Digital Economy and Urban Green Innovation: Empirical Evidence from Chinese Prefecture-Level Cities

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Abstract. Fully utilizing the ecological advantages of digital economy is of great significance in promoting urban green innovation. This paper discusses the impact of digital economy on urban green innovation based on a two-way fixed-effects model with panel data of 282 Chinese prefecture-level cities from 2011 to 2021. The findings show that digital economy can significantly promote urban green innovation and pass a series of robustness tests such as substitution variables, panel quantile model, and instrumental variables. The heterogeneity test shows that eastern cities and southern cities are more capable of promoting urban green innovation by the digital economy. This paper provides research support for the theory of digital economy in green development and the practice of urban development transformation.

Keywords: Digital economy, green innovation, sustainable development, fixed effects model.

1. Introduction

In order to cope with increasingly serious environmental pollution, the destruction of ecological resources, extreme climate change and other environmental problems, as well as the huge impact on the economy since the COVID-19 pandemic, China has taken active action to change the model of long term extensive economic development, to seek a path of sustainable economic development and to implement green innovation. Comprehensive green transformation in the new development stage has become the common expectation of the people's interests, from "green development" during Deng Xiaoping's period, which became the path that China adhered to in its development, to "advocating a green mode of production, lifestyle, and consumption" during the period of Comrade Hu Jintao. Since the 18th CPC National Congress, General Secretary Xi Jinping has put forward a series of important discussions on green science and technology innovation (Xu Hui et al., 2022). Green innovation has gradually become an important issue in China's development. Green innovation refers to a series of creative activities that can satisfy the value needs of consumers and enterprises, and also reduce the pollution and damage to the environment in order to achieve the goal of sustainable development (Wang Chuanjie et al., 2023). Different from traditional innovation, green innovation, as a new type of innovation with the dual advantages of environmental protection and economic development, is conducive to achieving carbon emission reduction while ensuring economic development. Green technological innovation can promote the improvement of production efficiency and resource utilization to effectively reduce carbon emissions, which helps to realize the green sustainable development of the country (Xin Daleng and Peng Zhiyuan, 2023). As an organic combination of the two development concepts of green and innovation, the green innovation strategy is of great practical significance for cities to realize quality growth and improve environmental efficiency. Meanwhile, as the gathering place of China's economic activities as well as the concentration of environmental pollution, improving the level of urban green innovation has become the prerequisite and key to enhancing China's green innovation strength. In this context, the influencing factors of urban green innovation have become a hot topic in current academic research, and related studies involve environmental regulation (Qingyuan Li and Zehua Xiao, 2020), industrial agglomeration (Hongqing Wang and Wenwen Hao, 2022), governmental R&D subsidies (Yonggui Wang and Xia Li, 2023), and governmental policy support (Qiao Wang et al., 2020).

The digital economy is a series of economic activities relying on data as a production factor and the effective use of information and communication technology and artificial intelligence as a carrier, which has become a basic strategic resource and an important productive force (Wang Jun et al., 2021). With the rapid development of information and communication technology and the continuous popularization of artificial intelligence in recent years, the development of China's digital economy has been rapid, and it has been integrated with all walks of life. On the one hand, the digital economy plays an important role in stimulating consumption, driving investment, creating employment, and enhancing innovation and competitiveness, providing a new kinetic energy and a feasible path to promote the high-quality development of China's economy and the construction of a modernized economic system (Jing Wenjun and Sun Baowen, 2019). On the other hand, the penetration of digital technology comprehensively promotes the optimization and upgrading of industrial structure, which makes the production factors transfer from low-efficiency sectors to high-efficiency sectors, improves the efficiency of resource allocation, and at the same time significantly drives the development of low-carbon industries through the two channels of energy flow and resource flow (Jiang Ruchuan and Jing Xinxin, 2023). In addition, the application of big data, cloud computing, and remote sensing technology can realize the government's real-time dynamic monitoring of environmental data resources such as air quality, river water quality, pollution discharge, environmental carrying capacity, etc., which can improve the early warning and perception of pollution sources, enhance the government's ability to supervise the environment by improving the accuracy and effectiveness of government environmental supervision, and improve the level of ecological and environmental governance. Therefore, actively exploring the factors of the digital economy, fully releasing the innovation potential and development momentum embedded in the digital economy has become an inevitable choice to bring the value of the digital economy into play. Studies have shown that urbanization, human capital, government behavior, economic growth level, trade openness, and advanced industrial structure will have a positive effect on the development of digital economy (Jiao Shuaitao and Sun Qiubi, 2021).

In the trend of the digital economy era, how to give full play to the advantages of the digital economy, and then promote the green innovation has become the question of the times. China ICT released "China's digital economy development report (2023)" shows that in 2022 China's digital economy scale reached 50.2 trillion yuan, a nominal year-on-year growth of 10.3%, has been 11 consecutive years significantly higher than the nominal growth rate of the same period of GDP, the digital economy accounted for the proportion of GDP is equivalent to the proportion of the secondary industry in the national economy, reaching 41.5%. This fully demonstrates that the digital economy has become a broad fertile ground and supportive carrier for realizing rapid urban development and high-quality green innovation, and has an important driving role in urban green innovation. On the one hand, under the guidance of the pilot policy of "Broadband China" strategy, not only the urban network infrastructure has been developed, but also the green innovation level of the pilot cities has been promoted through the policy's financial development effect, talent concentration effect and informationization enhancement effect (Xin Daleng and Peng Zhiyuan, 2023). On the other hand, digital finance, as the core of digital economy development and a new type of technology-driven financial innovation, can alleviate the financial constraints of the manufacturing industry and small and medium-sized micro and medium-sized green innovation subjects, and provide financial support for green innovation to better promote the high-quality development of cities (Zhao Jun et al., 2021). Therefore, studying the impact of digital economy on urban green innovation becomes the main content of this paper.

The marginal contributions of this paper are in the following two aspects: First, this paper broadens the existing research by including digital transformation and green innovation in the same analytical framework and attempting to explore the microeconomic consequences of digital transformation from the perspective of corporate green innovation. Second, this paper empirically tests the sample of A-share listed companies in Shanghai and Shenzhen from 2011 to 2021, which provides empirical evidence for the enhancement effect of digital transformation on enterprises' green innovation and its

mechanism, and helps enterprises to adopt differentiated and dynamic strategies in the practice of digital transformation, taking into account both economic and social benefits.

2. Theoretical mechanisms and research hypotheses

2.1. The direct contribution of the digital economy to green innovation in cities

First, the digital economy breaks through the space-time constraints and information barriers of the physical world and eases information friction. From the perspective of productivity development, the digital economy has improved the efficiency of resource allocation and significantly enhanced social productivity. From the perspective of the adjustment of production relations, the traditional factory assembly line workshop production mode has undergone a subversive reform in the digital era (Hong Yinxing and Ren Baoping, 2023). In the era of digital economy, the rapid development of emerging digital technologies represented by the Internet, cloud computing, big data, Internet of Things, artificial intelligence, etc., the digital economy has on the one hand expanded the geographic scope of information collection as well as the types of information collected, and on the other hand, it has also strengthened the in-depth utilization of data resources, realized the effective integration of fragmented supply information and demand information, and improved the efficiency of innovation resource collection, which makes the innovation subjects can obtain high-quality green innovation-related information more efficiently, solving the problem of inefficiency and high energy consumption caused by poor information in the early stage, and contributing to the improvement of the level of urban green innovation (Chen, 2023).

Secondly, the digital economy can reduce the cost of green innovation. The digital economy takes data as the key production factor, which exists in the form of virtual and non-physical objects, and has the environment-friendly characteristics of low natural resource consumption and low pollution emission in the process of factor acquisition and factor flow, while the replicability and shareability of data resources themselves make their marginal benefit incremental obvious, and their marginal cost almost zero, which in turn makes the production factor of data have the characteristics of low cost and high return (Hao et al., 2020), This characteristic makes data as a production factor with low cost and high return (Hao et al., 2023). In terms of search costs, the digital economy has broken through the information barriers, alleviated the information asymmetry in the market, narrowed the digital access gap, and thus reduced the cost of information search. In terms of production costs, the digital economy builds an efficient digital technology system, realizes the improvement of production efficiency and resource allocation efficiency among enterprises in the supply chain, reduces the consumption of resources, and promotes the construction of ecological environment as well as reduces production costs. In terms of transaction costs, through the information platform, production enterprises are able to quickly and accurately search for trading objects that meet the standards and communicate with them in a timely manner, breaking the geographical and spatial limitations, better solving various problems encountered in the transaction process, greatly improving the transaction efficiency (Yu Shihai et al., 2022), and lowering the cost of transactions. Under the trend of decreasing urban green innovation costs, it is conducive to enhancing the initiative of urban green innovation, improving the benefits of green innovation, and then promoting the increase of innovation investment, further promoting the development of urban green innovation.

Third, the digital economy can alleviate the financing constraints of urban innovation entities. The high-risk, irreversible and long investment cycle of green innovation projects, accompanied by the high costs, resource constraints and risk of failure faced in the process of urban transformation, have led to financing constraints that are a major limitation to urban green innovation. Therefore, solving the financial difficulties and alleviating the financing constraints become the key to urban green innovation. In the context of the digital economy era, the birth of digital finance can promote a series of integrated business including digital payment and network lending, realize business model innovation and integration, reduce the access threshold and service cost of micro and small enterprises and low-income groups (Zhai Huayun and Lewis, 2021), which can further expand the financing

channels of urban innovation subjects. At the same time, it helps to enhance the innovation and entrepreneurial activities in underdeveloped traditional financial regions, which in turn directly promotes the improvement of regional green innovation level. Relying on modern technology to innovate financial products, and with the characteristics of digital finance to collect and process market information efficiently and quickly, it can effectively alleviate the information asymmetry problem between borrowers and lenders, improve the transparency of the market and reduce the cost of external financing (Liu et al., 2022). To a certain extent, this can alleviate the financing constraints of the green innovation process of innovative subjects, enhance the green innovation power, and improve the level of urban green innovation as a whole.

However, while the digital economy promotes green innovation in cities, it also brings new challenges. Advances in digital technology should be inclusive, avoiding the "marginalization" of the central and western regions, rural areas and the elderly in the digital economy. Due to the realities of economic and social development in different regions, there are significant gaps in access to and use of digital dividends among individuals, households, enterprises and regions. The digital divide in the information age makes the positive effects of Internet development more concentrated in developed and urban areas, with no significant impact on less developed regions and rural areas. This is likely to trigger a "digital divide", making it difficult for disadvantaged groups to share the digital dividend, thus exacerbating the vicious circle of insufficient incentives for innovation and development - weak development of the digital economy - more lack of incentives for innovation and development. The risk of a vicious cycle of insufficient incentives for innovation and development - weak development of the digital economy - and even more lack of incentives for innovation and development. At the same time, the monopoly of digital technology may intensify the exploitation of surplus value by capital, for example, "takeaway riders are trapped in data algorithms, unable to realize the value of their own labor."

2.2. The indirect contribution of the digital economy to green innovation in cities

First, the digital economy can help create a new highland for the gathering of high-end composite talents and drive the green and innovative development of cities. With the development of information technology, the digital economy has deepened in the minds of the public and become the focus of attention, while practitioners have gradually taken the digital industry as a target industry because of its flexibility, inclusiveness and convenience. A large number of ordinary workers have begun to engage in jobs such as live streaming with goods, driving ride-hailing cars, and delivering takeaways, relying on various digital platforms. These economic activities have led to the possession of pervasive digital skills and the proficient use of digital tools, which have improved the digital literacy and skill level of the entire population and society as a whole. Cities, as the core places for the development of the digital economy, have the infrastructure, technology and other advantages needed for digital economy-related industries, attracting a constant pool of digital talent. Human capital is the source of economic growth and also an important endogenous driving force for the realization of green innovation. According to the classical distribution theory, factors tend to flow into industries with higher efficiency, i.e., improving the labor efficiency of industries between urban and rural areas will be conducive to the accumulation of more high-level human capital, thus providing human security for the realization of green innovation (Ouyang Haiqin, 2024). This spatial effect fully reflects the advantages of rapid flow and efficient agglomeration of high-end composite talents, as well as the extremely strong urban talent activity, which provides solid talent support for urban green innovation.

Secondly, the digital economy can enhance the green innovation capacity of cities by promoting the synergistic clustering of industries. By virtue of its unique linkage, diffusion and spillover effects, the digital economy can provide new impetus for the transformation and upgrading of the manufacturing industry, quality enhancement and sustainable development. First, the digital economy can promote the intelligent development of traditional industries. Nowadays, the digital economy is continuously penetrating into various industries, which can penetrate into each link of the industrial chain and apply science and technology to production and operation, guide the industrial structure

from labor-intensive to technology-intensive and gradually evolve, so as to promote the in-depth fusion of the digital economy and traditional industries, promote the upgrading of its industrial structure, and promote the synergistic agglomeration of industries. Secondly, the digital economy can expand new business forms to promote industrial synergistic agglomeration. As people's consumer demand continues to rise, relying on science and technology, the digital economy can adapt to the needs of consumers to constantly expand new industries, such as the Internet of Things, cloud computing, big data, intelligent education industry, cloud-based commercial retailing and so on. Collaborative industrial agglomeration in turn can have an impact on the research and development stage and results transformation stage of urban green innovation through three aspects: knowledge spillover effect, scale effect and competition effect, which in turn improves the level of urban innovation through technological spillover, improves industrial competition, and strengthens industrial cooperation (Chang Cheol-jen and Zheng Meng, 2023). Adjustment of industrial structure can bring about a rational distribution of resources among industries, so that resources can be fully utilized to promote green innovation.

Thirdly, the development of the digital economy can influence urban green innovation by improving the environmental governance capacity of Governments. Promoting urban green innovation so that people can enjoy the benefits of green development is not only the responsibility of the government, but also an important way to satisfy people's aspirations for a beautiful ecological environment. In terms of the government's environmental governance model, environmental pollution behavior is usually hidden, which can lead to greater difficulty in environmental supervision, while the digital economy can improve the government's information disadvantage through the development of platforms such as the urban environmental monitoring system, so that the government can efficiently collect, integrate, and share environmental data, and improve the accuracy and effectiveness of the government's environmental supervision, so as to enhance the government's ability to supervise the environment (Molongjiong et al. 2024). In terms of the government's environmental protection attention, digital media can realize the information interoperability and sharing between the government and society, reduce the environmental information asymmetry between the government and the public, which helps the government to obtain feedback on the effectiveness of environmental governance, but also provides the public with access to environmental governance information channels, improves the transparency of the government's environmental protection governance, facilitates the public's supervision of the implementation of the state of the environment and the pollution of behavior in a timely manner, and The formation of the supervision of the effectiveness of environmental enforcement, forcing the government to improve the importance of environmental protection, which will inadvertently improve the government's attention to environmental protection (Wang Hai et al., 2023).

3. Econometric modeling and data description

3.1. Model building

3.1.1 Benchmark modeling

In order to test the effect of digital economy to promote green innovation, this paper constructs the following benchmark model:

$$GRI_{it} = \alpha_0 + \alpha_1 DIGE_{it} + \alpha_c Z_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (1)$$

Where GRI_{it} is the green innovation of city i in period t, and $DIGE_{it}$ is the level of digital economy development of i in period t. In order to solve the interference of endogeneity problem caused by omitted variables, this paper introduces a control variable with a vector Z_{it} denoting the population density (*pnd*), which is expressed as the ratio of the total population at the end of the year to the area of the city area. Human capital is a source of economic growth and also an important endogenous driver of regional innovation capacity (Hu, 2021). Foreign capital openness (*fdi*), measured by the

ratio of FDI to GDP of the host city. By opening up to the outside world, it can promote the accumulation of high-end production factors such as knowledge, technology and experience in the region, provide bottom-up technical guarantee for environmental improvement, and help guide the concentration of factor flows to high-tech level green industries. The degree of financial development (*fin*) is measured by the ratio of the loan amount of financial institutions to GDP. Financial agglomeration exists innovation incentive effect, so as to provide sufficient financial guarantee for green innovation. Energy efficiency (*ENERGY*), which is measured by GDP/MT of standard coal. The improvement of energy efficiency is an important reflection of high-quality economic development and an important symbol of technological progress (Chen et al., 2021). Urbanization rate (*urban*), we measure the ratio of non-agricultural population to year-end resident population. The agglomeration effect brought by urbanization leads to the upgrading of production and consumption through advanced industrial structure, which in turn improves the efficiency of economic operation and environmental governance. Transportation Facilities Improvement Degree (*TRANS*), expressed as highway mileage/total area of the region for this indicator. Transportation facilities, as a major component of infrastructure, are conducive to the improvement of factor resource allocation efficiency in different regions (BU Xiaoning et al., 2019). At the same time, the model is designed to avoid individual heterogeneity in within-group regression, thus adding μ_i to indicate individual fixed effects and δ_t to indicate time fixed effects; and clustering the random error term ε_{it} to the city level to solve the systematic heteroskedasticity problem of the model. Estimated coefficients α_1 denotes the identification of causal effects between digital economy and green innovation, if $\alpha_1 > 0$ indicates that digital economy positively promotes green innovation.

3.2. Measurement of key variables

3.2.1 Green Innovation Measurement

Since there are no official statistics on green patents at the city level in China, based on existing studies (Xin Daleng and Peng Zhiyuan, 2023; Zhou Li and Shen Kunrong, 2020), this paper corresponds the classification of green patents in the Green List of International Patent Classification published by WIPO to the number of green patents filed in each city in the past year, which is recorded as gri. The number of green patents in each city is screened out from the patents filed in the past years as a proxy variable for green innovation, which is denoted as gri. Meanwhile, considering that green patents can be subdivided into invention patents and utility model patents, among which invention patents are more difficult to apply for and are more innovative in substance, green invention patents are adopted as a proxy variable for green innovation in the baseline regression part, and green utility model patents and total number of green patents are adopted as a proxy variable for green innovation in the robustness test part. utility model patents and the total number of green patents for testing. In the process of empirical test, the natural logarithm is taken after adding 1 to the variable, and the larger the value is, the higher the level of green innovation of the city is.

3.2.2 Measurement of the level of development of the digital economy

Considering the availability of data at the city level, drawing on the methodology of Zhao Tao et al. (2020), the Internet penetration rate (the number of Internet broadband access users per 100 people), the related employees (the proportion of employees in the computer services and software industry in the employees in urban units), the related outputs (the total amount of telecommunication services per capita), and the cell phone penetration rate (the number of cell phone subscribers per 100 people) are selected to represent the level of Internet development at the city level. China's digital inclusive finance index measured by Peking University was selected to characterize the level of digital finance development in cities. The entropy method is used to calculate the comprehensive development index of digital economy, which is *denoted* as *dige*.

3.3. Data sources and sample selection

The relevant data in this paper come from the China Urban Statistical Yearbook, EPS, Wind and Love Enterprise Search databases. Some of the missing value data are filled in using the interpolation method. At the same time, in order to prevent the influence of scale and outliers on the accuracy of regression, this paper carries out scale transformation processing for some variables, logarithmic processing for some variables, and shrinking of both ends by 1% for all variable values. On this basis, this paper carries out a series of subsequent analysis and discussion.

Table 1. Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max.
dige	2538	8.614	0.916	5.801	12.072
gri	2538	4.386	1.684	0.693	9.335
pnd	2538	7.237	3.959	0.000	14.000
fin	2538	1.561	3.294	0.025	44.898
fdi	2538	-6.443	1.268	-13.239	-3.257
trans	2538	1.575	4.461	0.061	90.679
eney	2538	1.630	0.074	1.397	1.865
urban	2538	-0.039	0.021	-0.100	-0.008
bet	2538	9.158	1.619	4.788	15.128
isu1	2538	-1.670	1.085	-8.830	5.332
isu2	2538	6.516	0.346	5.517	7.836
hcsu	2538	0.841	1.705	0.001	12.801

4. Empirical analysis

4.1. Return to baseline

Table 2. Benchmark regression

	OLS		fixed effects model	
	(1)	(2)	(3)	(4)
DIGE	0.217***	0.120***	0.039**	0.042**
	(0.010)	(0.013)	(0.019)	(0.019)
pnd		0.066***		0.010
		(0.005)		(0.006)
fdi		-2.047***		1.189*
		(0.661)		(0.663)
fin		0.145***		0.088***
		(0.009)		(0.005)
energy		1.497***		-4.990***
		(0.230)		(0.505)
urban		1.118***		2.638***
		(0.099)		(0.247)
trans		0.039***		0.034***
		(0.003)		(0.007)
_cons	8.775***	5.251***	9.058***	15.921***
	(0.021)	(0.401)	(0.032)	(0.817)
City FE	N	N	Y	Y
Year FE	N	N	Y	Y
N	3102	3102	3102	3102
adj. R^2	0.147	0.530	0.886	0.900

Note: ***, **, and * indicate significant at 1%, 5%, and 10% confidence levels, respectively, with standard errors in parentheses, as in the table below.

Table 2 presents the regression results for digital economy and urban green innovation. Columns (1) and (2) report the regression results of the OLS model. DIGE is significantly positive at the 1%

level regardless of whether control variables are included or not. Columns (3) and (4) report regression results for two-way fixed effects. The results still find that DIGE is significantly positive at the 1% level with or without the inclusion of control variables. For this reason, the research hypothesis is validated that the digital economy indeed improves urban green innovation.

In terms of control variables, the degree of financial development, energy use efficiency, urbanization rate and transportation facility improvement are significantly positive at the 1% level, indicating that the level of science and technology, science and technology expenditure and infrastructure construction are important factors in promoting urban green innovation. Population density is not significant in the fixed-effects model, implying that green innovation is more dependent on cultivating high-quality talents.

4.2. Robustness analysis

4.2.1 Substitution of variables

Drawing on Zhou Lei and Gong Zhimin's (2022) method, the comprehensive development index of the digital economy is calculated by the entropy method and denoted as DIGE2. In addition, green innovation is tested for robustness using green utility model patents (GRI2) and total patents (GRI3), respectively. The test results in columns (1) to (3) of Table 3 illustrate that different methods of measuring digital economy and green innovation do not affect the core conclusions of this paper, and that the positive effect of digital economy on green innovation has a certain degree of credibility.

4.2.2 Panel quantile model

Table 3. Robustness test

	(1) GRI	(2) GRI2	(3) GRI3	(4) Q=0.25	(5) Q=0.5	(6) Q=0.75	(7) IV_MEAN	(8)
DIGE2	0.273**							
	(0.132)							
DIGE		0.005***	0.209***	0.088***	0.133***	0.180***		0.989***
		(0.001)	(0.045)	(0.012)	(0.014)	(0.012)		(0.041)
IV_MEAN							-0.731***	
							(0.023)	
pnd	0.011*	0.003***	0.057***	0.043***	0.062***	0.062***	0.017**	-0.000
	(0.006)	(0.000)	(0.015)	(0.006)	(0.005)	(0.005)	(0.006)	(0.009)
fdi	1.211*	0.063***	-0.672	-1.433**	-1.336**	-1.417	-5.753**	6.103***
	(0.665)	(0.024)	(1.583)	(0.724)	(0.549)	(0.867)	(0.719)	(0.971)
fin	0.088***	0.000**	-0.026**	0.115***	0.166***	0.218***	0.008	0.079***
	(0.005)	(0.000)	(0.013)	(0.011)	(0.008)	(0.037)	(0.005)	(0.007)
energy	-5.148***	-0.168***	-4.558***	0.254	1.719***	2.102***	-2.321	2.586***
	(0.501)	(0.019)	(1.206)	(0.408)	(0.230)	(0.177)	(0.176)	(0.211)
urban	2.585***	-0.027***	-1.045*	0.701***	0.895***	1.045***	0.540**	2.142***
	(0.246)	(0.009)	(0.590)	(0.064)	(0.066)	(0.106)	(0.238)	(0.320)
trans	0.036***	-0.000	-0.096***	0.046***	0.039***	0.026***	0.049***	-0.003
	(0.007)	(0.000)	(0.017)	(0.004)	(0.002)	(0.006)	(0.008)	(0.011)
_cons	15.753***	0.446***	12.018***	7.301***	4.856***	4.380***		
	(0.838)	(0.030)	(1.949)	(0.705)	(0.391)	(0.300)		
Anderson LM								735.965***
Wald F								993.395***
10% Stock-Yogo							16.38	
City FE	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y
N	3102	3102	3102	3102	3102	3102	3102	3102
adj. R^2	0.900	0.937	0.797	0.900	0.900	0.900	0.222	0.222

The benchmark regression model portrays the effect of digital inclusion located in the mean interval on energy intensity, without specifically examining the differences in the role of digital

inclusion development in different energy intensity regions. Drawing on Chernozhukov et al. (2022), this paper further selects a panel quantile regression model for testing. The panel quantile regression model models the different quartiles separately based on the overall city data, which can make up for the shortcomings of mean regression, and at the same time, avoid the subjectivity of grouping the city samples, and more fully capture the overall characteristics of the distribution. In this paper, 25%, 50% and 75% are selected as the quantile points for regression, and the year and province (district and city) effects are fixed at the same time, and the regression results are shown in columns (4) to (6) of Table 3. The results show that the digital economy can still significantly promote urban green innovation at different quantile points.

4.3. Endogeneity test

The existence of certain unobservable factors as well as bidirectional causation can lead to endogeneity problems, thus this paper utilizes the instrumental variable method to do endogeneity testing to circumvent these problems. First, this paper draws on existing research to choose urban topographic relief as an instrumental variable (Niu, Ziheng and Cui, 2021). The reasons are as follows: first, the degree of topographic relief can reflect the complexity of regional topography, which has an impact on the installation and commissioning of digital infrastructure. Generally speaking, an increase in terrain relief will correspondingly increase the difficulty and cost of digital infrastructure construction, which satisfies the correlation condition of the instrumental variable. Second, the degree of terrain relief is a natural geographic factor that is not directly related to other economic variables, which satisfies the condition of exogeneity as an instrumental variable. It is worth noting that the raw data of the instrumental variable of terrain relief are in cross-sectional form, which cannot be used in the econometric analysis of panel data. Therefore, this paper refers to Nunn and Qian's (2011) treatment of this issue and introduces a time-varying variable to construct the panel instrumental variable. Specifically, the number of Internet users in the country in the previous year is constructed as an interaction term with the degree of topographic relief of each city respectively, as an instrumental variable for the city's digital economy index in that year.

Columns (5) and (6) of Table 3 show the regression results using terrain relief (Iv_ land) as an instrumental variable. It can be seen that the first stage of the model shows a significant negative correlation between urban topographic relief and the digital economy, while the coefficients of the digital economy variables in the second stage of the model are significantly positive at the 1% level, which is consistent with the baseline estimation. In addition, for the test of the original hypothesis "insufficient identification of instrumental variables", the p-value of LM statistic is 0.000, which significantly rejects the original hypothesis; in the test of the weak identification of instrumental variables, the Wald F-statistic is larger than the critical value of Stock-Yogo's test of weak identification at the 10% level. Overall, the above tests prove the reasonableness of the instrumental variables selected in this paper, and thus the role of digital economy in promoting urban green innovation is more robust.

4.4. Heterogeneity analysis

Considering the differences in the level of economic development, resource endowment and industrial structure among Chinese provinces and municipalities themselves, the digital economy on urban green innovation may be characterized by heterogeneity at the regional level. Therefore, this paper is divided into two groups according to the two regional divisions of East, Central and West, and North and South to carry out the test separately, and the results are shown in Table 4.

The results of columns (1) to (3) in Table 4 show that the digital economy has a positive impact on green innovation in both the eastern and western regions, and the impact on the eastern region is significantly positive at the 1% level, while the impact on the central region is negative and fails the test of significance. This may be due to the fact that the eastern region has obvious advantages in economic development, foreign trade and high-tech fields, and is in the stage of rapid development and application of the digital economy, which is more adaptable to the rapid development of the

digital economy and the rapid transformation of enterprises, and is conducive to giving full play to its advantages in promoting green innovation (Wang et al., 2022; Wang Hai and Shen Yingying and Li Yan, 2023). Although the western region is relatively backward in terms of economic development, it is able to rely on convenient financing services to realize capacity expansion in the context of the rapid development of digital finance. Considering that the western region is more difficult to finance and lags behind in the development of high technology, the marginal impact of digital economy on the eastern region and the intensity of the impact is higher.

The development of digital economy in Chinese cities has an obvious trend of stratification and north-south differences, so according to the geographical location of the sample is also divided into southern cities and northern cities for regression analysis (Zhu Jiexi and Li Junjiang, 2023), comparing the columns (4) and columns (5) of Table 4, it can be seen that the coefficient of the digital economy of the southern region on the green innovation of the city is 0.057, which passes the 1% significance test. And the coefficient of the northern region is 0.066, which does not pass the significance test, indicating that the impact of digital economy on urban green innovation in the northern region is not significant. The reason for this is that, on the one hand, the southern region is dominated by light industry and trade, and in the Pearl River Delta region, high-tech enterprises are clustered, and the level of development of the digital economy is relatively high, which provides a source of power for the development of green innovation in the city, compared with the southern region, the industrial structure of the northern region is mostly resource-consuming enterprises, and the proportion of high-energy-consuming and high-polluting industries is relatively high, and the difficulty of industrial restructuring and upgrading is great, and the economic development is increasingly in conflict with environmental protection. The economic development and environmental protection are increasingly conflicting, which limits the pace of green and innovative development of the city. On the other hand, after the reform and opening up, the southern region has set up special economic zones such as Shenzhen and Zhuhai, and the level of openness to foreign investment has been significantly increased, which accelerates the improvement of the city's innovation capacity.

Table 4. Heterogeneity test

	(1) eastern part	(2) Central Region	(3) western region	(4) Northern Areas	(5) Southern Region
DIGE	0.908***	-0.145	0.094	0.304	0.300**
	(0.249)	(0.127)	(0.307)	(0.259)	(0.140)
pnd	-0.000	0.017***	-0.008	0.008	0.015***
	(0.009)	(0.005)	(0.018)	(0.015)	(0.006)
fdi	2.348***	0.088	-1.565	-0.014	2.190***
	(0.806)	(0.479)	(3.457)	(1.263)	(0.721)
fin	0.094***	0.122***	0.033**	0.116***	0.004
	(0.015)	(0.004)	(0.013)	(0.008)	(0.008)
energy	-6.813***	-4.994***	-3.257**	-5.390***	-4.454***
	(0.741)	(0.403)	(1.335)	(0.996)	(0.560)
urban	2.120***	1.380***	5.265***	2.808***	2.324***
	(0.372)	(0.177)	(0.728)	(0.508)	(0.254)
trans	0.034***	0.053***	0.137	-0.098	0.041***
	(0.006)	(0.011)	(0.171)	(0.091)	(0.006)
_cons	17.444***	16.549***	12.446***	16.057***	14.756***
	(1.352)	(0.691)	(2.224)	(1.651)	(0.944)
City FE	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y
N	1078	1111	913	1132	1969
adj. R^2	0.947	0.970	0.792	0.866	0.932

5. Conclusions and recommendations

Digital economy and green innovation are important factors for China to realize high-quality development and accelerate the formation of new quality productivity. Based on the relevant panel data of 282 prefecture-level cities from 2011 to 2021, this paper provides an in-depth investigation of the impact of digital economy and green innovation and its heterogeneity using OLS regression, fixed-effects model, and quantile panel model. In general, the digital economy has a significant positive contribution to urban green innovation, which still holds after a series of robustness tests such as variable substitution, panel quantile model, and instrumental variables. The heterogeneity test also shows that the digital economy is more significant for promoting green innovation in eastern and southern cities compared to central and western cities and northern cities. This suggests that the eastern and southern regions enjoy more digital economy dividends, which on the one hand reflects the region's advantages in terms of economy, technology and resources, and on the other hand reflects the importance of promoting coordinated regional development to jointly realize the goal of promoting green innovation development. Based on the findings of this paper, the following recommendations are made.

First, the development of digital technology should be comprehensively promoted. Technological progress is an important force in the continuous development of green innovation. Therefore, the State should continue to strengthen its investment in the field of technological research and development in order to crack a series of difficult problems with technological progress. On the one hand, it should give strong support to scientific research and technology departments in terms of financial resources, encourage technological innovation in production technology and pollution prevention, and reduce the emission of various environmental pollutants while promoting the improvement of total factor productivity and productivity progress. On the other hand, through tax incentives for enterprises to provide positive incentives for technological innovation, and supplemented by strict environmental regulations and institutional arrangements to improve the internal economic cost of corporate pollution emissions, thus prompting enterprises to carry out technological innovation, so that the mode of production from the "high energy consumption and high pollution" to the "green low-carbon", thus realizing the purpose of emission reduction and pollution control. In addition, we should actively participate in international economic cooperation, keep abreast of the development of foreign advanced technology, introduce foreign advanced digital technology and equipment, learn and apply them in a targeted manner to complement each other's strengths and weaknesses, and promote the enhancement of China's digital economic development and the development of green innovation in the city.

Secondly, the introduction and cultivation of digital talents should be strengthened. The Government should play a leading role in the construction of the digital talent team, strengthen the introduction from the source, formulate policies for the introduction of digital talents, open green channels for high-quality talents and ease the barriers to the flow of talents, while improving preferential policies for talents and establishing a social security system for digital talents to maximize the satisfaction of talent needs. At the same time, the government has introduced a series of talent attraction policies, especially for high-level talents in the field of information technology. It has further increased investment in higher education, upgraded the level of regional human capital, established a rural skills training platform, encouraged the development of rural education, incentivized the return of high-quality talents, and realized two-way exchanges of people between urban and rural areas, which is conducive to giving full play to the synergistic and spillover nature of the digital economy-driven green innovation, so that urban and rural areas can share the digital dividend. In addition, in the cultivation of digital talents, it is necessary to strengthen the collaboration between industry, academia and research, relying on the talents and technologies of universities, research institutions and other talent training bases, as well as the funds and facilities of enterprises, and based on the development needs of the digital economy, so that both sides can stand on the same innovative talent cultivation mindset, accurately grasp the development trend of digital technology, and target the cultivation of high-quality composite talents.

Thirdly, industrial restructuring should be accelerated and synergistic industrial agglomeration should be deepened. At the government level, it is necessary to guide technological innovation through policy support, technical support and other means to promote the traditional industries to carry out industrial restructuring, tilting to high-tech industries and truly realizing green development. At the enterprise level, we should actively carry out technological innovation, introduce new technologies and products, improve the productivity and quality of enterprises, and at the same time establish a good relationship with the upstream and downstream industrial chain, strengthen the integration and optimization of the industrial chain, actively participate in the construction of industrial clusters, strengthen the cooperation with enterprises in the same industry, form the scale effect and the agglomeration effect, and jointly promote the vigorous development of the whole industry to promote the adjustment of the industrial structure and the synergistic agglomeration of the industry and then Promote the green and innovative development of the city. Local governments should actively break the time and space limitations between traditional development modes. At the same time, with the "the Belt and Road" this wind, encourage more Chinese digital economy enterprises to go out, foreign high-quality digital economy enterprises "brought in", to better share the digital dividends around.

Fourthly, the Government's capacity for environmental governance should be upgraded. Combine digital technology with environmental governance, carry out the infrastructure construction of environmental governance, strengthen the application research of digital economy in environmental governance, give full play to the real-time monitoring function and information sharing function of digital technology, improve the sustainability of the government's environmental governance effect, and enhance the government's environmental governance capacity. At the same time, improve the urban environmental governance system and laws and regulations, strengthen the utility of social supervision, guide the public to participate in the construction of the ecological environment, stimulate the public's enthusiasm for environmental protection, and promote the development of urban green innovation.

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