Humanities & Social Sciences Communications

ARTICLE

https://doi.org/10.1057/s41599-024-02787-y OPEN

Assessing the effect of urban digital infrastructure on green innovation: mechanism identification and spatial-temporal characteristics

Chengming Li[1,2,6], Meiyu Wen[1,2,6], Shaoxiang Jiang[3] & Huaxing Wang[4,5]✉

Under the background of digitization and greening in China, digital infrastructure offers new opportunities for developing green innovation. This paper investigates the effect of digital infrastructure on urban green innovation using panel data from 285 Chinese prefecture-level cities between 2011 and 2020, and explains the mechanism and its spatial-temporal dynamic effect. The results demonstrate that digital infrastructure promotes urban green innovation. Talent agglomeration, R&D investment increase, and industrial structure upgrading are crucial channels. Furthermore, depending on a city's size, human capital, environmental regulations, and financial subsidies, digital infrastructure contributes to urban green innovation differently. Also, there is not only a positive spatial spillover effect of digital infrastructure but a threshold effect that presents a nonlinear trend of rising marginal effect. This study provides a new perspective for promoting digital infrastructure and urban green innovation, which makes a difference in facilitating its high-level development collaboratively.

[1] School of Economics, Minzu University of China, 100081 Beijing, China. [2] China Institute for Vitalizing Border Areas and Enriching the People, Minzu University of China, 100081 Beijing, China. [3] Institute for Global Health and Development, Peking University, 100871 Beijing, China. [4] Law School, Hangzhou City University, 310000 Hangzhou, China. [5] School of Economics, Zhejiang University, 310000 Hangzhou, China. [6] These authors contributed equally: Chengming Li, Meiyu Wen. ✉email: wanghx@hzcu.edu.cn

Introduction

Green innovation is the primary engine behind efforts to advance green development, create a stunning China, and offer crucial support for excellent economic growth. It is also significant for building a green economic ecology and achieving sustainable development (Xue et al., 2022; Wang et al., 2022a; Wang et al., 2022b). These years, the Chinese government has paid much attention to green innovation and China's green innovation work has made significant progress. However, there are still shortcomings: on the one hand, green patents account for a relatively low proportion, green patents represent 6.3% of all patents issued in China between 2014 and 2017, with a rate of 6.2% in inventive patent applications; on the other hand, the development of innovation depth, innovation quality, and critical core technology breakthrough is still not ideal. Therefore, exploring the growth path of green innovation is of great strategic significance for improving environmental governance and promoting economic development.

Meanwhile, with the rapid development of digital technology and the steady advancement of the digital China strategy, China's digital infrastructure has made significant progress. The "Broadband China" policy led to the biggest optical fiber and mobile broadband network in the world, mobile communication realized the leap from '3 G' to '4 G' and then to '5 G', constructing the global integrated big data center system. Digital infrastructure has the characteristics of networking and intelligence. With its rich data resources and elements, it can be widely infiltrated into various fields of production and life. And its deep integration with the environment and energy fields can open up broad prospects for achieving green economic development. Therefore, it is necessary to comprehensively study the impact of digital infrastructure on urban green innovation, especially the mechanism and dynamic effects in time and space. In theory, this study helps to clarify and enrich the mechanism and path of digital infrastructure to empower green innovation, and in practice, it helps to provide empirical enlightenment for the coordinated development of digitization and greening.

The degree of Internet penetration as well as the amount of green patents in 30 Chinese provinces in 2020 from CSMAR are used in this study to reflect the digital infrastructure and urban green innovation level's relationship. Divide the data into five levels using the ArcGIS software's natural discontinuity point classification method, to create the distribution map of digital infrastructure and green innovation, as shown in Fig. 1. The green patent applications on each side of Hu's line are quite different. Compared to the western area, the eastern regions have more green patents. And it's even more in coastal regions, especially in Guangdong Province and Jiangsu Province, accounting for 30.6% of the country's total. The Internet penetration rate is significantly higher on the eastern side of Hu's line, and the Internet penetration rate of Guangdong Province also has pioneering advantages. The areas with more green patent applications are areas characterized by rapid Internet expansion. The distribution features of urban green innovation are positively correlated with digital infrastructure, while there is a causative connection that is unclear. Therefore, this paper further explores how digital infrastructure affects urban green innovation, in order to provide theoretical and practical help for promoting the construction of digital infrastructure and the development of urban green innovation.

The relationship between infrastructure and green development has received a lot of attention in the past. On the one hand, while the infrastructure system provides support for social development, it will also increase the vulnerability of nature and lead to the deterioration of resources; on the other hand, infrastructure construction can also reduce the damage to the ecological environment through waste treatment and waste recycling, and promote sustainable development (Thacker et al., 2019; Kong et al., 2018). In the era of digital economy, what is the green effect of digital infrastructure driven by digitization? Many scholars have found digital infrastructure can enhance energy efficiency (Song et al., 2023), reduce pollution (Wang et al., 2023c; Wang et al., 2023d), improve the ecological environment (Chu et al., 2021), and promote low-carbon development (Tang and Yang, 2023). Between 2005 and 2017, China's smart city projects helped cut a lot of industrial exhaust gas and wastewater (Chu et al., 2021). Digital infrastructure construction boosted low-carbon growth, and the effect is stronger with the improvement of digital infrastructure (Hu et al., 2023b). Digitization has a nonlinear and spillover effect on carbon emissions in China with the maturity of digitization (Zhang et al., 2022). The above literature may ignore the green innovation effect of digital infrastructure, which lays a foundation for further research in this paper.

Regarding green growth, the academic community has done a lot of related researches on the measurement of green economic growth level, spatial convergence, dynamic evolution (Wang et al., 2023e), and influencing factors (Wang et al., 2023f). As an important driving force for green development, green innovation has also received extensive attention from scholars in recent years. Researches found trade activities (Cao and Wang, 2017), environmental regulations (Hu et al., 2023c), low-carbon policies (Liu et al., 2023a; Li et al., 2023a), human capital (Munawar et al., 2022), R&D resources (Bai et al., 2019; Song et al., 2020), industrial structure (Li, 2023), economic policy uncertainty (Ren et al., 2023a) and digital development are

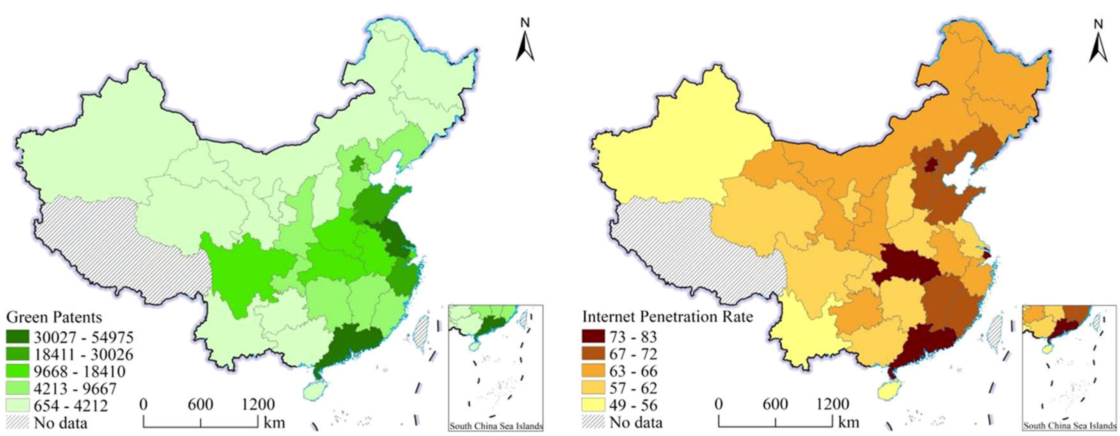

Fig. 1 The spatial pattern of green innovation (left) and digital infrastructure (right) in 2020.

important factors affecting green innovation. Among them, the most relevant to this study is the literature on digitization and green innovation, mainly focusing on digital transformation, digital finance, network infrastructure, etc. By boosting innovative resource investment and lowering debt costs, digital transformation promotes corporate green innovation (Liu et al., 2023b; Liu et al., 2023d; Ren et al., 2023c). Internal controls and financial constraints may operate as a mediating factor in enhancing green technology innovation through digital inclusive finance (Ma and Zhu, 2022; Ren et al., 2023b). "Broadband China" supported urban green innovation by boosting research and technology spending and fostering human capital (Feng et al., 2023). However, few studies have analyzed the impact of urban digital infrastructure on green innovation based on its overall development level.

This study analyzes the effect of digital infrastructure on green innovation at the city level using panel data from 285 Chinese prefecture-level cities from 2011 to 2020. The following are the primary conclusions: First, this paper finds that urban green innovation may be promoted by digital infrastructure. Second, mechanism analysis shows that urban green innovation may be supported by digital infrastructure through encouraging talent agglomeration, boosting R&D spending, and upgrading industries structure. Third, heterogeneity results show that the green effects of digital infrastructure are heterogeneous across cities of different sizes, human capital levels, environmental regulations, and financial subsidies. Digital infrastructure has a stronger boosting effect on a larger scale, higher human capital, higher environmental regulations, and greater fiscal subsidies cities. Fourth, further analysis finds that digital infrastructure has a spatial-temporal dynamic effect on urban green innovation. Digital infrastructure has a positive spillover effect in the spatial dimension, and there is a threshold effect in the temporal dimension, and as digital infrastructure improves, its empowering effect on urban green innovation presents a gradually increasing nonlinear characteristic.

Compared to previous studies, the primary contributions are as follows:

Firstly, at present, the academic community has conducted a lot of researches on digital infrastructure and green innovation, but there are relatively few studies on the relationship between the two, and few are directly involved. More literature mainly focuses on the effect of a certain type of infrastructure construction on urban green innovation, such as network infrastructure, emerging infrastructure and communication infrastructure. Based on the perspective of overall development, this paper uses principal component analysis to comprehensively measure the level of urban digital infrastructure construction, analyzes the effect of urban green innovation, and enriches the theoretical researches of digital infrastructure and green innovation.

Secondly, in terms of mechanism and heterogeneity analysis, the existing literature mainly analyzes the mechanism from the aspects of inclusive finance, economic agglomeration, and resource allocation, and discusses heterogeneity based on geographical location and economic development level. Based on the "human, financial, and material" path of social development, this paper comprehensively analyzes the transmission path of talent agglomeration, R&D investment increase, and industrial structure upgrading. Based on the two perspectives of urban resource endowment and policy environment, this paper analyzes heterogeneity from the perspective of urban scale, human capital level, environmental regulation intensity, and financial subsidy intensity. It is conducive to the further refinement of the researches on digital infrastructure and green innovation, and also conducive to the government's more targeted formulation of relevant policies.

Finally, the existing literature ignores the temporal and spatial dependence of digital infrastructure and green innovation. This paper further introduces time and space factors, uses the Durbin model to examine the spatial spillover effect of digital infrastructure, and uses the threshold model to reveal its nonlinear effect. This paper analyzes the relationship between digital infrastructure and green innovation from the perspective of time and space, provides new ideas for promoting the construction of digital infrastructure and the ways and measures to promote the development of green innovation.

The research framework is shown in Fig. 2.

Theoretical analysis and research hypothesis

Digital infrastructure promotes urban green innovation. Digital infrastructure is a vital cornerstone of the digital economy's long-term, stable growth, with significant enabling effects on both economy and society. It opens up new development paths and viable spaces for innovative activities, which will stimulate green innovation based on human, financial, and material paths.

First, digital infrastructure can influence the growth of urban green innovation through talent agglomeration. It can effectively break information, knowledge, industrial, and spatial boundaries and promote the convenient and efficient transmission of data and information in life. With its deep vertical penetration and remarkable information resource integration capability, it breaks barriers of knowledge and technology, enables knowledge dissemination and shares among different innovation subjects (Paunov and Rollo, 2016), improves urban informatization and recruits scientific and technological expertise. Talents are the creators and disseminators of advanced ideas and culture, and progress in science and technology requires advanced ideas to drive it, which ultimately requires talents to achieve it. The network clustering effect of digital infrastructure helps promote the establishment of knowledge networks that support urban green innovation with enough talent and knowledge.

Secondly, digital infrastructure can support green innovation through increasing R&D investment. Digital infrastructure offers more productive platforms and tools to encourage innovative R&D work and broadens access to R&D resources. Through digital platforms and open data resources, R&D institutions can access large-scale and diversified data, which helps them understand market demand and development trends, effectively avoiding the risk and waste of invested resources; meanwhile, digital technology combines technological innovation and business models, creates more market and commercialization opportunities. Digital infrastructure offers a platform for researchers to disseminate and apply their research results. Researchers and developers can translate innovative technological achievements into commercial products and services and realize economic value. Such commercialization opportunities stimulate increased investment in R&D and drive more profound green innovation.

Thirdly, digital infrastructure can support urban green innovation by upgrading industrial structures. Digital technologies can alter and empower traditional infrastructure and encourage the digital upgrading of traditional sectors effectively (Guo et al., 2023). It can also cause a close connection between the supply and demand sides, and bring out new industries and models. At the same time, emerging technologies and digital infrastructure can benefit from one another, and encourage digital technologies while facilitating cross-border industry integration. It hastens the demise of dormant industries, fosters the growth of new industries, and continuously optimizes the layout, structure, function, and development mode of industries, thus further influencing urban green innovation development.

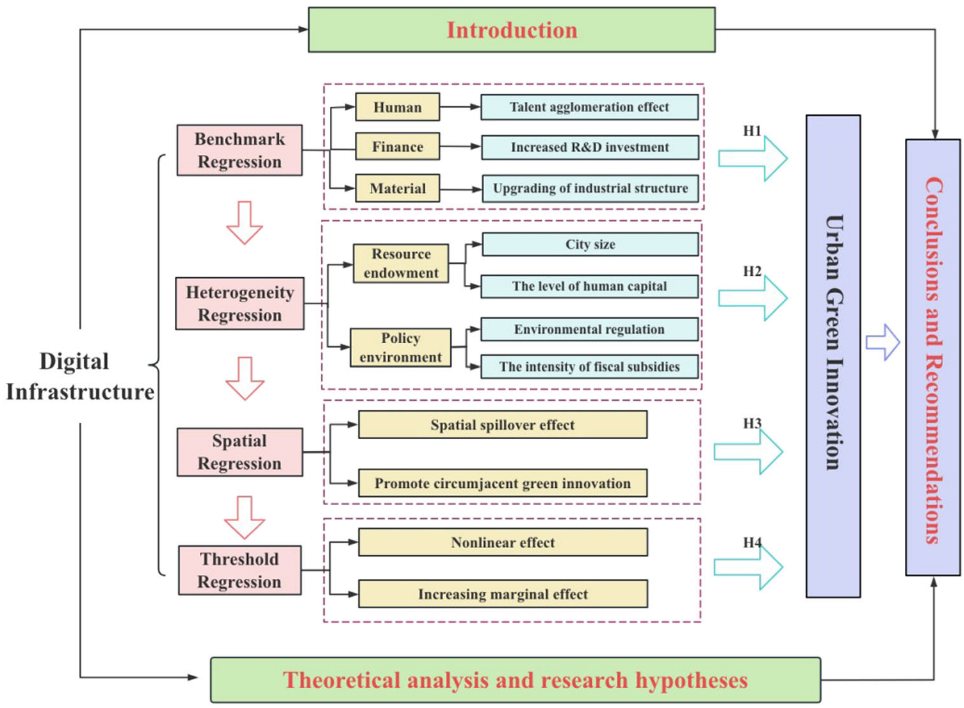

Fig. 2 Research framework.

Therefore, the hypothesis 1 is proposed:

H_1: Digital infrastructure can contribute to urban green innovation.

Regional heterogeneity in the green innovation effects of digital infrastructure. As the core carrier of regional economic development and an indispensable medium for building an ecological civilization, cities have the dual mission of stimulating innovation momentum and focusing on green development to improve the environment and the economy (Dong et al., 2023). Digital infrastructure can empower urban green innovation by enhancing fast and convenient information and knowledge flows through data elements and intelligent technologies. Considering the notable variations in resource endowments and policy environments of different cities, digital infrastructure may have various effects.

On the one hand, the internal resource endowments within cities, such as city size and human capital level, which show an important influence on developing digital infrastructure and promoting green innovation. Firstly, differences in city size. Cities of different sizes differ in economic level, industrial structure, and technological and financial development. Larger cities have the advantage of economic resources, human resources, and other factor endowments and attach more importance to green innovation, which may lead to more decisive in promoting green innovation. Secondly, disparities in human capital levels. Human capital-rich cities tend to have a more substantial knowledge and technology base for green innovation, a relatively more potent ability to absorb and utilize new digital technologies, more convenient interdisciplinary collaboration and knowledge sharing, and a more friendly innovation culture and entrepreneurial environment, which can better enhance green innovation.

On the other hand, the cities' external policy environment like environmental regulations and financial subsidies (Hu et al., 2023a), can also influence the green innovation implications of digital infrastructure. First, environmental regulations vary. Regions with stronger environmental regulations usually adopt stricter environmental protection policies, which exert external policy pressure on enterprises and innovators and provide clear directions and standards, inspiring innovators to use digital infrastructure more actively to support urban green innovation, thus boosting city transformation towards green and sustainable growth. Secondly, the difference in financial subsidies. Financial subsidies provide external policy incentives such as financial support for innovation agents, reduce the costs and risks for enterprises to undertake innovation activities, and make green innovation feasible and attractive (Wei et al., 2023). It also promotes the spread and development of digital infrastructure, accelerates continuous technological upgrading and innovation, and pushes cities to achieve a higher level of green development.

Accordingly, research hypothesis 2 is proposed:

H_2: The contribution of digital infrastructure to advancing urban green innovation is heterogeneity, showing a stronger effect on cities with larger sizes, higher human capital, higher environmental regulations and higher financial subsidies.

Digital infrastructure has a spatial spillover effect on urban green innovation. Digital infrastructure is characterized by integration, intelligence, and development, which can not only empower local green innovation but also break the spatial and temporal boundaries of factor flow, promote the flow of resources, enhance exchanges and cooperation, optimize resource allocation and industrial spatial layout, achieve integration of resources, and develop other regions' green innovation efficiently. Digital technology's ongoing development and wide-ranging uses reduce the time and cost of knowledge learning, increase the speed of dissemination and diffusion of green knowledge and technology between regions, shorten the spatial and temporal distance of green innovation resources transferring between different regions (Forman and van Zeebroeck, 2019), enhance the breadth of association and depth of exchange of innovation activities between regions (Li et al., 2022; Li et al., 2023b), and enhance the transfer of green knowledge technologies to nearby locations, stimulate more cities to reinforce green innovation. In addition, digital infrastructure makes it possible for the movement of production elements including labor, money, and technology to overcome geographic constraints. It is beneficial to improve capital and labor productivity, foster transforming and upgrading industries, and accelerate green innovation industries development. Create a positive feedback loop of talent agglomeration and spread it to related industries to generate the positive spatial spillover effect. At the same time, developing digital infrastructure can play a good demonstration and warning effect, which is conducive to promoting healthy competition, exchange, and cooperation among regions, forming a cross-regional green innovation ecosystem. Through digital platforms and collaboration tools, innovation agents in different cities can cooperate more closely and efficiently, and the formation and expansion of this cooperation network enhance the scale effect, further supporting the spread of green innovation.

Therefore, research hypothesis 3 is suggested:

H_3: Digital infrastructure has a positive spillover effect and can promote green innovation capacity in nearby places.

Digital infrastructure has a threshold effect on urban green innovation. Information technology influences every part of society due to the maturity of digital infrastructure. It has accelerated industrial digitization, accumulated abundant data resources, and realized transmission, sharing, and aggregation with the digital platform to form a powerful network effect. Big data encourages collaboration and cross-border integration among various organization departments, enterprises, and industries. This causes the value chain to be optimized and reorganized, weakens the boundary of innovation activities, lowers the threshold and marginal cost of parity, and increases innovation income. Therefore, with the continual growth of digital infrastructure, its role in fostering urban green innovation will strengthen. Meanwhile, digital infrastructure itself will show the characteristics of marginal increase. Digital technology has an apparent self-growth effect due to iteration and updating, which can lead to greater technical assistance, a larger collaborative platform, and a more conducive atmosphere for urban green innovation. It provides new development space and opportunities, and forms the marginal increase of digital infrastructure's effect on green innovation.

Accordingly, the study suggests the hypothesis 4:

H_4: Digital infrastructure has a threshold effect on urban green innovation, showing a nonlinear feature of increasing marginal effect.

Research design

Empirical model. The benchmark regression model for measuring the effect of digital infrastructure on urban green innovation is as below:

$$GI_{it} = \alpha_0 + \alpha_1 digital_{it} + \alpha_2 Control_{it} + \mu_i + \delta_t + \varepsilon_{it}$$

The indices i and t represent city and year, GI is the explained variable, digital is core explanatory variable, Control represents control variables, μ_i and δ_t is the city and year fixed effect, and ε_{it} is random error term.

The study utilizes the following spatial model to assess the spillover effect of digital infrastructure:

$$\begin{aligned} GI_{it} = {} & \beta_0 + \rho WCI_{it} + \beta_1 digital_{it} + \beta_2 Control_{it} \\ & + \beta_1^{'} Wdigital_{it} + \beta_2^{'} WControl_{it} + \mu_i + \delta_t + \varepsilon_{it} \end{aligned}$$

where W is the spatial weight matrix, and ρ is the spatial autoregressive coefficient, and the other letters have the same meanings as above.

To examine if digital infrastructure has a nonlinear effect on urban green innovation, the paper sets the panel threshold model referring to Hansen (1999) with digital infrastructure as the threshold variable:

$$\begin{aligned} GI = {} & \gamma_0 + \gamma_1 digital_{it} \times \mathrm{I}(th_{it} \le \theta_1) + \gamma_2 digital_{it} \times \mathrm{I}(\theta_1 < th_{it} \le \theta_2) \\ & + \gamma_3 digital_{it} \times \mathrm{I}(th_{it} > \theta_2) + \sigma Control_{it} + \mu_i + \delta_t + \varepsilon_{it} \end{aligned}$$

where I() is the demonstrative function, and th_{it} is the threshold variable, representing digital infrastructure, and θ is the threshold to be estimated, and the other letters have the same meanings as above.

Variables description

Explained variable. Urban green innovation: The end result of innovative activity is patents. Urban green innovation may be more naturally reflected and quantified by the number of urban green patents. The number of patent applications is more stable, reliable, and timely compared with the number of green patents granted. Therefore, referring to Yang et al. (2022), Zhang et al. (2019), and Liu et al. (2023c), this study measures urban green innovation using the quantity of green utility and inventive patent applications filed per 10,000 inhabitants.

Core explanatory variable. Digital infrastructure: Drawing on the China Regional Digital Development Index Report 2021 and referring to studies by Alderete (2017) and others, the study chooses eight dimensions of indicators based on the available data: ports for Internet broadband access, domain names registered on the Internet, amount of Internet web pages, length of optical fiber lines, Internet penetration rate, mobile phone availability rate, per-capita telecommunications services, computer software and software share. Using principal component analysis to measure can better reflect the comprehensive nature of the Chinese cities' digital infrastructure development.

Control variables. The study has identified the following control variables according to Feng et al. (2023) and Han et al. (2023): (1) pergdp (GDP), which measures a region's economic progress by the per capita GDP logarithm; (2) population size (people), represented by the annual total urban population's logarithm; (3) degree of opening up (open), determined as the foreign investment to GDP ratio; (4) fiscal expenditure level (fiscal), indicated as ratio of fiscal spending to GDP; (5) spending on science and education (education), the percentage of government spending on science and education; (6) environmental pollution (environment), indicated as industrial smoke (dust) emissions in relation to GDP.

Data sources and descriptive statistics. The National Bureau of Statistics, the China Economic and Financial Database, and the annual China City Statistical Yearbook all provide the economic data. This paper excludes cities with serious administrative area adjustment and missing data, selects data from 285 prefecture-level cities across China from 2011 to 2020, adopts alternative indicators and data to fill in data gaps, and integrates them into panel data finally.

Descriptive statistics results are shown in Table 1. Green innovation has a mean value of 1.437, a minimum value is 0, and a maximum value is 49.98, showing significant variability in green innovation across cities. Digital infrastructure's mean value is 3.450, with minimum and maximum values of 2.296 and 10.32, showing a wide range in digital infrastructure across cities. The control variables' values show significant individual differences.

Empirical results

Baseline regression. The regression results for the effect of digital infrastructure on urban green innovation are shown in Table 2. This paper uses a recursive regression approach. Regardless of whether to add control variables or control for city or time-fixed effects, digital infrastructure's coefficients are significantly positive, indicating that digital infrastructure contributes to urban green innovation.

As for control variables, economic development, fiscal expenditure, and spending on science and education, all have positive coefficients, demonstrating that green innovation in the area increases with them. The regression coefficient for openness is significantly negative. Foreign investment will bring in more highly polluting and energy-intensive production sectors, and it could inhibit the shift of technological innovation towards green and clean.

Endogeneity treatments

Controlling for provincial trend effects. The previous study shows that digital infrastructure significantly contributes to urban green innovation. However, this result may be endogenous due to reverse causality. Regions with high levels of green innovation have faster informatization processes and more advanced development of digital infrastructure. To reduce the macro-environmental changes that the ongoing development of digital infrastructure may cause, this paper conducts a regression analysis by controlling for province-fixed effects and province-year interaction effects. According to Table 3, digital infrastructure still promotes urban green innovation.

Instrumental variables method. This study refers to Huang et al. (2019), using the history of postal and telephone data represented by each city's telephone penetration per 10,000 residents in 1984. Traditional telecommunication tools are the roots of digital infrastructure, and related to the current digital infrastructure construction closely. In contrast, historical telecommunication can hardly impact urban green innovation directly, satisfying the requirements of relevance and exogenous. The study makes reference to Nunn and Qian's (2014) analysis, which introduced the number of national Internet users last year and created cross-product terms as panel instrumental variable to analysis.

As can be seen from Table 4, instrumental variable can promote digital infrastructure significantly, implying instrumental variable are highly relevant to digital infrastructure. It passes the *F*-test and under-identification test, confirming the rationality of the instrumental variable selection. Thus, digital infrastructure still contributes to urban green innovation.

Exogenous policy shock of "Broadband China". Digital infrastructure is often influenced by the economic level and industrial structure, and these factors can affect green innovation development (Zhang et al., 2019). Therefore, to verify the robustness of the result, the "Broadband China" pilot policy is used as a quasi-natural experiment to assess how exogenous policy shock affects urban green innovation through the double difference (DID) model.

$$GI_{it} = \varphi_0 + \varphi_1 treat_{it} + \varphi_2 Control_{it} + \mu_i + \delta_t + \varepsilon_{it}$$

where treat implies whether the city is in that year's Broadband China program pilot list, 1 if yes, 0 otherwise, and the rest of the letters mean the same as above.

Before conducting the regression, this paper referred to Beck et al. (2010) and conducted a parallel trend test. As shown in Fig. 3, it is indiscriminate between the coefficients of the experimental and control groups before the policy while the difference becomes increasingly prominent after the policy, so the parallel trend test passed.

The DID regression results are shown in Table 5. "Broadband China" pilot policy's execution encourages urban green innovation, the same as the previous results. There is no possible inherent bias.

To further exclude the effects of unobservable factors, this study uses a placebo test to mitigate the missed variables effects. The 500 regressions' kernel density of the coefficients is shown in Fig. 4. The estimated coefficients are about normally distributed and centered around 0, which fulfills the expectations of the placebo test, confirming the reliability of the findings.

Other robustness tests. This paper confirms the robustness of the benchmark regressions by replacing the explained variable,

Table 1 Descriptive statistics.

Variables	Mean	Std. dev.	Min	Max
GI	1.437	3.156	0	49.98
digital	3.450	0.870	2.296	10.32
gdp	10.72	0.573	8.613	13.06
people	5.875	0.697	3.148	8.074
open	0.0164	0.0170	0	0.198
fiscal	1.629	54.07	0	2282
education	0.0381	0.0186	0.00800	0.195
environment	0.00281	0.0227	0	1.001

Table 2 Baseline regression results.

Variables	(1)	(2)	(3)	(4)
	GI	GI	GI	GI
digital	0.856*** (0.102)	2.108*** (0.0572)	0.880*** (0.0967)	0.812*** (0.103)
gdp		1.620*** (0.113)	1.024*** (0.169)	0.476** (0.216)
people		0.663*** (0.0556)	1.561** (0.651)	0.441 (0.625)
open		10.34*** (2.286)	−10.13*** (3.542)	−7.246** (3.431)
fiscal		0.00246*** (0.000682)	0.00222*** (0.000604)	0.00195*** (0.000572)
education		26.71*** (2.782)	21.12*** (5.553)	16.30*** (5.797)
environment		1.043 (2.869)	1.08 (2.618)	1.302 (1.370)
City fixed	Yes	No	Yes	Yes
Year fixed	Yes	Yes	No	Yes
Observations	2850	2850	2850	2850
R-squared	0.780	0.620	0.754	0.782

Note: ***, **, and * denote regression results passing significance tests at 1%, 5%, and 10% confidence levels, respectively. Robust standard errors are reported in brackets in the table.

Table 3 Controlling for provincial trend effects.

Variables	(1) GI	(2) GI
digital	0.812*** (0.103)	0.401*** (0.106)
Controls	Yes	Yes
City fixed	Yes	Yes
Year fixed	Yes	Yes
Province fixed	Yes	Yes
Province and year interaction fixed	No	Yes
Observations	2850	2790
R-squared	0.782	0.822

Note: ***, **, and * denote regression results passing significance tests at the 1%, 5%, and 10% confidence levels, respectively. Robust standard errors are reported in brackets in the table.

Table 4 Test results for the instrumental variable.

Variables	digital	GI
IV	17.047*** (0.249)	
digital		2.844*** (0.078)
Controls	Yes	Yes
City fixed	Yes	Yes
Year fixed	Yes	Yes
Observations	2850	2850
R-squared	0.771	0.553
First stage *F*-stat	37.6735	
Weak identification test	26.447	

Note: ***, **, and * denote regression results passing significance tests at the 1%, 5%, and 10% confidence levels, respectively. Robust standard errors are reported in brackets in the tables.

Table 5 Exogenous shock test results.

Variables	(1) GI	(2) GI
treat	1.162*** (0.122)	1.046*** (0.120)
Controls	No	Yes
City fixed	Yes	Yes
Year fixed	Yes	Yes
Observations	2565	2565
R-squared	0.808	0.817

Note: ***, **, and * denote regression results passing significance tests at the 1%, 5%, and 10% confidence levels, respectively. Robust standard errors are reported in brackets in the table.

shrinking the tails, and changing the sample range. The results are shown in Table 6.

Replacing explained variable. Green patent applications are used to assess urban green innovation in baseline regression, the study substitutes the output of each 10,000 green patents for the explained variable. As shown in column (1), the result is consistent with those above.

Tailing treatment. To prevent outliers from skewing the data, the research uses a 1% level of tailing for each variable. As shown in Column (2), digital infrastructure contributes to urban green innovation because of the significantly positive estimated coefficient.

Changing sample range. To demonstrate that specific areas don't affect the results, the sample data from Beijing, Tianjin, Shanghai, and Chongqing, as well as Xinjiang and Tibet, are excluded and re-estimated for testing. The results are still reliable, as seen in column (3).

The influence mechanism and heterogeneity effect of digital infrastructure on urban green innovation

The influence mechanism of digital infrastructure on urban green innovation. Through the above analysis, urban green innovation can be enhanced by digital infrastructure. The comprehensive use of digital infrastructure across the whole economy and society is conducive to forming a green production and lifestyle, promoting scientific and technological progress, and providing several ideas for developing green innovation in cities. According to the above theoretical analysis, this paper refers to Jiang et al. (2022) and further reveals the channel and path mechanism of digital infrastructure for urban green innovation from talent agglomeration, R&D investment increase, and industrial structure upgrading. Mechanism analysis diagram is shown in Fig. 5. Table 7 displays the regression results.

Talent agglomeration. First, at the level of human resource elements, the path of the talent agglomeration effect is examined. The paper chooses the logarithm of the number of staff in the information transmission, software, and information technology services industry to express talent agglomeration. From column (1), digital infrastructure contributes to the talent agglomeration.

In the era of digitization and networking, information transfer has broken through the original restriction of "geospatial agglomeration", and digital infrastructure can promote knowledge sharing by improving the informationalized level, reducing information exchange cost, and attracting talent gathering by providing a broader development platform and a more prosperous resource environment. High-quality talents are the most crucial elements of green innovation since they serve as the foundation for scientific and technical innovation and serve as a vital conduit for the transfer of information. On the one hand, the concentration of talents provides cities with rich knowledge and innovation resources, forming a good ecosystem for innovation, and talents from various backgrounds interact and collide with each other, stimulating the spark of innovation; on the other hand, diverse talents have different perspectives and viewpoints and can provide diversified solutions and innovative ideas, promot the formation of innovative thinking and culture. In addition, the concentration of urban talents lays a good foundation of human capital for urban green innovation. Also, it injects a strong impetus for urban green innovation, thus supporting urban green advancement.

Increasing R&D investment. Secondly, at the level of financial resources, the path of increasing R&D investment is tested. The study makes use of each city's per-capita spending on research and technology to measure the R&D investment. The raw data were subjected to natural logarithms for comparison purposes. As column (2) shows, investment in R&D increases with the extent of digital infrastructure. As digital infrastructure becomes more crucial, it will encourage R&D investments in technology to better enable green innovation.

On the one hand, increasing R&D investment can effectively strengthen the capacity to assimilate external information, encourage the sharing of technology and knowledge, help them improve innovation output, and strengthen their competitive advantages in green innovation, thus enhancing urban innovation capacity; on the other hand, it can decrease the funding barrier

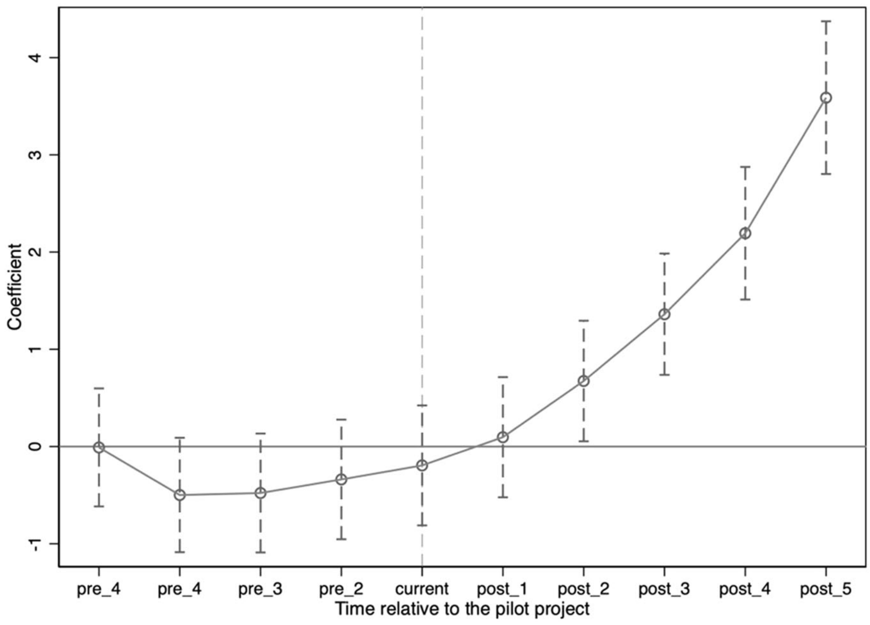

Fig. 3 Parallel trend test.

Table 6 Robustness tests.

Variables	(1) Substitution of explanatory variables	(2) Indented finish	(3) Change the sample range
digital	0.387*** (0.0549)	0.845*** (0.0757)	0.751*** (0.102)
Controls	Yes	Yes	Yes
City fixed	Yes	Yes	Yes
Year fixed	Yes	Yes	Yes
Observations	2849	2850	2810
R-squared	0.750	0.837	0.772

Note: ***, **, and * denote regression results passing significance tests at 1%, 5%, and 10% confidence levels, respectively. Robust standard errors are reported in brackets in the table.

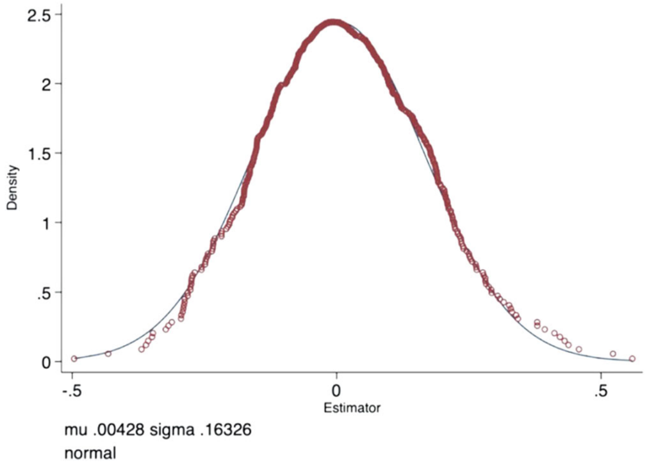

Fig. 4 Placebo test.

and expense, and promote the further flow of fiscal funds to green innovation (Khin and Ho, 2018). It can also ensure the effective distribution and use of funds, provide green innovation enterprises with more sustainable and stable financial support to accelerate technological innovation activities process, and better meet the enterprises' needs for green innovation, which promotes sustainable and green development.

Upgrading industrial structure. Lastly, at the level of material resources, the path of upgrading industrial structure is examined. The paper uses the proportion of secondary industry output to tertiary industry output to measure. Column (3) of Table 7 shows that digital infrastructure contributes to upgrading industrial structure. Digital infrastructure may effectively encourage digital businesses, technology, and services while giving the industrial structure-upgrading process fresh energy. It will promote cities away from their dependence on traditional industries, gradually eliminate backward industries with significant energy and pollutant emissions, and foster green and innovative industries to guide the economy's development in a sustainable, low-carbon manner. Additionally, optimizing the city's industrial structure can enhance resource allocation efficiency and support the innovation environment. By introducing and nurturing high-end talents and increasing investment in scientific research, the development and application of green technologies will be enhanced, and the city's green innovation capacity can be improved. Meanwhile, the unionization and cooperative growth of industries strengthen the cooperation and resource sharing between different industries, offering urban green innovation greater opportunity and space.

Heterogeneity analysis

City size. Digital infrastructure may have a varied impact on urban green innovation because of the differences in regional green innovation resources and the significance caused by differences in population size. This study performs independent regressions after classifying the sample into three categories based on population size: mega-cities, large cities, and small and medium-sized cities.

From Table 8, digital infrastructure can promote green innovation in three samples, and the promotion grows with the city's size. Larger scale cities have a more developed digital economy and industrial agglomeration, are more likely to introduce advanced production factors and have more complete digital infrastructure and more widespread digital technology applications, which is a bigger part in encouraging green innovation in cities.

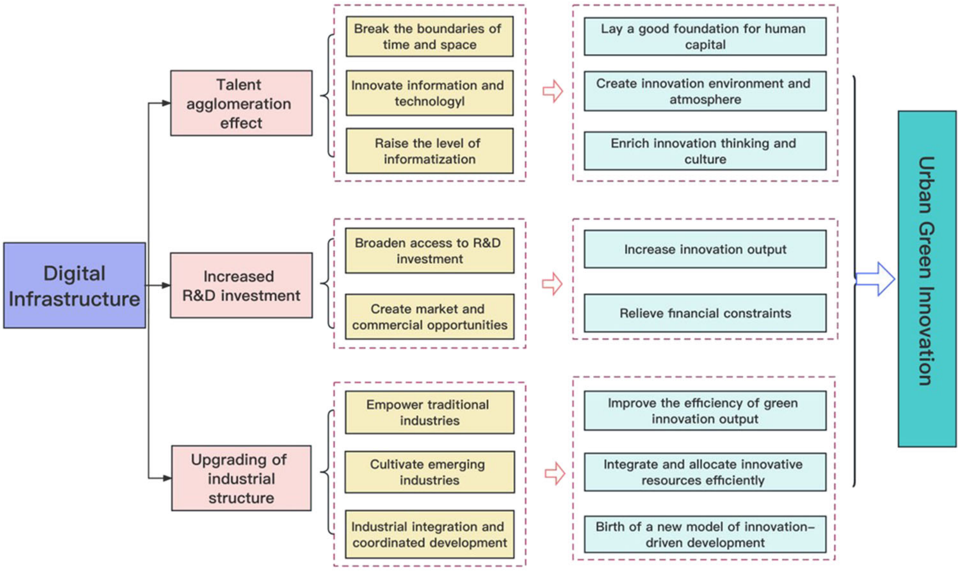

Fig. 5 Mechanism analysis diagram.

Table 7 Results of the mechanism of action test.

Variables	(1) Talent agglomeration	(2) Increased R&D investment	(3) Upgrading industrial structure
digital	0.0777** (0.0324)	0.278*** (0.0183)	3.405*** (0.235)
Controls	Yes	Yes	Yes
City fixed	Yes	Yes	Yes
Year fixed	Yes	Yes	Yes
Observations	2850	2850	2850
R-squared	0.005	0.710	0.279

Note: ***, **, and * denote regression results passing significance tests at the 1%, 5%, and 10% confidence levels, respectively. Robust standard errors are reported in brackets in the table.

Table 8 Heterogeneity analysis of city size.

Variables	Mega-cities	Large Cities	Small and medium-sized cities
	GI	GI	GI
digital	1.703*** (0.216)	0.469***(0.129)	0.446*** (0.141)
Controls	Yes	Yes	Yes
City fixed	Yes	Yes	Yes
Year fixed	Yes	Yes	Yes
Observations	1001	1686	120
R-squared	0.802	0.789	0.840

Note: ***, **, and * denote regression results passing significance tests at the 1%, 5%, and 10% confidence levels, respectively. Robust standard errors are reported in brackets in the table.

Human capital level. Human capital may influence on how digital infrastructure affects green innovation, as it is a major factor affecting green innovation. Therefore, this study examines the population's ratio of general undergraduate students to gauge the human capital level and divides the sample into two groups with varying human capital levels for the heterogeneity analysis. As shown in Table 9, digital infrastructure's contribution to green innovation is significantly higher in cities with higher human capital levels. Because they have more R&D staff, knowledge, and skills and better access to digital technology and data elements, thus making digital infrastructure a more potent driver of green innovation.

Table 9 Heterogeneity analysis of the level of human capital.

Variables	Low level of human capital	Higher levels of human capital
	GI	GI
digital	0.105*** (0.0310)	1.311*** (0.148)
Controls	Yes	Yes
City fixed	Yes	Yes
Year fixed	Yes	Yes
Observations	1490	1347
R-squared	0.807	0.838

Note: ***, **, and * denote regression results passing significance tests at the 1%, 5%, and 10% confidence levels, respectively. Robust standard errors are reported in brackets in the table.

Environmental regulations. Since environmental regulation is an external force influencing green innovation, different environmental regulations may have different effects on digital infrastructure's ability to promote green innovation. The heterogeneity analysis is carried out by dividing the sample into two groups: lower and higher degree of environmental regulations. As seen in Table 10, in cities with higher environmental regulations, the contribution to green innovation is higher. Higher environmental regulation is conducive to strengthening firms' motivation to innovate, optimizing their innovation model, effectively compensating for the unfavorable competitive situation caused by the rising cost of environmental governance and penalties, and thus promoting green innovation.

Financial subsidies. Financial subsidies are another external driver of urban green innovation. Divide the sample into two groups to analyze the different effects. Table 11 shows that the digital infrastructure in the more financial subsidies cities strongly affects green innovation. Financial incentives entice businesses to boost their spending on technological innovation, support their technological R&D activities, and maximize the allocation of resources for innovation to increase green innovation capacity.

Further discussion

Analysis of spatial spillover effects

Global spatial autocorrelation analysis. Moran's I index is used to test spatial autocorrelation. The global Moran's I indices for green innovation and digital infrastructure are shown in Table 12. It indicates that the green innovation capacity and digital infrastructure construction in Chinese cities are not spatially distributed in a disorderly manner but show significantly positive spatial correlation, they exhibit a spatial agglomeration effect.

Table 10 Heterogeneity analysis of environmental regulation.

Variables	Lower environmental regulation	Higher environmental regulation
	GI	GI
digital	0.215*** (0.0678)	0.907*** (0.199)
Controls	Yes	Yes
City fixed	Yes	Yes
Year fixed	Yes	Yes
Observations	1439	1383
R-squared	0.805	0.794

Note: ***, **, and * denote regression results passing significance tests at the 1%, 5%, and 10% confidence levels, respectively. Robust standard errors are reported in brackets in the table.

Table 11 Heterogeneity analysis of the intensity of financial subsidies.

Variables	Lower financial subsidies	Higher financial subsidies
	GI	GI
digital	0.0976*** (0.0242)	1.000*** (0.175)
Controls	Yes	Yes
City fixed	Yes	Yes
Year fixed	Yes	Yes
Observations	1415	1414
R-squared	0.783	0.805

Note: ***, **, and * denote regression results passing significance tests at the 1%, 5%, and 10% confidence levels, respectively. Robust standard errors are reported in brackets in the table.

Local spatial autocorrelation analysis. This paper describes Moran scatter plots of digital infrastructure and green innovation in each city in 2011 and 2020 to examine the spatial connection between the two, as shown in Fig. 6. The majority of the observations are in the first and third quadrants, indicating that the positive spatial agglomeration features of digital infrastructure and green innovation in 2011 and 2020.

Spatial regression results. Following an assessment of the geographical relevance of green innovation and digital infrastructure, the study chooses the Dubin model in light of the LM and Robust LM tests, employs the fixed effect model based on the Hausman test. From Table 13, digital infrastructure regression coefficients under the three weighting matrices are significantly positive in both local and neighboring places. As the spatial lag term in the Dubin model, the effects need to split to examine the spatial spillover effects.

Table 13 shows that the direct effect of digital infrastructure is significantly positive under geographic neighborhood and

Table 13 SDM model regression results.

Variables	Adjacency	Geographical	Economic
digital	0.812*** (0.0718)	0.812*** (0.0713)	0.814*** (0.0717)
Wxdigital	0.311** (0.131)	1.752* (1.026)	0.339* (0.198)
Direct effect	0.809*** (0.0725)	0.808*** (0.0736)	0.814*** (0.0720)
Indirect effect	0.251** (0.121)	0.379 (0.476)	0.329* (0.194)
Total effect	1.060*** (0.116)	1.187*** (0.450)	1.144*** (0.192)
rho	−0.0526* (0.0280)	−1.152*** (0.242)	−0.00683 (0.0343)
sigma2_e	1.020*** (0.0270)	1.007*** (0.0268)	1.023*** (0.0271)
Controls	Yes	Yes	Yes
City fixed	Yes	Yes	Yes
Year fixed	Yes	Yes	Yes
Observations	2850	2850	2850
R-squared	0.133	0.448	0.432

Note: ***, **, and * denote regression results passing significance tests at the 1, 5, and 10% confidence levels, respectively. Robust standard errors are reported in brackets in the table.

Table 12 Moran's *I* index.

Year	GI			Digital		
	Adjacent	Geography	Economy	Adjacent	Geography	Economy
2011	0.324***	0.070***	0.189***	0.447***	0.100***	0.205***
2012	0.351***	0.078***	0.214***	0.483***	0.111***	0.206***
2013	0.318***	0.071***	0.220***	0.462***	0.107***	0.202***
2014	0.348***	0.080***	0.250***	0.455***	0.112***	0.212***
2015	0.384***	0.091***	0.264***	0.435***	0.105***	0.209***
2016	0.404***	0.097***	0.251***	0.461***	0.108***	0.219***
2017	0.445***	0.106***	0.248***	0.493***	0.119***	0.251***
2018	0.410***	0.101***	0.233***	0.495***	0.126***	0.237***
2019	0.367***	0.092***	0.265***	0.404***	0.102***	0.208***
2020	0.344***	0.092***	0.325***	0.375***	0.093***	0.197***

Note: ***, **, and * denote regression results passing significance tests at 1%, 5%, and 10% confidence levels respectively.

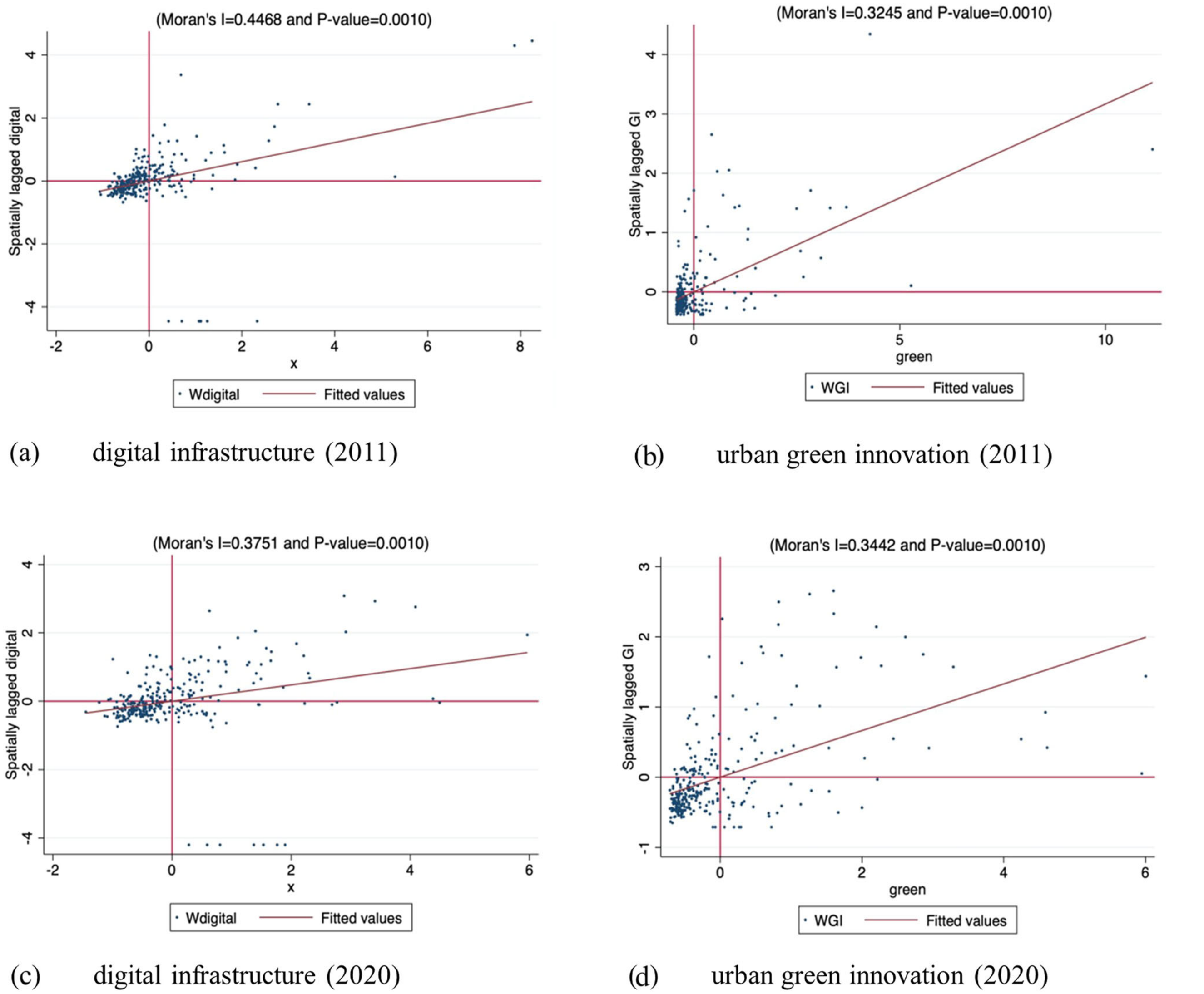

Fig. 6 Local Moran's *I* scatter plot of digital infrastructure and urban green innovation in 2011 and 2020. **a** digital infrastructure (2011); **b** urban green innovation (2011); **c** digital infrastructure (2020); **d** urban green innovation (2020).

Table 14 Results of the threshold effect test.

Threshold variables	Number of thresholds	*F*-value	*P*-value	Threshold	95% confidence interval
digital	Single	231.99	0.0000	5.4257	[5.3659,5.4558]
	Double	90.55	0.1910		
	Three	36.92	0.8600		

economic distance matrix. A higher potential for urban green innovation is linked to higher levels of digital infrastructure. The indirect effect of digital infrastructure is significantly positive, which suggests that digital infrastructure can influence green innovation in nearby regions. In addition, the total effect is significantly positive, showing that the total green innovation degree will rise as digital infrastructure develops. In the digital economy era, developing digital infrastructure rapidly has promoted the efficient and convenient flow of innovation factors. Through the new information and communication technology, innovation factors can achieve real-time communication and cooperation, and talent, capital, and technology can quickly respond to market demand, expanding the spatial scope of innovation factor allocation and creating a good innovation environment for inter-regional cooperation and sharing.

Analysis of threshold effects. This study used Hansen's (1999) methodology to perform a panel threshold existence test. The *F* and *P* values were acquired by running the bootstrap procedure 1000 times. From Table 14, the single threshold significance test is passed, but neither the double nor triple threshold significance test, shows a single threshold effect of digital infrastructure for urban green innovation, with a threshold value of 5.4257. The single threshold effect diagram is shown in Fig. 7.

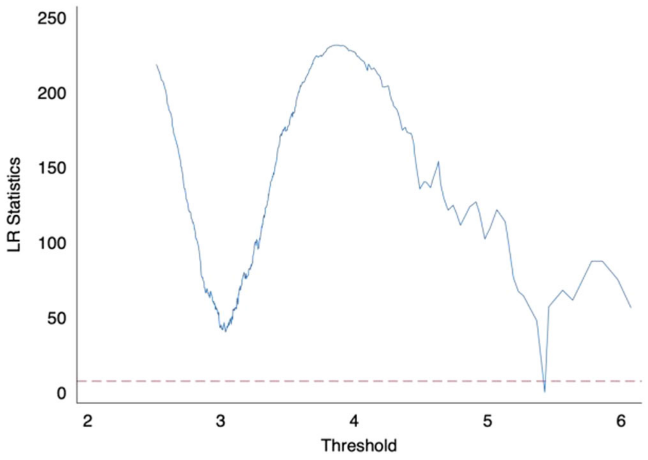

Fig. 7 Single threshold effect diagram.

Table 15 Threshold model regression results.

Variables	GI
digital (th≦5.4257)	1.084*** (0.0843)
digital (th> 5.4257)	1.833*** (0.0575)
Controls	Yes
City fixed	Yes
Year fixed	Yes
Observations	2850
R-squared	0.588

Note: ***, **, and * denote regression results passing significance tests at the 1%, 5%, and 10% confidence levels, respectively. Robust standard errors are reported in brackets in the table.

As shown in Table 15, digital infrastructure exerts a nonlinear influence on urban green innovation. It has a diverse effect at various stages of digital infrastructure. When digital infrastructure construction is low (digital< = 5.4257), urban green innovation is less impacted, and for every 1% increase in digital infrastructure, it rises by 1.084%; when digital infrastructure crosses the threshold and reaches a higher level (digital > 5.4257), it empowers urban green innovation more significantly. Improving the digital infrastructure construction level will promote urban green innovation ability by 1.833%. Digital infrastructure has a single threshold nonlinear impact on urban green innovation. When digital infrastructure construction crosses the threshold value, its contribution to urban green innovation keeps growing, showing a marginal increase feature.

Conclusions and recommendations

Conclusions. The rapid development of digital technology and its infiltration and integration into numerous societal sectors have contributed to the success of digital infrastructure. The government has repeatedly emphasized strengthening digital infrastructure development at relevant meetings. Meanwhile, the development model of the economy has gradually shifted to an innovation-driven one. Digital infrastructure is considered an essential support for promoting cities' ability for green innovation and the rise of economy and society in a sustainable and high-quality manner. Exploring the green effects of digital infrastructure will help clarify the internal logic between digital infrastructure and urban green innovation in theory, and enhance digital and green development in practice.

Based on the panel data of 285 prefecture-level cities in China from 2011 to 2020, this study measures the comprehensive development index of urban digital infrastructure using principal component analysis. Furthermore, using the fixed effect model, Dubin model, and threshold model to empirically investigate the mechanism and dynamic characteristics of digital infrastructure on urban green innovation in China. Here are the main conclusions: Firstly, digital infrastructure significantly improved urban green innovation. Following a set of tests for endogeneity and robustness, the study's findings still hold. Secondly, regarding the mechanism, digital infrastructure can positively affect urban green innovation by talent agglomeration, increasing R&D investment, and upgrading industrial structure. Thirdly, according to heterogeneity analysis, in terms of internal resource endowment, cities with higher scales and human capital benefit more from promoting green innovation; in terms of external policy environment, the green innovation effects are more potent in cities with higher environmental regulations and financial subsidies. Fourthly, the Dubin model test implies digital infrastructure has a positive spillover effect on the neighborhood in addition to supporting local green innovation. Fifthly, urban green innovation experiences a threshold effect from digital infrastructure, displaying the nonlinear features of increasing marginal effect.

Recommendations. First, make the logical design and advanced digital infrastructure development stronger. We'll expedite the process of bringing intelligence, networking, and digitization to outdated infrastructure; expand the reach of digital infrastructure; improve its security, reliability, efficiency, and coordination; and bolster the development and utilization of critical digital infrastructure technologies. Additionally, we will delve deeper into the immense possibilities of digital infrastructure in promoting green innovation.

Second, investigate the multifaceted route of urban green innovation powered by digital infrastructure. In order to activate the talent agglomeration at the human resources level, cities should establish a laid-back and welcoming atmosphere, set up venues and procedures for interdisciplinary collaboration, boost financial support and investment, offer more resources and opportunities, and concentrate on the development and introduction of exceptional green innovation talents with all-encompassing skills and creative thinking. In terms of financial resources, R&D funding ought to be increased in order to encourage more R&D endeavors, enhance the development of digital infrastructure and green innovation, and so foster the prosperity and sustainable expansion of the green economy. At the level of material resources, the government should provide financial and policy incentives, as well as a conducive climate and circumstances for the growth of green and innovative enterprises. Simultaneously, enhance collaboration and synchronization among governmental bodies, corporations, and academic establishments to foster the adoption of green innovation.

Third, encourage cooperation between green innovation and digital infrastructure. The government should execute a varied development plan that is suited to local conditions since cities differ in terms of size, growth stage, and regulatory environment. In smaller and lower human capital cities, government support should be increased to intensify digital infrastructure and expand new technologies. This will enable digital infrastructure to better support urban green innovation as compared to cities with superior internal endowment conditions. Furthermore, in order to foster the growth of green innovation, cities with significant environmental regulations and financial subsidies should make the most of the role that government regulation and policy support play in influencing urban green innovation. They should also set environmental standards and regulatory measures that guide cities' practices in digital and green innovation and bolster financial subsidies, tax breaks, and innovation rewards to enhance digital infrastructure and foster an environment that fosters creativity.

Fourth, enhance the positive influence that digital infrastructure has on urban green innovation. Reduce regional barriers to information, knowledge, and business; promote cooperative digital infrastructure design; and enhance information sharing on green science researches and accomplishments. Improve the capacity of the digital infrastructure to propagate urban green innovation and distribute digital dividends by disseminating innovation knowledge through digital technologies.

Fifth, constantly improve the digital infrastructure to better promote urban green innovation. In the early stage, the development level of digital infrastructure was low, and its promotion effect on green innovation was relatively weak. With the continuous improvement of digital infrastructure, its green innovation effect was continuously enhanced. Therefore, in order to promote the development of green innovation in regions with low levels of digital infrastructure, the government needs more patience, and policymakers should further increase their investment in digital infrastructure to better play its role in promoting green innovation.

Limitations. This paper studies the effect and mechanism of digital infrastructure on urban green innovation and draws valuable conclusions, but there are still aspects that need to be improved and expanded: Firstly, this paper refers to relevant literature and combines data availability. Eight indicators were selected to measure the level of digital infrastructure by principal component analysis. There may be deviations in the selection of indicators. In the future, more objective indicators for measuring digital infrastructure can be sought to obtain more accurate conclusions. Secondly, this paper studies the mechanism of digital infrastructure affecting urban green innovation from three aspects: talent agglomeration, R&D investment increase, and industrial structure upgrading. However, digital infrastructure may affect green innovation through multiple channels, and more potential paths can be explored in the future. In addition, this study is based on the urban level of China, which can be extended to many countries in the future to strengthen the universality of research conclusions.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Received: 6 November 2023; Accepted: 6 February 2024;
Published online: 26 February 2024

References

Alderete MV (2017) Mobile broadband: a key enabling technology for entrepreneurship? J Small Bus Manag 55(2):254–269

Bai Y, Song S, Jiao J, Yang R (2019) The impacts of government R&D subsidies on green innovation: evidence from Chinese energy-intensive firms. J Clean Prod 233:819–829

Beck T, Levine R, Levkov A (2010) Big bad banks? The winners and losers from bank deregulation in the United States. J Financ 65(5):1637–1667

Cao B, Wang S (2017) Opening up, international trade, and green technology progress. J Clean Prod 142:1002–1012

Chu Z, Cheng M, Yu NN (2021) A smart city is a less polluted city. Technol Forecast Soc Change 172:121037

Dong S, Ren G, Xue Y, Liu K (2023) Urban green innovation's spatial association networks in China and their mechanisms. Sustain Cities Soc 93:104536

Feng Y, Chen Z, Nie C (2023) The effect of broadband infrastructure construction on urban green innovation: evidence from a quasi-natural experiment in China. Econ Anal Policy 77:581–598

Forman C, Van Zeebroeck N (2019) Digital technology adoption and knowledge flows within firms: can the Internet overcome geographic and technological distance? Res Policy 48(8):103697

Guo B, Wang Y, Zhang H, Liang C, Feng Y, Hu F (2023) Impact of the digital economy on high-quality urban economic development: evidence from Chinese cities. Econ Model 120:106194

Han X, Fu L, Lv C, Peng J (2023) Measurement and spatio-temporal heterogeneity analysis of the coupling coordinated development among the digital economy, technological innovation and ecological environment. Ecol Indic 151:110325

Hansen BE (1999) Threshold effects in non-dynamic panels: Estimation, testing, and inference[J]. J Econ 93(2):345–368

Hu H, Xiong S, Wang Z, Wang Z, Zhou X (2023a) Green financial regulation and shale gas resources management. Resour Policy 85:103926

Hu J, Zhang H, Irfan M (2023b) How does digital infrastructure construction affect low-carbon development? A multidimensional interpretation of evidence from China. J Clean Prod 396:136467

Hu S, Wang M, Wu M, Wang A (2023c) Voluntary environmental regulations, greenwashing and green innovation: empirical study of China's ISO14001 certification. Environ Impact Assess Rev 102:107224

Huang Q, Yu Y, Zhang S (2019) Internet development and productivity growth in manufacturing industry: internal mechanism and China experiences. China's Ind Econ 8:5–23

Jiang T (2022) Mediating effects and moderating effects in causal inference. China's Ind Econ 5:100–120

Khin S, Ho TCF (2018) Digital technology, digital capability and organizational performance: a mediating role of digital innovation. Int J Innov Sci 11(2):177–195

Kong J, Zhang CH, Han CH (2018) Growth strategy of infrastructure system interacting with natural ecology. China Popul Resour Environ 28(1):44–53

Li C, Liang F, Liang Y, Wang Z (2023a) Low-carbon strategy, entrepreneurial activity, and industrial structure change: evidence from a quasi-natural experiment. J Clean Prod 427:139183

Li C, Wang Y, Zhou Z, Wang Z, Mardani A (2023b) Digital finance and enterprise financing constraints: structural characteristics and mechanism identification. J Bus Res 165:114074

Li K (2023) Can resource endowment and industrial structure drive green innovation efficiency in the context of COP 26? Resour Policy 82:103502

Li L, Li M, Ma S, Zheng Y, Pan C (2022) Does the construction of innovative cities promote urban green innovation? J Environ Manag 318:115605

Liu B, Gan L, Huang K, Hu S (2023a) The impact of low-carbon city pilot policy on corporate green innovation: Evidence from China. Finance Res Lett 58:104055

Liu K, Meng C, Tan J, Zhang G (2023b) Do smart cities promote a green economy? Evidence from a quasi-experiment of 253 cities in China. Environ Impact Assess Rev 99:107009

Liu K, Xue Y, Chen Z, Miao Y (2023c) The spatiotemporal evolution and influencing factors of urban green innovation in China. Sci Total Environ 857:159426

Liu X, Liu F, Ren X (2023d) Firms' digitalization in manufacturing and the structure and direction of green innovation. J Environ Manag 335:117525

Ma D, Zhu Q (2022) Innovation in emerging economies: research on the digital economy driving high-quality green development. J Bus Res 145:801–813

Munawar S, Yousaf HQ, Ahmed M, Rehman S (2022) Effects of green human resource management on green innovation through green human capital, environmental knowledge, and managerial environmental concern. J Hosp Tour Manag 52:141–150

Nunn N, Qian N (2014) US food aid and civil conflict. Am Econ Rev 104(6):1630–1666

Paunov C, Rollo V (2016) Has the internet fostered inclusive innovation in the developing world? World Dev 78:587–609

Ren X, Xia X, Taghizadeh-Hesary F (2023a) Uncertainty of uncertainty and corporate green innovation—evidence from China. Econ Anal Policy 78:634–647

Ren X, Zeng G, Sun X (2023b) The peer effect of digital transformation and corporate environmental performance: Empirical evidence from listed companies in China. Econ Model 128:106515

Ren X, Zeng G, Zhao Y (2023c) Digital finance and corporate ESG performance: Empirical evidence from listed companies in China. *Pacific-Basin Finance*. Pac-Basin Financ J 79:102019

Song M, Pan H, Vardanyan M, Shen Z (2023) Evaluating the energy efficiency-enhancing potential of the digital economy: Evidence from China. J Environ Manag 344:118408
Song M, Wang S, Zhang H (2020) Could environmental regulation and R&D tax incentives affect green product innovation? J Clean Prod 258:120849
Tang K, Yang G (2023) Does digital infrastructure cut carbon emissions in Chinese cities? Sustain Prod Consum 35:431–443
Thacker S, Adshead D, Fay M, Hallegatte S, Harvey M, Meller H, Hall JW (2019) Infrastructure for sustainable development. Nat Sustain 2(4):324–331
Wang H, Qi S, Zhou C, Zhou J, Huang X (2022a) Green credit policy, government behavior and green innovation quality of enterprises. J Clean Prod 331:129834
Wang KL, Sun TT, Xu RY, Miao Z, Cheng YH (2022b) How does internet development promote urban green innovation efficiency? Evidence from China. Technol Forecast Soc Change 184:122017
Wang X, Yang W, Ren X, Lu Z (2023c) Can financial inclusion affect energy poverty in China? Evidence from a spatial econometric analysis. Int Rev Econ Financ 85:255–269
Wang Z, Deng Y, Zhou S, Wu Z (2023d) Achieving sustainable development goal 9: a study of enterprise resource optimization based on artificial intelligence algorithms. Resour Policy 80:103212
Wang Z, Liang F, Li C, Xiong W, Chen Y, Xie F (2023e) Does China's low-carbon city pilot policy promote green development? Evidence from the digital industry. J Innov Knowl 8(2):100339
Wang Z, Zhang S, Zhao Y, Chen C, Dong X (2023f) Risk prediction and credibility detection of network public opinion using blockchain technology. Technol Forecast Soc Change 187:122177
Wei L, Lin B, Zheng Z, Wu W, Zhou Y (2023) Does fiscal expenditure promote green technological innovation in China? Evidence from Chinese cities. Environ Impact Assess Rev 98:106945
Xue L, Zhang Q, Zhang X, Li C (2022) Can digital transformation promote green technology innovation? Sustainability 14(12):7497
Yang H, Li L, Liu Y (2022) The effect of manufacturing intelligence on green innovation performance in China. Technol Forecast Soc Change 178:121569
Zhang D, Rong Z, Ji Q (2019) Green innovation and firm performance: Evidence from listed companies in China. Resour Conserv Recycl 144:48–55
Zhang M, Hong Y, Zhu B (2022) Does national innovative city pilot policy promote green technology progress? Evidence from China. J Clean Prod 363:132461

Acknowledgements
This work was supported by Zhejiang Province Philosophy and Social Science Planning Research Methods Innovation Special Topic. "Research on Judges' Adjudication Behavior and Trial Quality Based on Big Data of Adjudication Documents and Experimental Methods" (Grant No. 23SYS07ZD). This work was also supported by research incubation project funding, Urban Digital Governance Science and Education Innovation Complex, Hangzhou City University. "Urban digital security evaluation and monitoring index system and database construction" (Grant No. 22FHXMO6). This work was also supported by research incubation project funding, from Hangzhou City University. "An empirical study on the public law protection system of citizens' personal information based on judicial big data" (Grant No. Z2022037).

Author contributions
HW: writing—review & editing, conceptualization, methodology, project administration; CL: writing—original draft, conceptualization, methodology, resources; MW: writing—review & editing, data curation, visualization, formal analysis; SJ: writing—original draft, formal analysis, supervision, validation. Ultimately, all of the authors declared no conflicts of interest, contributed to the work, and approved the version that was submitted.

Competing interests
In order to eliminate any potential conflict of interest, the authors declare that their research was conducted in the absence of any commercial or financial relationships.

Ethical approval
Ethical approval was not required as the study did not involve human participants.

Informed consent
The study did not involve experimental subjects and therefore did not require an ethical review and informed consent statement.

Additional information
Correspondence and requests for materials should be addressed to Huaxing Wang.