innovation to coordinate specific issues such as the construction of innovation enclaves and the unification of technical standards.

6. Conclusions and Discussion

6.1. Conclusions

Guided by the dual strategic backgrounds of high-quality development and the construction of national central cities, this study takes the innovation radiation function of Xi'an (a national central city) and the coordinated development of the Guanzhong Plain Urban Agglomeration as the core research topics. It conducts a systematic investigation following the logical framework of "Background Definition - Evolution Analysis - Obstacle Diagnosis - Mechanism Analysis - Path Construction - Summary and Outlook". Theoretically, this research integrates regional innovation system theory, core-periphery theory, and collaborative governance theory to construct an analytical framework encompassing "Innovation Core Evolution - Collaborative Obstacle Identification - Multi-dimensional Mechanism Analysis - Systematic Path Construction". Methodologically, it comprehensively applies quantitative methods such as Kernel Density Estimation (KDE) and the Obstacle Degree Model, combined with case analysis, to achieve an organic integration of qualitative and quantitative research. Spatially, it takes Xi'an as the core research object and covers 11 sample cities in the Guanzhong Plain Urban Agglomeration, forming a "core-periphery" spatial research perspective. The main conclusions are as follows:

(1) A quantitative analysis based on panel data from 2010 to 2022 reveals that the spatial evolution of Xi'an's innovation function has experienced a four-stage transition: "single-core polarization - dual-core axial extension - multi-core diffusion - networked collaboration". In 2010, the High-tech Zone in Yanta District served as the sole high-density core with a kernel density peak of 8.6, presenting a typical "core-periphery" structure. By 2015, dual cores had formed in Yanta-Changan and Weiyang-Economic Development Zones, with innovation diffusion extending along traffic corridors. In 2020, Xixian New Area emerged as a new high-density zone, and the coverage of high-density areas expanded by 127% compared with 2015, reflecting the significant policy-driven effect of the Qinchuangyuan Platform. By 2022, the four high-density zones had merged contiguously, forming a cross-city innovation agglomeration belt and achieving full coverage of innovation functions across the region.

(2) The evolutionary process is collaboratively driven by four factors: policy guidance, factor agglomeration, transportation support, and market orientation. Policies act as an "institutional catalyst", anchoring the direction of innovation through the positioning of a national central city and the construction of the Qinchuangyuan Platform. Factor agglomeration provides a "source of support", with an R&D investment intensity of 5.23% and 63 institutions of higher education forming a comprehensive knowledge-capital-talent system. Transportation serves as a "spatial link", compressing the travel time for factor mobility within 1 hour via metro networks and cross-regional corridors. The market functions as a "transformation engine", with a turnover of 305.35 billion yuan in technology contracts guiding the industrialization of innovations. Together, these four factors have promoted the transformation of the innovation space from polarization to networking.

(3) Administrative barriers, industrial isomorphism and innovation chain rupture, and gradient gaps in the innovation ecosystem are the key obstacles restricting coordinated development, with a cumulative obstacle degree of 88.9%. Among them, administrative barriers pose the highest obstacle degree (35.2%), manifesting as "institutional barriers" such as the mutual recognition of professional titles across Shaanxi, Shanxi, and Gansu covering only 32 job categories and low efficiency in cross-regional approval. Industrial isomorphism and innovation chain rupture (28.7%) have led to a 63% overlap in the new energy battery industries of Xi'an, Xianyang, and Baoji, with only 41% of Xi'an's semiconductor achievements being transformed within the urban agglomeration. The gradient gap in the innovation ecosystem (25.0%) has created an unbalanced pattern of "strong agglomeration in Xi'an's core and weak ecosystems in surrounding areas". For instance, the R&D investment intensity in Weinan is less than one-third of that in Xi'an, and the shortage of high-skilled technicians in Yulin reaches 35%.

6.2. Discussion

The innovation radiation and regional coordination of Xi'an as a national central city constitute a long-term and systematic project that requires continuous optimization of paths and improvement of mechanisms in practice. The findings of this study can provide theoretical and practical support for this process, facilitating the high-quality integrated development of the Guanzhong Plain Urban Agglomeration and setting a precedent for regional coordination in western China. Future research can be

expanded in the following directions: First, expand the spatial scale by extending the research scope to urban agglomerations in the middle reaches of the Yellow River Basin. This will enable an exploration of the innovation collaboration and division of labor mechanisms between Xi'an and other core cities such as Taiyuan and Zhengzhou, as well as an analysis of radiation laws within a polycentric network. Second, deepen quantitative analysis methods by introducing spatial Durbin models, system dynamics, and other approaches. A quantitative model of "innovation input - radiation effect - collaborative performance" can be constructed to accurately measure the implementation effects of different paths. Third, strengthen policy tracking and evaluation. Establish long-term databases for policies such as the Qinchuangyuan Platform, and use the difference-in-differences method to evaluate the net effects of policies, thereby optimizing the combination of collaborative policy tools.

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