The impact of digital economy development on the quality of urban innovation: Empirical evidence from 256 cities in China

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Abstract. The digital economy enabling urban innovation has become essential for the country to implement the innovation-driven development strategy. This study uses panel data from 256 Chinese cities spanning the period from 2011 to 2021 to examine the influence of the digital economy on the quality of urban innovation and its underlying mechanism. The findings indicate that the growth of the digital economy has a beneficial influence on the level of innovation in Chinese cities. Furthermore, this impact remains statistically significant even after conducting robustness tests to ensure the reliability of the results. Investments by the government in technology and science and foreign direct investment are the primary mechanisms through which the digital economy enhances the quality of urban innovation. The research conclusions have significant implications for the Chinese government in fostering the growth of the digital economy and improving the calibre of urban innovation.

Keywords: digital economy; urban innovation quality; mediating effect.

1 Introduction

After transitioning into the new economic normal, China urgently needs a paradigm shift from an investment-driven growth model to an innovation-driven development model. Since the "Innovation-Driven Development Strategy" proposal at the 18th National Congress, China's investment in innovation has shown sustained growth, accompanied by a steady increase in technology indicators. According to data from the National Intellectual Property Administration, in 2022, China's total patent applications reached 5.365 million, with the cumulative number of effective invention patents reaching 4.212 million, securing the top position globally. However, the proportion of invention patent applications is only 30.2%, with the implementation and industrialization rates of effective invention patents being 48% and 36.7%, respectively. A prevalent "high quantity, low quality" issue highlights the challenge of efficiently transitioning and upgrading economic development from a factor-driven to an innova-

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tion-driven approach. Cities, serving as the spatial nexus for innovation activities, are hubs for innovation elements and the primary locus for innovation output. Therefore, enhancing the quality of urban innovation stands out as a crucial avenue for the nation to enact the innovation-driven development strategy.

From an empirical standpoint, a significant observation closely tied to the quality of urban innovation is the recent flourishing of China's digital economy. With the profound advancement of the latest technological revolution and industrial transformation, digital technologies—embodied by big data, cloud computing, and artificial intelligence—extensively permeate diverse economic sectors, encompassing agriculture, industry, and services. Data has evolved into a pivotal production factor, marking the real economy's gradual transition into the digital economy era. As of 2022, the scale of China's digital economy has surged to 50.2 trillion yuan, constituting 41.5% of the GDP and emerging as a crucial component of the national economy. The digital economy, facilitated by digital technology and information networks, enables the efficient aggregation and precise alignment of urban innovation elements, including technology, talent, and capital. This process not only delves into the latent innovation potential of cities but also amplifies urban innovation efficiency, serving as a pivotal impetus for elevating the innovation quality of Chinese cities. The 14th Five-Year Plan explicitly outlines the proportion of the added value from the core industries of the digital economy in GDP as a critical indicator of innovation-driven development. This explicit inclusion underscores the Chinese government's profound recognition of the pivotal role played by the digital economy in empowering urban innovation development. Against this backdrop, an in-depth exploration of strategies to harness the impetus of the digital economy for unleashing urban innovation vitality and augmenting urban innovation quality holds paramount significance for facilitating China's transition from a factor-driven to an innovation-driven developmental paradigm.

Does the advancement of the digital economy favorably influence the quality of urban innovation? If indeed, what constitutes its inherent mechanism? Elucidating these inquiries contributes to comprehensively comprehending the digital economy's role in augmenting urban innovation quality and its underlying mechanisms. It furnishes theoretical direction and insightful policy recommendations for optimizing the impact of digital economy development on enhancing urban innovation quality and for more efficaciously executing the innovation-driven development strategy in the contemporary developmental phase.

2 Theoretical Analysis and Research Hypotheses

2.1 The Direct Impact of the Digital Economy on Urban Innovation Quality

Enhancing innovation quality relies significantly on strengthening innovation capability and improving efficiency [1-2]. Firstly, the digital economy can boost urban innovation vitality and improve innovation capability. The digital economy's development enhances resource integration efficiency, ensuring innovation entities receive efficient services. This promotes the generation and exchange of innovative ideas, increasing urban innovation vitality and frequency and ultimately enhancing the city's innovation

capability. Secondly, the digital economy can reduce innovation costs, improving overall efficiency. The rise of the digital economy facilitates the dissemination and diffusion of innovation elements, overcoming temporal and spatial barriers. This enhances the mobility of these elements, mitigates issues related to information asymmetry, and substantially diminishes the costs associated with search, communication, and collaboration for innovation entities. Consequently, it improves the research and development efficiency of research institutes, universities, and other innovation entities. In light of this, the paper posits the research hypothesis:

H1 the digital economy positively influences the quality of urban innovation.

2.2 Indirect Mechanisms of the Digital Economy on Urban Innovation Quality

2.2.1 Government department's technology spending generates a guiding effect

Specifically, fiscal technology investment is an essential means for local governments to enhance the quality of urban innovation. Primarily, within the framework of digital economic development, local governments allocate fiscal resources to construct and enhance digital infrastructure, finance universities, and research institutions, steer social funds towards innovative enterprises, tackle the financial constraints faced by urban innovation entities [3], draw and consolidate technology innovation talents, optimize the local innovation milieu, and bolster the growth of digital and high-tech industries. Consequently, these efforts collectively contribute to the enhancement of urban innovation quality. Secondly, the digital economy also promotes the digital transformation of government public services. Under the influence of digital technology, public services have reduced information asymmetry among innovation entities, lowered various transaction costs within the city, and provided strong support for the aggregation, optimization, and allocation of innovation resources, further enhancing the quality of urban innovation [3]. Lastly, the success and profitability of urban innovation, to some extent, reflect that government innovation funds can obtain good returns. This will motivate the government to increase its investment in technology further, and such mutually reinforcing positive effects ultimately lead to a virtuous cycle of upward-spiraling urban innovation quality.

2.2.2 Foreign direct investment will produce incentive effects

On the one hand, under the backdrop of the digital economy, the development of areas such as big data, cloud computing, and intelligent manufacturing provides new business opportunities for foreign direct investment that are both highly growth-oriented and lucrative. The influx of foreign direct investment with advanced technology brings positive technological spillovers, making it easier for local enterprises to enhance technical accumulation by imitating, replicating, and learning advanced foreign technologies. On the other hand, foreign-funded enterprises, to reduce labor costs, typically employ locally educated and experienced "talent," increasing the opportunities for local employees to learn knowledge and skills further. This is beneficial for raising the local level of human capital, and an elevated level of human capital

can promote the improvement of innovation quality, a relationship recognized by many economists. Based on this, the paper proposes a research hypothesis:

H2 the digital economy can indirectly enhance the quality of urban innovation by increasing government technology investment and attracting foreign direct investment.

3 Research Design

3.1 Model Specification

To assess the immediate influence of the digital economy on the quality of urban innovation, we have formulated the subsequent econometric model.

$$inno_{i,t} = \alpha_0 + \alpha_1 die_{i,t} + \alpha_i X_{i,t} + \lambda_i + \mu_t + \varepsilon_{i,t} \tag{1}$$

Where $inno_{i,t}$ is the urban innovation quality in city i in year t; $die_{i,t}$ is the level of digital economic development in city i in year t; vector $X_{i,t}$ represents the set of control variables; λ_i and μ_t respectively denote city fixed effects and year fixed effects; $\varepsilon_{i,t}$ represents the random disturbance term.

Next, according to research hypothesis 2, empirical tests are conducted on whether government technology spending and foreign direct investment serve as mediating variables between the digital economy and the quality of urban innovation. The specific steps are as follows: on the basis of the significant test of regression coefficient α_1 in model (1), regression equations are separately constructed for the digital economy on the mediating variable and for the digital economy and the mediating variable on the quality of urban innovation. The existence of the mediating effect is determined by the significance of coefficients β_1, γ_1, and γ_2. The model is set as follows:

$$media_{i,t} = \beta_0 + \beta_1 die_{i,t} + \beta_i X_{i,t} + \lambda_i + \mu_t + \varepsilon_{i,t} \tag{2}$$

$$inno_{i,t} = \gamma_0 + \gamma_1 die_{i,t} + \gamma_2 media_{i,t} + \gamma_i X_{i,t} + \lambda_i + \mu_t + \varepsilon_{i,t} \tag{3}$$

3.2 Variable analysis

3.2.1 The dependent variable

Urban innovation quality (inno). Currently, using patent data to characterize regional innovation is a common practice. This study draws on the approach of Wang Yue (2021)[4] to comprehensively depict urban innovation quality from the perspectives of substantive innovation and green innovation.

Substantive innovation (sub-inno). Utility model and design patents tend to lean towards imitative innovation, contributing less to the quality of innovation. The research and development cost and technical complexity of invention patents are higher, better reflecting a city's substantive innovation capability. This study uses the number of invention patent applications per 10,000 people to measure a city's substantive

innovation. The use of patent application quantity, rather than granted patents, is due to the former representing the city's current research and development achievements. At the same time, the latter often takes several years to be authorized after application.

Green innovation (gre-inno). Achieving resource conservation and pollution reduction through green innovation is one of the core connotations of improving innovation quality. This study, following the approach of Dong Zhiqing and Wang Hui (2019)[5], uses the number of green patent applications per 10,000 people to represent green innovation. Based on the green patent list provided by the World Intellectual Property Organization, information on all patent applications published by the National Intellectual Property Office is collected, thereby obtaining green innovation data for 256 Chinese cities from 2011 to 2021.

3.2.2 The independent variable

Digital economy (die). Regarding the measurement indicators of the digital economy, scholars currently lack a clear consensus. This study borrows from the method of Zhao Tao et al. (2020)[6] to measure the level of digital economic development from the perspectives of internet development and digital inclusive finance.

3.2.3 The mediating variable

Government technology expenditure (gov). Local financial technology expenditure is the fundamental guarantee and conditional support for improving urban innovation quality. Generally, the more a city spends on technology, the greater its potential for innovation output. This study uses the ratio of local government technology expenditure to regional gross domestic product as the representation.

Foreign direct investment (fdi). The increase in foreign direct investment can promote technology spillover and the introduction of advanced foreign technological concepts, thereby empowering the improvement of urban innovation quality. This study uses the total amount of actual foreign investment the city uses in the current year as the representation.

3.2.4 The control variable

This study selects control variables that may affect the quality of urban innovation. The chosen variables are as follows: Economic development level (pgdp), represented by the logarithm of per capita GDP; Population density (den), measured by the population quantity per square kilometer; Fiscal decentralization degree (fd), represented by the ratio of municipal per capita fiscal expenditure to the sum of municipal, provincial, and national per capita fiscal expenditures; Financial development level (fin), indicated by the ratio of institutional loans to the regional gross domestic product; Industrial structure (is), represented by the ratio of the value added of the tertiary industry to the regional gross domestic product.

3.2.5 Data Source

Given the accessibility of data, this study uses panel data from 256 Chinese cities spanning from 2011 to 2021; missing values are complemented using the linear interpolation method, and the data are sourced from the CSMAR Database, "China Urban Statistical Yearbook," and local statistical bureau websites.

4 Empirical Analysis

4.1 Baseline Regression Results

Table 1 presents the baseline regression results of the impact of the digital economy on urban innovation quality. Columns (1) and (3) represent the model estimation results when urban innovation quality is measured by the quantity of patent applications for inventions and green patents, respectively. The regression coefficients of the digital economy are both significantly positive, indicating that the digital economy promotes the improvement of urban innovation quality. Even after incorporating control variables in columns (2) and (4), the regression coefficients of the digital economy remain significantly positive. The development of the digital economy not only stimulates innovation vitality, promotes the collision of innovative thinking, and enhances urban innovation capabilities but also significantly reduces various innovation costs, improving urban innovation efficiency. Thus, hypothesis 1 is validated.

Table 1. Baseline Regression Results

Variable	sub-inno		gre-inno	
	(1)	(2)	(3)	(4)
die	39.6523***	46.4360***	3.9394***	5.0846***
	(3.46)	(4.45)	(2.99)	(4.80)
pgdp		-4.2928***		-0.5617***
		(-2.65)		(-3.39)
den		0.0443***		0.0070***
		(8.27)		(10.35)
fd		11.4526***		0.7808*
		(2.98)		(1.95)
fin		-0.2189*		-0.0153
		(-1.66)		(-1.24)
is		-0.1425***		-0.0152***
		(-5.89)		(-5.42)
constant	55.8813***	43.9407***	7.0530***	4.5035***
	(6.73)	(3.46)	(5.66)	(2.84)
Obs	256	256	256	256
F	33.14	40.01	24.95	30.49
R^2	0.8746	0.8975	0.8098	0.8668

Note: *, **, and *** refers to the statistical significance at 10%, 5% and 1% respectively, the same below.

4.2 Analysis of Impact Mechanisms

Previously, the theoretical analysis delved into the indirect mechanisms by which the digital economy impacts urban innovation quality, examining perspectives such as government technology spending and foreign investment. Following this, an empirical test is undertaken utilizing the mediation effect model. The regression results in Table 2, specifically in columns (1-3), depict the estimated outcomes of two models, wherein government technology spending serves as the mediating variable. In column (1), the regression coefficient between the digital economy and government technology spending is significantly positive, suggesting that the digital economy positively influences the developmental level of government technology spending. In columns (2) and (3), upon introducing the mediating variable, the impact coefficients of government technology spending on urban innovation quality remain significantly positive. Relative to the baseline regression model, the impact coefficient of the digital economy on urban innovation quality decreases. This implies that the digital economy can indirectly enhance urban innovation quality by elevating government technology spending. Correspondingly, columns (4-6) depict the estimated outcomes of two models wherein foreign investment is the mediating variable. Specifically, in column (4), the regression coefficient reflecting the positive association between the digital economy and foreign investment is statistically significant. Furthermore, in columns (5) and (6), after introducing the mediating variable, the impact coefficients illustrating the positive influence of foreign investment on urban innovation quality remain statistically significant. In contrast to the baseline regression model, the impact coefficient denoting the relationship between the digital economy and urban innovation quality exhibits a decrease. The above empirical evidence indicates that government technology spending and foreign investment are essential transmission mechanisms for the digital economy to enhance urban innovation quality, thereby validating hypothesis 2 in this study.

Table 2. Regression results of influencing mechanisms

Variable	gov	sub-inno	gre-inno	fdi	sub-inno	gre-inno
	(1)	(2)	(3)	(4)	(5)	(6)
die	0.0231***	43.2776***	4.7651***	249.3825***	42.4175***	4.5579***
	(2.75)	(4.37)	(4.71)	(4.49)	(4.10)	(4.42)
gov		136.712***	13.8304***			
		(4.17)	(3.94)			
fdi					0.0161***	0.0021***
					(4.70)	(4.42)
pgdp	0.0215***(	-7.2341***	-0.8592***	144.4864***	-6.6209***	-0.8668***
	6.61)	(-4.48)	(-4.92)	(7.04)	(-4.11)	(-5.18)
den	0.00003***	0.0392***	0.0065***	0.2177***	0.0408***	0.0066***
	(4.26)	(8.57)	(11.15)	(8.52)	(7.47)	(9.54)
fd	-0.0120**	13.0994***	0.9474**	91.5300***	9.9777***(	0.5874
	(-1.99)	(3.49)	(2.38)	(2.65)	2.64)	(1.50)
fin	-0.0006**	-0.1305	-0.0064	-2.5910	-0.1772	-0.0098

	(-2.09)	(1.14)	(-0.54)	(-1.52)	(-1.46)	(-0.83)
is	0.0001*	-0.1552***	-0.0165***	0.8651***	-0.1563***	-0.0171***
	(1.71)	(-6.60)	(-6.07)	(3.45)	(-6.56)	(-6.09)
constant	-0.0848***	55.5371***	5.6766***	-204.7236	47.2395***	4.9359***
	(-4.32)	(4.62)	(3.68)	(-1.29)	(3.92)	(3.34)
Obs	256	256	256	256	256	256
F	96.00	42.77	30.49	77.63	39.88	30.49
R^2	0.7862	0.9041	0.8668	0.8650	0.9016	0.8668

4.3 Robustness test

Core variables were replaced: The dependent variable was replaced by calculating the urban innovation index (2011-2021) following the method in the "China City and Industrial Innovation Report 2017." The index used a patent renewal model to estimate the average value of each patent, partially alleviating the heterogeneity problem of patent quality and quantity. The results in Table 3, column (1), indicate that after replacing the dependent variable, the estimated results remain significantly positive, and the model remains robust.

Inspired by Zhao Tao et al. (2020) [6], this study employed a method using the product of the number of telephones per 10,000 people in each prefecture-level city in 1984 and the previous year's national internet user count as an instrument variable for the core explanatory variable to test the endogeneity between the digital economy and urban innovation quality. The 1984 telephone count represents the historical communication infrastructure of the region. As the digital economy relies on communication technologies such as the Internet for development, traditional infrastructure conditions would significantly impact the subsequent development of the digital economy, partially meeting the relevance requirements of the instrumental variable. However, the historical prevalence of telephone numbers has minimal impact on cities' current innovation quality, meeting the instrumental variable's homogeneity requirements. Results in Table 3, columns (2) and (3), show that even after considering endogeneity, the positive effect of the digital economy on urban innovation quality remains significant. Additionally, the Kleibergen-Paap rk LM statistic has a p-value of 0.000, significantly rejecting the null hypothesis of unidentifiability of the instrument variable, and the Kleibergen-Paap rk F statistic exceeds the critical value for the weak.

Table 3. Robustness test

Variable	Replace the dependent variable	Instrumental variable method	
	innovation index	sun-inno	gre-inno
	1	2	3
die	209.7834**	257.4847***	32.3919***
	(2.28)	(4.97)	(4.72)
Control Variable	YES	YES	YES
Kleibergen-Paaprk LM		36.722	36.722

Kleibergen-Paaprk F		48.761	48.761
Obs	256	256	256
F	30.74	151.28	112.43
R^2	0.7821	0.6341	0.4908

5 Conclusion and Policy Implications

5.1 Research Conclusion

This study empirically investigates panel data spanning 256 cities from 2011 to 2021, aiming to elucidate the impact and underlying mechanisms of the digital economy on the innovation quality of cities. The findings can be summarized as follows:

(1) The Positive Impact of the Digital Economy

The digital economy significantly enhances urban innovation quality, a conclusion robustly validated through various tests.

(2) Mechanism Tests and Indirect Enhancement

Examinations of mechanisms reveal that the digital economy indirectly elevates urban innovation quality by augmenting government technology investment and attracting foreign direct investment, with foreign direct investment playing a notably significant role.

5.2 Policy Implications

Drawing from the research findings, this paper advances the following policy recommendations:

Strengthen Support for the Digital Economy: The government is urged to augment its investment in digital infrastructure and fortify the development platform for the digital economy. This entails harnessing its advantages in information dissemination, resource integration, and knowledge sharing. Such measures are envisioned to facilitate the comprehensive integration of the digital economy across diverse societal sectors, thereby fostering its emergence as a pivotal driving force propelling the high-quality development of cities.

Enhance the Quality of Foreign Capital Utilization: Aligned with the context of executing the innovation-driven development strategy in China, it is recommended that foreign capital management policies be recalibrated promptly. This involves judiciously controlling the overall volume of foreign capital, optimizing its structure, and maximizing its positive regulatory impact on empowering the quality of urban innovation within the digital economy.

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