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Digital Technology Innovation and Regional Synergy Development of Urban Agglomerations in China

Binyu Wei[1], Jiawen Zhang[2], Waihang Yu[3]*, Yunhe Feng[4]

1. School of Finnance and Trade, Zhuhai College of Science and Technology, Zhuhai, 519041, China
2. School of Business, Macau University of Science and Technology, Macau, China
3. Faculty of Hospitality and Tourism Management, Macau University of Science and Technology, Macau, China
4. Kent School, Connecticut, United States

Corresponding author: Waihang Yu, whyu@must.edu.mo

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Abstract: Against the background of the Digital China strategy and integrated development of urban agglomerations, digitaldriven intercity linkage has become a core issue for regional highquality development. Taking China's five major urban agglomerations (the Yangtze River Delta, Pearl River Delta, Beijing-Tianjin-Hebei, Mid-Yangtze River, and Chengdu-Chongqing) as research samples, this paper adopts granted digitaleconomy patents to measure digital technological innovation. Based on prefecturelevel panel data from 2010 to 2024, this study combines timeseries statistical analysis and threedimensional kernel density estimation to systematically analyse the spatiotemporal evolution and internal distribution heterogeneity of digital technology innovation across urban agglomerations. The results indicate that digital innovation output of all five urban agglomerations presents a phased upward trend. A multitiered spatial hierarchy has gradually formed, with prominent Matthew effects: eastern coastal urban agglomerations take the lead in innovation scale, while centralwestern urban agglomerations grow from relatively low bases. Obvious intraagglomeration divergent evolution patterns are identified by kerneldensity results. The Yangtze River Delta and Pearl River Delta show the characteristics of overall upgrading and stratified differentiation; BeijingTianjinHebei and ChengduChongqing exhibit strong coreperiphery bipolar polarization; the MidYangtze River demonstrates multinode parallel development with intraregional gaps expanding first and then converging. Restricted by institutional barriers and siphon effects, digital innovation dividends cannot be spontaneously converted into regional linkage benefits. Targeted innovation strategies are therefore proposed for different types of urban agglomerations, together with a fivedimensional implementation framework covering innovationnetwork construction, factor transformation, public platform development, crossadministrative governance and gradientoriented coordination. This paper provides empirical evidence for understanding digitalmediated innovation patterns in Chinese urban agglomerations and offers policy references for advancing differentiated regional linkage development.

Keywords: Digital Technology; Regional Innovation; High-quality Development; Urban Agglomerations
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1. Introduction

Digital technologies represented by big data, artificial intelligence, cloud computing and digital platforms are restructuring

the spatial organisation of economic activities and innovation activities worldwide. Unlike traditional innovation activities that rely heavily on geographic proximity and face-to-face interaction, digital innovation enables knowledge, information and innovative resources to flow across administrative boundaries at lower cost, which creates new possibilities for breaking the spatial constraints of regional cooperation. As the primary spatial units for promoting coordinated regional development in China, urban agglomerations gather core innovation factors, undertake the task of building cross-city collaborative systems, and are regarded as key carriers to reshape the national spatial economic pattern. Against the national strategy of advancing digital China and promoting integrated development of urban agglomerations, exploring how digital innovation shapes intercity relationships has become an urgent practical issue.

Nevertheless, the real effects of digital technology innovation on regional linkage remain ambiguous in the Chinese urban agglomeration context. On the one hand, digital innovation can reduce information friction, optimise the allocation of innovation resources and facilitate the integration of industrial chains and market systems among cities, thereby strengthening regional linkages. On the other hand, uneven digital endowments, hierarchical city structures and intercity institutional barriers may lead to a digital divide within urban agglomerations. In such circumstances, digital innovation may instead widen intercity gaps and generate selective connection, failing to promote inclusive regional linkage. Such contradictory practical observations suggest that the linkage effect of digital innovation cannot be taken for granted. It is still unclear whether digital technology innovation can effectively facilitate regional linkage within China's urban agglomerations, through which pathways the effects operate, and whether substantial differences exist across urban agglomerations with varied development foundations. These uncertainties constitute the starting point of this paper.

This paper aims to examine the spatiotemporal patterns of digital technology innovation and its association with regional linkage development across China's urban agglomerations. Starting from digital technological innovation, it seeks to unpack how digital innovation reshapes the configurations of intercity linkages. Drawing on prefecture-level city data of China's major urban agglomerations, this study traces the temporal trends and spatial dynamics captured by digital patents and further explores heterogeneous responses across different urban agglomerations.

2. Literature Review

Digital technologies are continuously reshaping the structure of urban agglomeration innovation networks and regional coordination models. A systematic review of foundational theories and cutting-edge literature helps establish the analytical framework for this study, clarify existing research progress, identify knowledge gaps, and define the research entry point. As resource allocation theory and regional coordinated development theory have advanced, research perspectives have increasingly focused on the dimension of factor efficiency, highlighting that the fundamental challenges in urban agglomerations' innovative development stem from spatial mismatches and inefficient allocation of innovation-related factors such as talent, technology, and capital. Digital technologies can optimize cross-regional factor reallocation by improving information matching, thereby alleviating issues of resource idleness and supply-demand imbalance, effectively addressing shortcomings in traditional resource allocation models[1-2]. From a theoretical standpoint, regional coordinated development emphasizes institutional and governance dimensions, underscoring that breaking administrative barriers and achieving functional complementarity and shared benefits among regions are core objectives for integrated urban agglomeration development. Digital technologies offer feasible pathways for regional coordination by reducing transaction costs across regions and establishing collaborative governance platforms[3-4]. Overall, the mechanisms of micro-level innovation spillovers and the origins of spatial patterns jointly point toward resolving issues related to optimizing factor allocation efficiency and implementing regional coordinated governance, laying a theoretical basis for examining the spatiotemporal evolution of digital innovation and its linkage with intercity connection in urban agglomerations.

In the study of innovation networks and regional coordination within urban agglomerations, existing research has systematically analyzed the evolution characteristics and barriers to coordination in China's urban innovation systems from perspectives such as spatial structure, network collaboration, and institutional constraints. Scholars commonly employ spatial econometrics and complex network analysis to characterize structural features of innovation nodes across different urban clusters, including node hierarchy, spatial connectivity strength, network density, and core-periphery patterns. These

studies confirm that China's urban innovation development exhibits a distinct pattern of uneven hierarchy, with central cities consistently dominating the core positions in innovation networks while peripheral small and medium-sized cities remain disadvantaged in absorbing innovation[5-6]. Numerous studies have demonstrated that real-world challenges, such as administrative boundary fragmentation, local protectionism, homogenized industrial competition, and the absence of cross-regional benefit-sharing mechanisms are key bottlenecks restricting the free flow of innovation resources and hindering deep regional integration. Traditional innovation coordination among urban clusters heavily relies on geographical proximity and physical industrial complementarity, resulting in significant distance decay effects in knowledge and technology spillovers, which further entrenches the core-periphery spatial structure[7]. Existing works include case analyses of individual urban clusters to identify network structures and test influencing factors, as well as comparative analyses across China's major urban agglomerations to interpret the dynamic restructuring of urban innovation networks amid digital transformation. Nevertheless, most studies treat digital development as a contextual background variable rather than the core innovation subject, and few independently trace the spatiotemporal dynamics of digital technology innovation itself.

With the deepening advancement of the digital economy strategy, the role of digital technologies in promoting coordinated development among urban clusters has gradually become a key research focus in regional economics. These studies have moved beyond traditional limitations imposed by geographical constraints and administrative boundaries, establishing an analytical framework for integrated urban cluster development from a digital and networked perspective. Existing research systematically demonstrates the enabling value of digital technologies for coordinated urban development across three dimensions: theoretical mechanisms, empirical effects, and practical pathways. It is clear that digital technologies can effectively break down regional segmentation barriers and continuously reduce transaction costs for cross-regional collaboration through digital transformation of production factors, networked information dissemination, and intelligent governance upgrades, thereby reshaping patterns of innovation factor flows and spatial spillover mechanisms within urban clusters[8-9]. Empirical studies further confirm that digital economic development, joint construction of cross-regional digital platforms, and orderly circulation of data elements significantly promote innovation coordination, industrial synergy, and integration of public services in urban clusters. They also optimize the industrial division systems of urban clusters, facilitating a transition from traditional agglomeration-based development to networked, collaborative growth, and supporting the formation of multi-center innovation structures[10]. Some studies rely on qualitative theoretical reasoning or case analyses of specific urban clusters, while others conduct nationwide comparative studies of different urban clusters. However, prior literature often conflates broad digital economy indicators with digital technological innovation measured by digital patents. Less attention has been paid to how digital innovation itself shapes regional linkage, and heterogeneous responses of regional linkage to digital innovation shocks across different urban agglomerations remain underexplored.

In summary, academic research has established a solid foundation in areas such as digital technology innovation, urban agglomeration innovation networks, and regional coordinated development. These studies have thoroughly demonstrated the enabling value of digital technologies for urban innovation, the uneven structural characteristics of urban agglomeration innovation networks, and the pivotal role of digitalization in promoting regional coordination. They have also clarified how traditional geographical constraints and administrative barriers hinder innovation linkages within urban clusters, providing a robust theoretical foundation and valuable reference for this study's exploration of how digital technologies empower urban cluster innovation and regional integration[11]. Building on this literature, this paper takes digital patent-based digital innovation as the starting point, and further examines its spatiotemporal distribution and linkage relationship with regional coordinated development across China's urban agglomerations.

3. Spatiotemporal Evolution Characteristics of Digital Technology Innovation in China's Urban Agglomerations

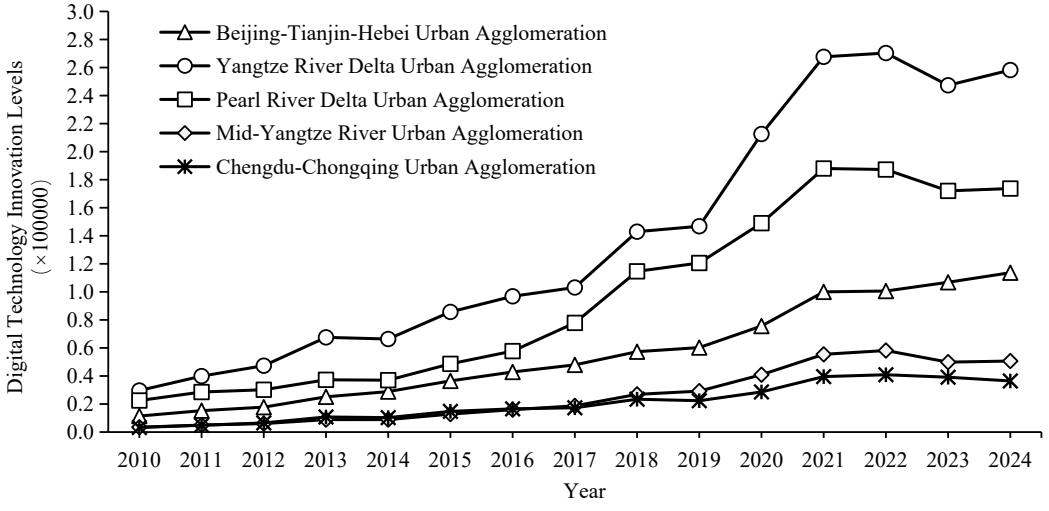
This study adopts the number of digital economy patents granted as a proxy indicator for the level of digital technological innovation[12-13]. Based on panel data from five major urban agglomerations spanning 2010–2024, combined with time-series evolution charts, we depict the trends in digital technological innovation and analyze the spatial differentiation patterns of innovation across urban clusters from a geographical perspective. We further elucidate the mechanisms through which digital

technology enhances regional coordination among urban agglomerations, and examine the practical challenges currently facing inter-agglomeration digital innovation collaboration. These findings provide empirical foundations for developing differentiated innovation strategies and regional coordination pathways discussed later.

3.1 Temporal and Spatial Evolution Characteristics of Digital Technology Innovation l; Evels in the Five Major Urban Agglomerations

Figure 1 shows the trend in digital technology innovation levels of the five major urban clusters, Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta, Mid-Yangtze River Region, and Chengdu-Chongqing, from 2010 to 2024, measured by the total number of authorized digital economy patents. Overall, in 2010, all five urban clusters had relatively low patent authorization volumes, with only modest differences in their digital technology innovation levels. From 2010 to 2017, patent authorizations across these regions grew steadily, indicating a phase of gradual accumulation in digital innovation. After 2017, the pace of digital innovation accelerated significantly, and patent authorizations entered a period of rapid growth, reflecting the impact of digital industry policies and the industrialization of next-generation information technologies, which continuously expanded regional digital innovation output. Around 2021, most urban clusters reached a temporary peak in digital patent authorizations, followed by a slight decline between 2021 and 2023, before stabilizing and recovering in 2024. This fluctuation pattern is closely related to cycles in digital technology R&D, patent examination processes, and changes in the external industrial environment.

Figure 1. Digital Technology Innovation Levels of China's Five Major Urban Agglomerations



From the perspective of urban clusters, the Yangtze River Delta has consistently ranked first, demonstrating significant advantages in digital technology innovation and development. As early as 2010, the Yangtze River Delta already had the highest foundation for digital innovation among the five major urban clusters, and after 2017 its growth rate increased markedly, rapidly widening the gap in innovation output compared to other clusters. It reached a peak in 2021, followed by a slight decline but still maintaining an absolute leading position, reflecting the strong support from a comprehensive digital industrial system and an intercity innovation collaboration network that continuously drives digital patent output. In contrast, the Pearl River Delta ranks second overall in digital technology development, with a temporal evolution trend highly similar to that of the Yangtze River Delta. The number of authorized digital economy patents in the Pearl River Delta steadily rose, peaking in 2021 before experiencing a slight downturn. Its overall innovation output volume remains second only to the Yangtze River Delta. Relying on a market-oriented regional innovation environment, the cluster has seen robust growth in application-oriented digital patents, although it also experienced a phase of temporary adjustment later on. By comparison, the Beijing-Tianjin-Hebei urban cluster has shown continuous and steady improvement in digital technology innovation, with relatively smaller fluctuations. The number of authorized digital economy patents in this region has maintained a year-on-year upward trend without evident peaks and subsequent declines, indicating a more gradual growth pattern. This reflects its innovation output being heavily dependent on research institutes and universities in Beijing, resulting in stable production

of foundational digital patents at the frontier, though the elasticity of patent growth in industrialization lags behind that of the Yangtze River Delta and Pearl River Delta. The Mid-Yangtze River Region has sustained continuous growth in digital innovation, currently in a stage of cultivation and ascent. Starting from a low base in 2010, its growth accelerated after 2017, gradually forming a stable trajectory. However, its total number of digital patents remains significantly lower than the three major eastern urban clusters. Under a multi-center innovation structure, digital innovation outputs from Wuhan, Changsha, and Nanchang are progressively emerging, yet the overall scale of innovation still lags behind. Finally, the Chengdu-Chongqing urban cluster started with the lowest base but has maintained consistent growth, positioning it as a promising cluster. Its authorized digital economy patents accumulated slowly between 2010 and 2020, then saw accelerated growth after 2020. Nevertheless, it has remained at the bottom among the five major clusters. Its dual-center digital innovation system is still under development, and there remains substantial room for growth in patent output. Overall, the time-series differences reveal a gradient differentiation in digital technology innovation levels across the five urban clusters: mature coastal clusters in the east have earlier starts and larger patent accumulations, while central and western clusters began from lower bases but have maintained long-term growth, gradually revealing their potential as latecomers in digital innovation.

From a spatial perspective, the innovation capacity among urban agglomerations has continued to diverge, forming a stable gradient-based spatial pattern. In 2010, the scale of digital economy patent grants across the five major urban agglomerations was generally low, with minimal gaps between the curves and relatively small differences in regional digital innovation output, indicating limited spatial variation. Over time, however, digital patent outputs across all urban agglomerations have steadily increased, though at significantly different rates. The vertical distances between the curves have widened progressively, gradually establishing a tiered innovation hierarchy among the five regions. The Yangtze River Delta urban agglomeration consistently ranks at the top, far outpacing others in innovation volume, while the Chengdu-Chongqing region remains at the bottom. This indicates that digital innovation resources continue to concentrate spatially in mature eastern urban clusters, reinforcing inter-agglomeration spatial imbalance over time and revealing an increasingly pronounced Matthew effect[14-15]. Meanwhile, the spatial response dynamics of innovation growth vary across urban agglomerations, exhibiting phased spatial differentiation. From 2010 to 2017, all five urban agglomerations experienced steady but gradual increases in digital innovation, accumulating slowly and synchronously, resulting in a relatively stable spatial structure. After 2017, the Yangtze River Delta and Pearl River Delta saw sharp increases in their growth slopes, with rapid surges in digital patent output, pulling ahead of the other three agglomerations. The Beijing-Tianjin-Hebei region maintained a steady and uniform pace without explosive growth, while the Middle Yangtze and Chengdu-Chongqing regions showed modest acceleration but limited upward movement. These temporal differences reflect stage-specific characteristics in spatial evolution: mature eastern urban clusters entered the phase of accelerated digital innovation earlier, whereas digital innovation gains in central and western regions emerged later, leading to asynchronous entry into expansion phases. After 2021, the curves for the Yangtze River Delta and Pearl River Delta began to decline from their peaks, while the other agglomerations showed only minor fluctuations, further highlighting the phased adjustment typical of high-level eastern urban clusters, as opposed to the ongoing growth phase observed in central and western regions. Consequently, over time, this spatial structure has evolved from a low-level equilibrium toward a multi-tiered hierarchy characterized by high-level leadership and parallel development[16]. At the beginning of the study period, all five urban agglomerations were at similar low levels of innovation, reflecting a state of low-level spatial equilibrium. As digital patent outputs continued to rise, the Yangtze River Delta and Pearl River Delta emerged as first-tier digital innovation hubs; Beijing-Tianjin-Hebei formed the second tier, maintaining a stable mid-to-high level of innovation; the Middle Yangtze region ranked third, steadily catching up; and the Chengdu-Chongqing region remained in fourth place, serving as a potential growth area. Thus, a multi-tiered spatial structure has gradually taken shape, with each tier assuming distinct roles within the digital innovation system and displaying a clear evolutionary pattern of eastern leadership and central-western followership. The technological innovation hierarchy among urban agglomerations has remained largely unchanged, with their rankings staying stable over time and no instances of cross-tier overtaking occurring. Although both the Chengdu-Chongqing and Middle Yangtze regions have seen year-on-year increases in digital patent grants, the growth rates in the Yangtze River Delta and Pearl River Delta have been substantially

higher, causing the absolute gap in innovation output to widen continuously. The spatial hierarchy of digital innovation thus demonstrates strong stability.

3.2 Dynamic Evolution Characteristics among the Five Major Urban Agglomerations

This section employs kernel density estimation to capture the dynamic characteristics of the temporal evolution of digital technology innovation levels across urban agglomerations. Kernel density estimation is a non-parametric approach widely used to identify spatial imbalance by fitting continuous density curves to the distribution of observations, which can overcome the limitation of simple descriptive statistics that only reflect aggregate mean performance and fail to reveal the internal distribution structure, multimodal features and dynamic convergence or divergence of the sample[17]. Using Matlab, we plot three-dimensional kernel density surfaces for digital technology innovation of the five major urban agglomerations. Different from two-dimensional static kernel density plots, the three-dimensional surface integrates the cross-sectional distribution and time dimension, enabling us to track the continuous evolution of distribution patterns year by year. The analysis focuses on four dimensions of the density curves: peak position, moving trend, distribution width, and polarization features.

Figure 2 presents three-dimensional kernel density plots of digital technology innovation levels for the Yangtze River Delta, Pearl River Delta, Mid-Yangtze River, Chengdu-Chongqing, and Beijing-Tianjin-Hebei urban agglomerations, illustrating the evolutionary dynamics of digital innovation from 2010 to 2024. Overall, all five agglomerations witness a consistent upward trend in digital innovation, yet substantial heterogeneity exists in their internal concentration patterns, polarization trajectories and the speed of distribution upgrading. Such divergent evolutionary paths are not merely the outcome of differences in innovation resource endowments, but also reflect the constraints of intercity governance structures, administrative coordination mechanisms and industrial foundation within each urban agglomeration. First, regarding the location and shifting direction of the main peak, the kernel density surfaces of all five urban agglomerations shift rightward over time, but the magnitude of movement, the smoothness of the shift and distribution coverage differ markedly. The continuous rightward drift of the main peak in each region signals a general rise in digital innovation capacity across the sample period, which coincides with the nationwide rollout of digital infrastructure construction, digital industry support policies and the patent incentive system after 2010. In terms of distribution range, the Yangtze River Delta and Pearl River Delta show the most prominent rightward shift of the main peak and the whole density surface, with their high-value intervals extending far to the right. Their density surfaces gradually form a flattened and stretched shape, indicating that a growing number of cities have crossed the medium-level innovation threshold and entered the high-value interval. By comparison, the main peaks of Chengdu-Chongqing and Mid-Yangtze River remain largely clustered within the low-value interval (0-5), with modest rightward displacement. Although their innovation levels have improved slowly, the overall distribution is still trapped in the low-level range, and only a tiny fraction of cities can break through to the medium and high innovation tier. The main peak of the Beijing-Tianjin-Hebei agglomeration is also positioned relatively leftward. This pattern demonstrates that the digital innovation development of coastal eastern urban agglomerations (Yangtze River Delta, Pearl River Delta) is ahead of the central, western and northern counterparts, forming a spatial gradient where eastern coastal regions lead while central and western regions lag behind. This gradient is closely tied to the early accumulation of high-tech industries, market-oriented innovation environment and complete industrial supporting chains in the coastal regions.

Second, peak height and surface shape reveal divergent patterns of internal concentration and inequality. The Chengdu-Chongqing urban agglomeration has the steepest and tallest main peak (nearly 0.8), which implies that most prefecture-level cities in this region are concentrated at a narrow, low level of digital innovation, reflecting pronounced low-level clustering. This low-level agglomeration suggests that the spillover effect originating from Chengdu and Chongqing has not effectively diffused to surrounding prefecture-level cities; the innovation radiation channel is blocked, and the vast majority of peripheral cities lack independent digital innovation capacity. For the Mid-Yangtze River agglomeration, the main peak height fluctuates over the period: it first declines and then rebounds, which suggests that inter-city innovation gaps initially widened moderately before gradually converging. The fluctuation can be partly attributed to the relatively independent provincial administrative divisions within the Mid-Yangtze River region. Wuhan, Changsha and Nanchang each serve as provincial cores, and the competition among provincial capitals once enlarged innovation gaps, while subsequent cross-provincial

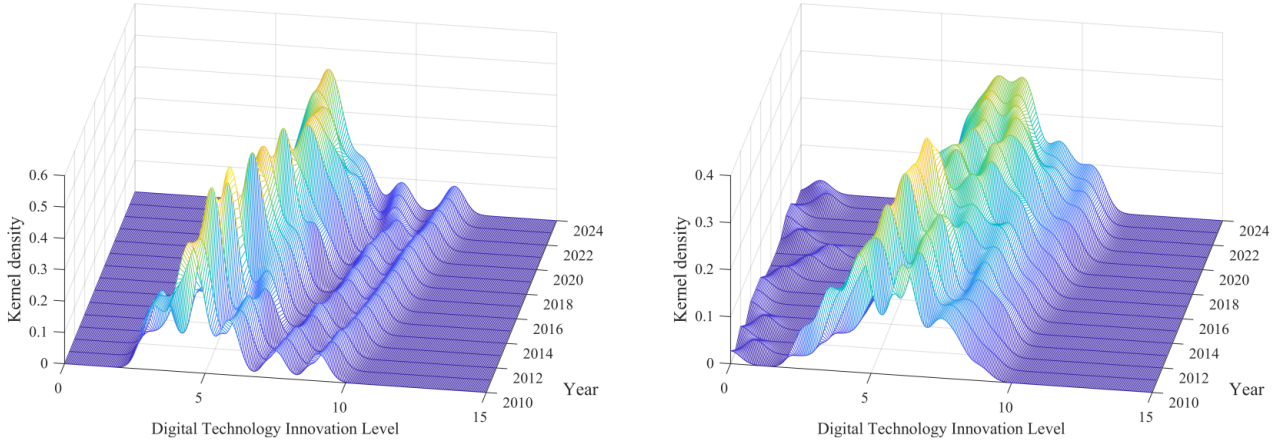
coordination policies promoted the re-convergence of regional innovation distribution. By contrast, the Yangtze River Delta and Pearl River Delta exhibit relatively gentle, low main peaks, and their density surfaces gradually broaden year by year. This indicates that while these two advanced agglomerations achieve rapid overall innovation growth, absolute disparities among internal cities are gradually enlarging. The broadening distribution does not mean deterioration of coordinated development; instead, it reflects a stratified and multi-tiered innovation system: core cities undertake high-end original digital innovation, sub-central cities focus on applied innovation and industrial transformation, and peripheral cities undertake supporting digital manufacturing links, forming a differentiated division of labour system.

Third, we examine the tail extension and polarization characteristics of the density surfaces. Beijing-Tianjin-Hebei and Chengdu-Chongqing show strong bipolar polarization. The main peak of Beijing-Tianjin-Hebei is concentrated at low innovation levels, accompanied by an obvious right tail and secondary peaks. This feature reflects a typical bipolar structure: a small set of core cities (Beijing, Tianjin) reach high digital innovation levels, while most peripheral cities remain at a much lower stage. The root cause lies in the strong administrative hierarchy of the Beijing-Tianjin-Hebei urban agglomeration; innovation resources are highly concentrated in the capital, and factor backflow and siphon effects are far stronger than innovation spillover. Similarly, Chengdu-Chongqing and Mid-Yangtze River also display a main peak with a stretched right tail, consistent with core-periphery dynamics, where the core cities (Chengdu, Chongqing, Wuhan etc.) pull ahead while peripheral cities lag.

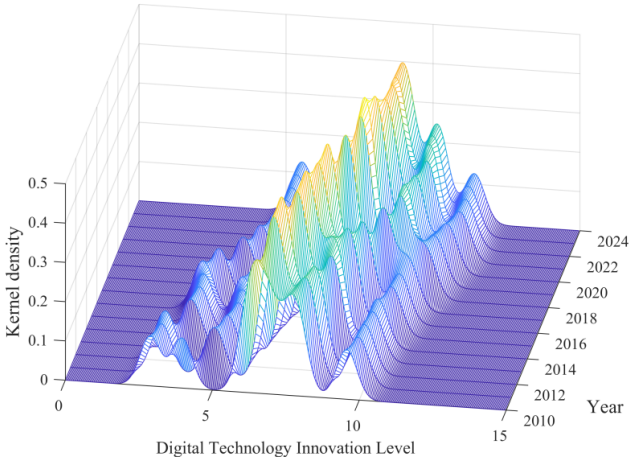
Notably, the polarization form of the Yangtze River Delta and Pearl River Delta differs from the above three agglomerations. Their secondary peaks and long tails are distributed on the left side of the main peak, rather than the right. This means that the polarization is mainly driven by a group of laggard cities with far lower innovation performance than the core cities, rather than a small elite group pulling far ahead. Compared with the sharp core-periphery split in Beijing-Tianjin-Hebei and Chengdu-Chongqing, the innovation distribution in the Yangtze River Delta and Pearl River Delta is more dispersed across the middle and high-value segments. Their inter-city gaps are persistent but do not generate extreme bipolar separation, which implies relatively stronger foundation for coordinated and integrated innovation within these two agglomerations. Driven by cross-city industrial cooperation and integrated innovation platforms, the innovation spillover can radiate to sub-central cities more smoothly, avoiding the extreme siphon effect observed in the Beijing-Tianjin-Hebei and Chengdu-Chongqing regions.

In summary, the distribution dynamics captured by three-dimensional kernel density estimation confirm that the evolution of digital innovation within China's five major urban agglomerations follows heterogeneous paths. The coastal agglomerations are characterised by overall upgrading and stratified differentiation, while the central and western agglomerations are dominated by low-level agglomeration and core-periphery polarisation. Such differentiated distribution patterns further lay the empirical foundation for the subsequent econometric analysis on how digital technology innovation shapes regional linkage and the heterogeneous effects across different urban agglomerations.

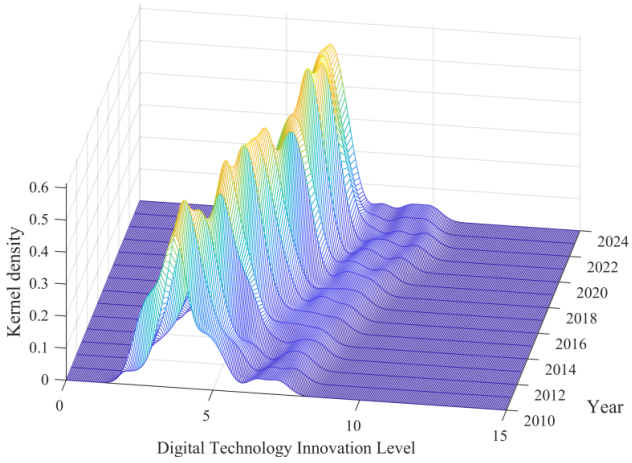
Figure 2: Kernel Density Estimation of Digital Technology Innovation Levels in the Five Major Urban Agglomerations



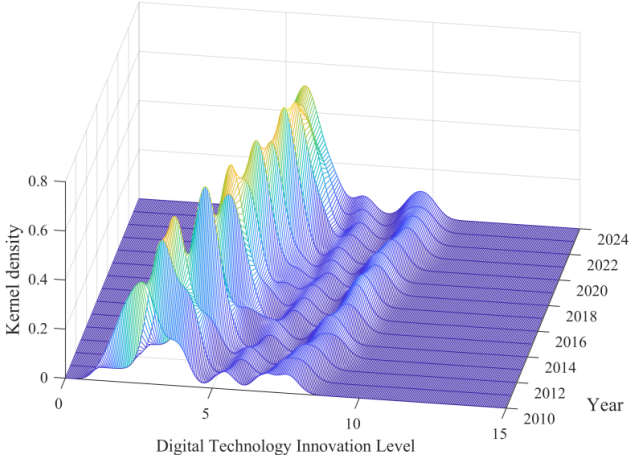
(a) Beijing-Tianjin-Hebei urban agglomeration (b) Yangtze River Delta Urban Agglomeration



(c) Pearl River Delta urban agglomeration



(d) Mid-Yangtze River Urban Agglomeration



(e) Chengdu-Chongqing Urban Agglomeration

4. Digital Technology Innovation Empowering the High-Quality Development of Urban Agglomerations

The time-series characteristics of digital economy patent grants and the results of kernel density estimation across China's five major urban agglomerations reveal differences in the scale of digital patent accumulation, spatial distribution patterns, and conditions for innovation factor flows. These agglomerations exhibit a significant hierarchical gradient in digital innovation capacity. However, constrained by real-world factors such as misallocation of resources, insufficient connectivity within innovation networks, and cross-regional institutional barriers, the technological knowledge embodied in digital patents struggles to be fully transformed into collaborative momentum across cities, preventing the automatic realization of internal mechanisms that enable digital technology to drive regional integration. Therefore, policies should be tailored according to each urban agglomeration's innovation endowments and internal polarization features. A multidimensional coordination system should be established at the levels of innovation networks, factor circulation, platform infrastructure, and collaborative governance, to facilitate the spillover and industrialization of digital patent technologies and unlock the synergistic benefits of digital innovation.

4.1 Digital Innovation Development Strategy

The Yangtze River Delta urban agglomeration ranks first among the five major urban clusters in terms of total digital patents. Kernel density analysis shows that the region's overall innovation level is rising rapidly, yet absolute disparities among cities continue to widen, indicating it has evolved into a mature, high-level innovation cluster. The focus of innovation development

should shift from expanding patent quantity to enhancing the quality of high-value patents, with targeted breakthroughs in foundational digital technologies such as basic software, integrated circuits, and artificial intelligence, and increased strategic layout of core digital invention patents. Leveraging key cities like Shanghai, Nanjing, Hangzhou, and Hefei, a cross-provincial collaborative R&D mechanism should be established to encourage joint digital patent applications across cities. Application-oriented digital patents and non-core R&D activities should be gradually transferred to peripheral cities in Jiangsu, Zhejiang, and Anhui, supported by improved industrialization infrastructure for patents. This will help moderate the resource-siphoning effect of core cities and strengthen the region's role as a national hub for digital innovation.

The Pearl River Delta demonstrates active output of applied digital patents and strong market-driven innovation vitality, with a kernel density curve indicating high overall levels but significant disparities among cities. By aligning technological innovation with industrial demands, the region is strategically developing digital patents in key sectors such as intelligent manufacturing, next-generation information and communications, and digital commerce. Leveraging the market-oriented institutional advantages of the Bay Area, it is essential to improve service systems for digital patent valuation, intellectual property pledging, and technology trading markets, reduce transaction costs for cross-city patent transfers, accelerate the integration of digital patent outcomes into industrial applications, and build a market-led digital innovation ecosystem.

The total number of patents in the Beijing-Tianjin-Hebei urban agglomeration has grown steadily, with kernel density estimation revealing a strong polarization pattern characterized by a prominent low-value concentration peak and a long rightward tail. Innovation output is highly concentrated in Beijing, while digital innovation capabilities in Tianjin and Hebei lag significantly behind. The regional strategy should focus on optimizing the spatial structure of innovation, maintaining Beijing's strengths in cutting-edge digital technologies and high-end digital patent outputs, while systematically relocating mid-scale trials and industrialization stages of digital technologies to Tianjin and Hebei. It is essential to strengthen digital infrastructure and industrial support systems in Tianjin and Hebei, establish cross-regional platforms for patent commercialization and technology implementation, and facilitate the spillover channels for Beijing's digital patents to reach surrounding areas, thereby alleviating innovation gaps within the urban agglomeration.

The digital patent scale in the mid-reach Yangtze River urban agglomeration has steadily increased, with a kernel density pattern characterized by multiple nodes developing in parallel and internal disparities first widening then converging. A multi-center structure centered on Wuhan, Changsha, and Nanchang is beginning to take shape. However, patent collaboration among cities remains insufficient, posing risks of homogenized R&D. It is essential to strengthen differentiated competition among multiple centers, guide the three major central cities toward diversified development in digital R&D fields, and reduce redundant investment in digital technology. Cross-city innovation alliances should be established to promote joint research and collaborative patent applications among universities, research institutes, and enterprises, enhancing innovation connectivity between cities and fostering a networked, balanced innovation ecosystem.

The Chengdu-Chongqing urban agglomeration has a relatively low overall patent base, with the main peak of patent density concentrated in the lower range, exhibiting characteristics of low-level agglomeration combined with dual-core polarization, a typical potential-type urban cluster. Prioritizing the strengthening of digital innovation foundations, it should leverage Chengdu's comparative advantages in digital software services and Chongqing's strengths in industrial digitization to establish a differentiated patent layout between the two centers. It is essential to enhance joint R&D and patent collaboration among innovation entities in both cities, enabling the two hubs to drive digital innovation capacity development in surrounding medium- and small-sized cities, thus creating a growth pole for digital innovation in western China.

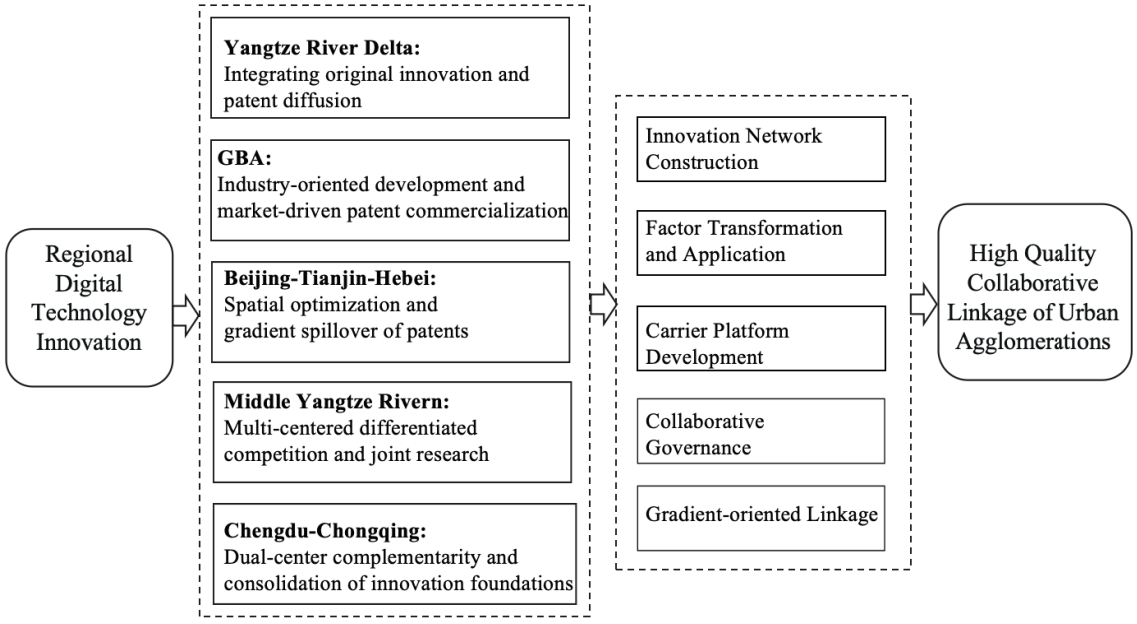
4.2 Implementation Pathways for Regional Coordination in Urban Agglomerations Empowered by Digital Technology

To address the practical challenges mentioned above, such as uneven development among urban clusters, internal polarization, loose innovation networks, and institutional barriers, the implementation pathway for urban regional collaboration is illustrated in Figure 3. Relying on digital patents as a carrier of technological knowledge, this pathway is structured around five dimensions: network construction, factor transformation, platform infrastructure, collaborative governance, and gradient coordination models.

First, establish an innovation network connectivity pathway anchored by patent collaboration. Leverage cross-city digital patent joint applications, patent licensing and transfer, and technological cooperation as key drivers for building innovation networks, encouraging enterprises, universities, and research institutes to form cross-regional innovation coalitions. In mature regions such as the Yangtze River Delta and the Pearl River Delta, focus on optimizing network structures to alleviate excessive concentration at core nodes; in the Beijing-Tianjin-Hebei region, emphasize strengthening the outward radiation of core cities; and in the mid-Yangtze River and Chengdu-Chongqing urban clusters, prioritize increasing the frequency of intercity patent collaboration to address insufficient innovation linkages. Rely on dynamic monitoring of digital patent data to track the evolution of innovation networks and promote multidirectional spillovers of knowledge and technology across network nodes.

Second, improve the integrated pathways linking cross-regional factor mobility with patent transformation. Break down intellectual property protectionist barriers arising from administrative divisions, establish an integrated digital intellectual property public service system across urban clusters, and streamline procedures for cross-regional digital patent transfers, licensing, and pledging. Develop a division-of-labor model in which core cities generate patents while peripheral cities take charge of industrialization and implementation, deploy cross-regional digital technology pilot bases, and promote two-way flows of talent, data, and technology. Establish inter-urban cluster technical assistance mechanisms to enable mature digital patents and transformation experiences from the Yangtze River Delta and the Pearl River Delta to be shared with mid-Yangtze River regions and the Chengdu-Chongqing area, thereby alleviating the Matthew effect in regional innovation.

Figure 3: Digital Technology-Driven Innovation Strategies and Regional Collaboration Pathways for Urban Agglomerations



Third, establish an integrated digital innovation public platform. By consolidating digital patent databases, large-scale scientific instruments, and technology supply-demand information, build a unified and open digital innovation service platform for urban clusters that integrates functions such as patent search, value assessment, technology matching, and technology transfer. Mature urban clusters should focus on iterative upgrades of the platform; while the mid-reach Yangtze River region and the Chengdu-Chongqing area should prioritize addressing shortcomings in hardware infrastructure and data resources, reducing the cost for small and medium-sized cities and enterprises to access digital technologies, bridging regional digital information gaps, and providing a platform foundation for cross-regional innovation collaboration.

Fourth, deepen the coordination of cross-regional governance systems. Establish a regular digital innovation collaboration mechanism for urban clusters to promote mutual recognition and coordination in innovation planning, industrial policies, and intellectual property protection standards. Optimize institutional supply according to local conditions: the Beijing-Tianjin-Hebei region should focus on improving supporting systems for the gradient transfer of digital innovation outcomes; the

Pearl River Delta should advance market-oriented innovations in intellectual property systems; and the mid-Yangtze River and Chengdu-Chongqing urban clusters should promote mutual recognition of cross-provincial innovation policies to reduce institutional transaction costs in cross-regional innovation cooperation and eliminate systemic barriers hindering the cross-border circulation of digital patents.

Fifth, implement a categorized and tiered coordination model. Match different urban clusters with their respective endowments to select appropriate coordination models: the Yangtze River Delta and the Pearl River Delta will adopt deep network integration for efficient patent resource circulation and profound industrial collaboration; the Beijing-Tianjin-Hebei region will follow a tiered spillover model, progressively releasing innovation radiations from core cities; the mid-Yangtze River Urban Cluster will promote a multi-center collaborative model, strengthening division of labor and cooperation among multiple nodes; and the Chengdu-Chongqing Urban Cluster will implement a dual-center leadership model, leveraging two major hubs to drive overall innovation advancement, avoiding a one-size-fits-all policy approach.

5. Conclusion

Taking China's five major urban agglomerations as research subjects, this paper employs granted digitaleconomy patents to measure digital technological innovation, and systematically investigates its spatiotemporal evolution and practical implications for regional linkage development over 20102024. The study finds that digital innovation output of all urban agglomerations shows an overall upward trend with phased growth characteristics. Obvious interagglomeration hierarchical gaps have gradually taken shape, presenting a prominent Matthew effect, where eastern coastal urban agglomerations maintain leading innovation scale while centralwestern counterparts grow from low starting points. Results from threedimensional kernel density estimation further reveal distinct internal heterogeneity: the Yangtze River Delta and Pearl River Delta follow the path of overall upgrading as well as stratified differentiation; BeijingTianjinHebei and Chengdu-Chongqing feature severe coreperiphery bipolar polarization; the MidYangtze River shows multinode parallel development with intraregional gaps expanding first and then converging. Digital innovation dividends cannot automatically translate into regional linkage gains due to institutional barriers and siphon effects. Accordingly, this paper proposes targeted innovation strategies for each urban agglomeration and fivedimensional collaborative pathways covering innovation network construction, factor transformation, public platform building, crossadministrative governance and classified coordination. Future research can enrich digitalinnovation indicators beyond patent data and further test the quantitative spillover effects. Policymakers should avoid uniform policies, attach importance to both innovation output and spillover diffusion, and remove institutional obstacles to advance highquality integrated development of urban agglomerations.

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