

Impact of digital infrastructure on urban green eco-efficiency: an empirical analysis in China

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Abstract

Purpose – This paper takes 267 prefecture-level cities that have implemented the “Broadband China” strategy as empirical research objects, aiming to study the impact of digital infrastructure on the green eco-efficiency of Chinese cities and put forward corresponding policy recommendations based on the empirical results.

Design/methodology/approach – By integrating the super-efficiency Undesirable-SBM model with the asymptotic difference-in-differences approach, the research delves into the policy impacts and the mechanisms by which digital infrastructure affects urban green eco-efficiency.

Findings – The results reveal a notable influence of advancements in digital infrastructure on the eco-efficiency of urban areas, and these advancements have the capacity to bolster eco-efficiency through the influence of green technological innovation, the upgrading of industrial structure, and its rationalization. Notably, significant variations are found in the effectiveness of digital infrastructure in boosting eco-efficiency, with the effect being relatively stronger for large-scale cities and eastern regions.

Originality/value – From a research standpoint, this paper seeks breakthroughs in harmonizing ecological environments with economic quality in the digital era’s new paradigms. Methodologically, it avoids the incomparability of traditional measurements, ensuring accurate urban ecological efficiency assessments. Content-wise, it elucidates how the digital economy enhances eco-efficiency through green technological innovation, industrial structure advancement and rationalization. This comprehensive analysis provides valuable insights for China and similar developing nations on balancing green ecological efficiency with urban digitization, offering practical guidance for sustainable development.

Keywords Digital infrastructure, Urban green eco-efficiency, “Broadband China” strategy

Paper type Research paper



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1. Introduction

The pursuit of rapid industrialization in developing nations often creates a tension between economic growth and environmental protection, manifesting in challenges like global warming and air pollution (Onwe *et al.*, 2024a, 2024b). This duality underscores the urgency of adopting the eco-efficiency principle – a metric that quantifies sustainability by optimizing economic output per unit of environmental input. Crucially, such alignment resonates with SDG-9’s call for sustainable infrastructure that integrates resource-efficient technologies. Here, digital infrastructure (5G/artificial intelligence [AI]/cloud computing) emerges as a nexus: it operationalizes eco-efficiency by enabling “more with less” (Lei *et al.*, 2024), while simultaneously addressing SDG-9’s industrial innovation targets and developing country stakeholders’ dual needs for stable growth and excellent environments (Onwe *et al.*, 2024a, 2024b). China’s experimentation with digital solutions for pollution control exemplifies this synergy, offering a replicable model where digitalization serves as both an economic catalyst and an environmental governance tool, thus reconciling the traditionally competing paradigms of development and sustainability.

Originating from the German scholar Schaltegger, the concept of eco-efficiency encapsulates the input–output efficiency, taking into account the utilization of resources like capital, labor and energy, alongside diverse outputs, particularly undesirable ones such as carbon emissions (Schaltegger and Sturm, 1990). As an extension of the concept, green eco-efficiency not only emphasizes the harmonious interplay among economic society and ecological protection but also offers the scientific basis for the improvement of the construction of ecological civilization (Maxime *et al.*, 2006), and functions as a commonly used indicator for measuring sustainable development. The existing scholarship on green eco-efficiency can be summarized in terms of measuring methods and influencing factors (Xu *et al.*, 2022). Regarding measurement methodologies, existing studies have mainly adopted the ratio method (Jiang and Tan, 2020), material flow analysis (Kuusmanen and Kortelainen, 2005), data envelopment analysis (Moutinho *et al.*, 2020; Charnes *et al.*, 1978) and stochastic frontier analysis (Song and Chen, 2019) to assess eco-efficiency. Among them, the super-efficiency DEA method that contains the SBM model with the undesirable output (Yasmeen *et al.*, 2020) has gradually become the mainstream method in this field because it improves the basic DEA framework and can solve the limitations of traditional methods to better capture the complexity of the real world. The influencing factors mostly concentrate on technological progress, environmental regulation and population agglomeration (Ahmad and Wu, 2022; Yang and Liang, 2023; Liu and Wu, 2023). Some scholars also analyze the specific driving factors from aspects such as local government governance (Li *et al.*, 2017) and industrial structure (Cui and Wang, 2023). Therefore, unlike previous studies that primarily focused on these traditional factors, this research offers new insights by examining the factors of green technology innovation, industrial structure upgrading and industrial structure rationalization. These insights are of particular significance in promoting environmental conservation and achieving high-quality economic growth.

Initial research on the digital economy primarily defined it, analyzed trends and proposed promotional strategies from a theoretical perspective. With the advancing tech revolution, digital infrastructure, fueled by innovation, has emerged as a crucial academic focus driving digital economy development. Relevant literature can be categorized into two main areas. First, the literature extensively explores the multifaceted economic impacts of digital infrastructure. One focus is on technological innovation, contending that digital infrastructure enhances urban technological innovation by fostering capital and financial development (Nie *et al.*, 2023), knowledge and technology spillovers and workforce quality

improvement. Another focus emphasizes industrial structure optimization, asserting that effective resource allocation prevents imbalances (Gong *et al.*, 2023), thereby facilitating rationalization and upgrading of industrial structures, with advanced structures exhibiting stronger transmission mechanisms (Liang and Tan, 2024). The last focus is on the economic growth effect, where digital infrastructure boosts urban high-quality development by enhancing total factor productivity through industrial optimization and spatial diffusion (Zou *et al.*, 2024; Liu, 2023). Second, the literature addresses the ecological optimization effects of digital infrastructure, albeit with limited in-depth discussions, closely relating to our work and focusing on carbon emission reduction and green development (Peng *et al.*, 2024), including promoting renewable energy technology innovation and optimizing industrial structures to enhance green total factor productivity (Lyu *et al.*, 2023).

In recent years, the impact of digital infrastructure on green ecological efficiency in the big data era has garnered scholarly attention. Research focuses on whether digital infrastructure significantly enhances green ecological efficiency, divided into two perspectives. The first, facilitation theory, contends that digital infrastructure has the potential to significantly improve green ecological efficiency by promoting more effective resource allocation, reducing information asymmetry and enabling advanced monitoring and control systems, thereby aiding China in pollution reduction and environmental sustainability (Deng and Zhong, 2024). This positive effect is most evident in the economically developed central and eastern regions with narrower digital divides (Xiufan *et al.*, 2024).

The second, constraint theory, presents the opposite view. Some scholars argue that the production and use of digital infrastructure consume substantial energy, particularly in underdeveloped countries reliant on non-renewable energy with limited electricity and technology (Hossain *et al.*, 2022), exacerbating fossil fuel dependency and increasing carbon emissions. Studies provide empirical evidence supporting this theory, highlighting environmental challenges associated with rapid digital infrastructure expansion (Avom *et al.*, 2020; Wang *et al.*, 2022). Elements such as data centers, cloud computing and other tools also require substantial energy, potentially hindering green ecological efficiency and leading to environmental degradation (Nguyen *et al.*, 2023; Hossain *et al.*, 2022).

Although extensive research has been conducted on digital infrastructure's impact on the economy and society, unresolved issues remain regarding its influence on urban green eco-efficiency in the context of dual digitalization and greening economic development. Specifically, although studies show a positive link between digital infrastructure and urban development, the mechanisms affecting green eco-efficiency require further clarification. In addition, regional heterogeneity in this impact, especially across city tiers and under various policy interventions, has not been fully addressed. The role of socioeconomic factors has also not been systematically analyzed. Therefore, to overcome resource constraints and promote high-quality development and ecological sustainability, improving urban green eco-efficiency is crucial.

The unique contributions of this study to the existing knowledge system are primarily manifested in the following dimensions:

- integrates digital infrastructure and green eco-efficiency within a single analytical framework, offering a comprehensive view beyond traditional single-factor analysis;
- revealing regional variations and scale heterogeneity in their relationship through empirical analysis, emphasizing the need for differentiated policies to maximize green benefits; and
- exploring the underlying mechanisms through which digital infrastructure affects green eco-efficiency, focusing on green technological innovation, industrial structure upgrading and rationalization.

Overall, this study underscores digital infrastructure's potential to drive economic and ecological progress and provides practical insights for policymakers globally.

The subsequent sections of this paper are structured as follows: Section 2 discusses the background of the Broadband China policy and its associated theoretical frameworks. Section 3 outlines the model specification, variable choice, and data origins. Section 4 presents the baseline regression outcomes and their underlying mechanisms. Finally, Section 5 summarizes the key findings and offers policy implications.

2. Policy background and theoretical analysis

2.1 Policy background

As the information era dawns, broadband networks have become pivotal for socioeconomic progress, prompting numerous nations to prioritize their development strategically. Since the 21st century, leading developed countries have introduced digital industry strategies centered on broadband, such as the U.S. National Information Infrastructure (NII), the UK's Digital Britain, and Japan's E-Japan and U-Japan initiatives (Ma and Sheng, 2025). China, since establishing broadband connectivity in 1994, has seen significant growth in coverage and transmission capacity, though it still lags behind developed nations in network coverage, application utilization, and industrial support. In August 2013, China prioritized broadband infrastructure development as a national strategy with the Broadband China plan. Between 2014 and 2016, the Ministry of Industry and Information Technology (MIIT), in partnership with the National Development and Reform Commission, selected 120 cities/urban agglomerations for phased pilot implementations, focusing on network optimization, industry chain improvement and application capacity enhancement. The program's core is digital infrastructure planning, aiming for nationwide demonstration and leadership. After persistent efforts, China's digital infrastructure is rapidly upgrading, with a growing user base, increasing household penetration and basic digital broadband applications infiltrating various socio-economic sectors, bringing positive transformations to citizens' lives (Guo *et al.*, 2022). Beyond communication and digital lifestyle advancements, do these upgrades include adjustments for urban sustainable development? To explore this issue, this study uses the Broadband China policy as a quasi-natural experiment for digital infrastructure development, assessing its impact on urban green ecological efficiency. The goal is to transform China's experience into a resource for developing nations, aiding them in accelerating digital infrastructure development and achieving sustainable development goals.

2.2 Theoretical analysis

2.2.1 Direct impact of digital infrastructure construction on urban green eco-efficiency.

Unlike traditional frameworks, digital infrastructure leverages advancements in 5G, big data, cloud computing, Internet of Things (IoT) and AI to accelerate the digital and low-carbon transitions in urban energy systems (Ren *et al.*, 2023). Digital infrastructure enhances urban green eco-efficiency through fostering low-carbon lifestyles, promoting green corporate transformations and strengthening eco-governance.

First, at the individual level, according to resource dependence theory, individuals rely on resources provided by the environment for exchange, and these social resources and the environment in turn shape individuals' production and lifestyles (Liu *et al.*, 2024). Coupled with transaction cost theory, the proliferation of digital infrastructure, such as 5G and gigabit broadband, has significantly reduced transaction costs and enhanced organizational resource – dependence strategies, thereby contributing to the rapid rise of workstyles like telecommuting, online meetings and platform sharing, which in turn have led to a substantial reduction in energy and resource losses from transportation. In addition, the implementation of digital

payments, smart homes, intelligent transportation and telemedicine (Zou and Deng, 2022) has more effectively minimized energy waste, promoting a shift toward green and low-carbon lifestyles among residents. Second, enterprises use intelligent sensing devices for smart control of production processes (Li *et al.*, 2016), establish production management databases, encourage digital business integration and enhance energy efficiency. All these actions contribute to transforming corporate production methods into more environmentally friendly ones. Finally, from a governmental perspective, big data centers facilitate smart city governance in aspects such as services, transportation and emergency response, thereby saving labor, financial and material resources. Digital technology aids in accurately identifying, detecting, and addressing new environmental issues, improving ecological governance capabilities and building an interactive green bridge between government, enterprises and the public (Yang *et al.*, 2020), thereby achieving green governance and advancing digital government construction (Ayres and Williams, 2004; Ouyang *et al.*, 2020). On this basis, the following hypotheses are proposed:

H1. The development of digital infrastructure can substantially enhance urban green eco-efficiency.

2.2.2 Indirect impact of digital infrastructure construction on urban green eco-efficiency. Endogenous growth theory, as espoused by Romer (1986) and Lucas (1988), underscores that economic growth stems from endogenous technological progress (Cheng *et al.*, 2023). Technological innovation plays a pivotal role in transforming extensive production modes, enhancing efficiency, and reducing environmental costs. Digital infrastructure with strong information dissemination capabilities (Ren *et al.*, 2021) amplifies the dissemination and external benefits of innovative knowledge, integrates information resources (Lai *et al.*, 2024), strengthens urban ecological quality supervision, and boosts green technological innovation output. Cities have also reduced the costs of storing and transferring green innovation elements, expanding green technology applications across industries, transportation, construction and residential life, supported by blockchain and cloud computing. These technologies are widely used in renewable energy, cleaner production and pollutant monitoring. By promoting a circular economy, eco-friendly products enter the market, improving resource use efficiency, lowering pollution and enhancing green eco-efficiency (Liu *et al.*, 2016). Aligning with Porter's hypothesis, technological innovation promises to decrease environmental regulation costs and enhance overall environmental quality (Yu *et al.*, 2023). In addition, technological innovation increases the adoption of cleaner production technologies, reducing energy consumption and waste (Hao *et al.*, 2021). The application of environmental monitoring technologies also provides new monitoring means for local governments (Lv *et al.*, 2023), aiding in pollution control from the source and further enhancing urban green eco-efficiency.

The composition of the industrial structure is crucial for economic growth and eco-efficiency (Wang *et al.*, 2024). During the transition from high-speed to high-quality growth, the advancement and rationalization of the industrial structure drive economic expansion. The literature supports their significant impact on urban green eco-efficiency (Niu *et al.*, 2024; Zhou *et al.*, 2019). As the industrial structure evolves, digital infrastructure transcends temporal and spatial constraints, making data a new production factor. Schumpeter's innovation theory suggests that novel combinations replace outdated ones in competitive economies. Thus, digital infrastructure fosters new industries (Feng and Liu, 2023), accelerating the shift from traditional to digital-intensive sectors. Resource allocation and structural dividend theories also indicate that an advanced industrial structure directs resources to higher-productivity industries. This "structural dividend" propels economic growth, facilitating the transition of high-energy, high-emission industries to sustainable,

low-carbon production, ultimately enhancing urban green eco-efficiency (Xu *et al.*, 2022; Hao *et al.*, 2020).

Rationalization of the industrial structure aims to effectively allocate resources and adjust unreasonable components based on regional supply. As the largest industrial nation globally, China holds a crucial position in advancing urban green development by optimizing resource allocation via the adjustment of factors among diverse industries. The rationalization of industrial structure exemplifies the influence of improved efficient resource allocation, achieved through the ongoing dynamic adjustment and reallocation of input elements like labor, capital and technology across various sectors. As network broadband becomes more widely used, it facilitates the flow of technical and market demand information, potentially quickly and accurately matching supply and demand. This matching allows production factors to flow between various industries, resulting in more rational and coordinated resource allocation between them (Röller and Waverman, 2001). Ultimately, this approach results in greater output with reduced input, thereby augmenting urban eco-efficiency (Han *et al.*, 2021). Accordingly, the following hypotheses are formulated:

- H2. Urban green eco-efficiency can be bolstered by digital infrastructure through fostering green technological innovations, advancing industrial structures and rationalizing industrial compositions.

2.2.3 Heterogeneous impact of digital infrastructure construction on urban green eco-efficiency. Due to regional disparities in economic development, industrial mix and internet adoption (Zhang *et al.*, 2023), the impact of digital infrastructure projects, like Broadband China, on urban green eco-efficiency varies. Starting with economic disparities, the eastern region, more advanced economically and richer in talent, capital and technology than the central and western regions (Ahmed *et al.*, 2021), this superiority allows the eastern region to outperform the western region in promoting advancements in eco-friendly technology and refining industrial structures. The eastern region also boasts a sophisticated digital infrastructure, rational integration of traditional industries with digital technology, and effective green governance. Population size has an impact on network benefits performance. Cities with larger populations are more likely to benefit from network effects, according to the theory of network externalities (Liu *et al.*, 2016). Therefore, compared with large-scale cities, small- and medium-sized cities have yet to harvest the benefits of the diffusion effects stemming from the digital economy's development in large cities but instead have been deeply affected by the siphon effect, and their own talent, capital, knowledge and other factors continue to flow to large cities. Consequently, the impact on urban green eco-efficiency remains insignificant. The subsequent hypotheses are therefore formulated:

- H3. The effect of advancing digital infrastructure differs among urban areas of varying geographical locations and sizes, in relation to green ecological efficiency.

3. Model construction and variable selection

3.1 Model setting

3.1.1 Superefficiency Undesirable-SBM model. This research uses the super-efficiency Undesirable-SBM model (SBM) to assess urban ecological efficiency. Traditional data analysis methods have centered on the CCR and BCC models, focusing solely on desirable outputs. Tone introduced the SBM model within the DEA framework, offering a non-oriented approach that addresses the shortcomings of traditional radial and angular models by incorporating slack variables (Tone, 2001). The super-efficiency SBM model also assigns

scores greater than 1 to effective decision-making units (DMUs), allowing for a nuanced differentiation among high-performing DMUs beyond the conventional constraint of a score of 1 (Liu and Shi, 2025). Given the increasing emphasis on environmental quality in recent years, the inclusion of pollutant emissions as undesirable outputs in the model is essential for an accurate measure of urban eco-efficiency. The model is outlined below:

$$\begin{aligned} \min \rho = & \frac{1 + \frac{1}{m} \sum_{i=1}^m \frac{s_i^-}{x_{ik}}}{1 + \frac{1}{q_1 + q_2} \sum_{p=1}^{q_1} \frac{s_r^+}{y_{pk}} + \sum_{t=1}^{q_2} \frac{s_t^{b-}}{b_{tk}}} \left(\begin{aligned} & \sum_{j=1, j \neq j_k}^n x_j \lambda_j - s^- \leq x_k (i = 1, \dots, m) \leftarrow \\ & \sum_{j=1, j \neq j_k}^n y_j \lambda_j + s^+ \geq y_k (p = 1, \dots, q_1) \leftarrow \\ & \sum_{j=1, j \neq j_k}^n b_j \lambda_j - s^{b-} \leq b_k (t = 1, \dots, q_2) \leftarrow \\ & 1 - \frac{1}{q_1 + q_2} \sum_{p=1}^{q_1} \frac{s_r^+}{y_{pk}} + \sum_{t=1}^{q_2} \frac{s_t^{b-}}{b_{tk}} > 0 \\ & \lambda_j, s_i^-, s_r^+, s_t^{b-} \geq 0 (j = 1, \dots, n, j \neq j_k) \end{aligned} \right) \quad (1) \end{aligned}$$

Among them: ρ is the evaluation value of ecological efficiency; n represents the number of decision-making units; m , q_1 and q_2 , respectively, represent the number of input, desirable output and undesirable output factors; s_i^- is the input relaxation variable, s_r^+ is the desirable output relaxation variable, and s_t^{b-} is the undesirable output relaxation variable. λ_j is the intensity variable; x_{ik} , y_{pk} and b_{tk} are, respectively, the input variable, output variable and undesirable output variable of DMU_k. And a value of $\rho > 1$ signifies that the city's green eco-efficiency has achieved a robust and effective state. When $\rho < 1$, it indicates that urban green eco-efficiency is in an inefficient state. When $\rho = 1$ and s^+ and s^- are both 0, the urban green eco-efficiency also reaches a strong effective state. When $\rho = 1$ and at least one of s^+ and s^- is not 0, the green eco-efficiency reaches a weakly efficient state. This paper calculates the city's green eco-efficiency by using MaxDEA 7.0 software, utilizing the super-efficiency SBM model, along with the evaluation index system detailed in Table 1.

3.1.2 Asymptotic double-difference model. This paper considers the Broadband China strategy as a quasi-natural experiment born out of green eco-efficiency, then introduces a double-difference model to assess its policy effects. Considering that the pilot policy is promoted in batches, this paper constructs a progressive double-difference model as follows:

$$GEE_{it} = \alpha_0 + \alpha_1 Time_{it} \times Group_{it} + \sum \gamma_j X_{it} + \mu_i + \nu_t + \lambda_{it} \quad (2)$$

In this model, the explanatory variable is represented by GEE_{it} , which signifies the green eco-efficiency of urban i in year t . The variable $Time \times Group$ functions as an indicator for digital infrastructure, specifically reflecting the Broadband China policy. The coefficient α_1 quantifies the influence of this policy on the outcome variable. In addition, X encompasses

Table 1. System for assessing urban green eco-efficiency in China

Indicators type	First-level indicator	Second-level indicator
Investment indicators	Water consumption	Total water supply
	Energy consumption	Total gas supply
	Land consumption	Urban built-up area
	Human consumption	Number of employees at the end of the year
	Capital consumption	Total annual water use
Output indicators	Desirable output	Regional GDP
	Undesirable output	Industrial wastewater discharge volume
		Industrial sulfur dioxide emissions

Source(s): Authors' own creation

the set of control variables, μ_i shows individual fixed effects, λ_{it} accounts for random errors, and v_t represents time fixed effects. This setup enables the model to efficiently account for variations in characteristics and time trends between pilot and non-pilot cities.

3.2 Variable selection

3.2.1 Explained variables. The paper's explained variable is green ecological efficiency (GEE). Early research on GEE primarily employed conventional radial DEA models (such as CCR or BCC) and the Malmquist index, but these methods face limitations. Therefore, this paper adopts the super-efficiency SBM model proposed by Tone to evaluate GEE in relevant Chinese cities from 2011 to 2020. The model effectively mitigates deviations from radiality while accounting for input and output slack variables. By incorporating undesirable outputs and utilizing full reference technology, we enhance the model's intertemporal comparability and establish the comprehensive GEE evaluation index system (Table 1).

The input indicators include water, energy, land, labor and capital, which are widely recognized as essential resources and drivers of urban productivity growth. Water is a necessary resource for industrial processes and municipal use, energy supports various economic activities, land is a scarce resource that must be used effectively, labor is a key input in the production process, and capital is a financial means of investment and expansion. Output indicators include both desirable outputs, such as gross regional product (GDP), a widely used measure of economic output that reflects the overall size and growth of a city's economy, and undesirable outputs, such as industrial wastewater and sulfur dioxide emissions, which are significant contributors to environmental degradation.

3.2.2 Core explanatory variables. The core explanatory variable is whether the city implements the Broadband China strategy pilot (did), and its assignment takes the form of setting virtual variables. More precisely, when a city is approved to become a Broadband China city in the year and thereafter, the value of this variable is 1; otherwise, it is set to 0. This variable is essentially the product of a dummy variable that categorizes Broadband China pilot cities and another dummy variable indicating the relevant policy period.

3.2.3 Mediator variables. In this paper, mediator variables encompass green technology innovation, industrial structure upgrading, and its rationalization. The metric used to measure green technological innovation is the number of green patent applications submitted by the city in the specified year. For the measurement of industrial structure upgrading (ais), we use the following formula to determine the proportional relationship between industries and their respective weighted labor productivities:

$$ais_{it} = \sum_{m=1}^3 Y_{imt} \times LP_{imt}, m = 1, 2, 3 \quad (3)$$

$$LP_{imt} = Z_{imt} / L_{imt} \quad (4)$$

In [equation \(3\)](#), Y_{imt} represents the proportion of m industry in the GDP of region i at t time, whereas LP_{imt} signifies the labor productivity of industry m in region i at time t . In formula (4), Z_{imt} stands for the industrial added value of the m industry in region i during the t period, and L_{imt} is used to represent the employees of the m industry in region i during the t period.

The rationalization of industrial structure uses the Theil index to measure it ([Zhao et al., 2023](#)). Below is the outlined formula for the calculation:

$$TI_{it} = \sum_{m=1}^3 Y_{imt} \ln(Y_{imt}/P_{imt}), m = 1, 2, 3 \quad (5)$$

In [equation \(5\)](#), Y_{imt} is consistent with that in [equation \(3\)](#), while P_{imt} denotes the proportion of employees in industry m of region i during period t relative to the overall workforce.

3.2.4 Control variables. Considering that urban green eco-efficiency may be impacted by numerous urban characteristics in addition to policy factors, based on existing references, this paper adds relevant control variables in the regression. Population density (PD): This paper uses the proportion of each city's year-end population to its administrative area as a measure of population density, population density serves as a tangible indicator of the extent of urban population agglomeration, which, in turn, exerts a considerable influence on both the urban economy and the environment. Industrial structure (PTI): This study uses the proportion of the tertiary industry's added value to the city's GDP as a proxy indicator. Science and technology level (RD): The ratio of a city's science and technology expenditures to its overall fiscal budget serves as a proxy for its technological capability. Level of economic development (PCGDP): As the economic development of a city escalates, so too does its desirable output, thereby influencing the city's ecological efficiency. This study uses per capita gross national product as an indicator of the economic development status of each city. The environmental regulation (ER) variable is represented by the ratio of investment in environmental pollution control to GDP, given the intimate correlation between a city's green eco-efficiency and its environmental pollution levels. The degree of openness to foreign direct investment (FDI) is measured by the proportion of the actually utilized foreign capital, converted into CNY at the current year's exchange rate, to the GDP of each prefecture-level city.

3.3 Data sources and descriptive statistics

Adhering to the principles of scientific and logical index selection, and ensuring the reliability of data sources, this paper selects 267 cities at or above the prefecture level (excluding Hong Kong, Macao, Taiwan, and certain other cities due to recent changes in urban administrative divisions and data unavailability) as the research subjects. The research spans the years from 2011 to 2020, employing data sourced from various entities including the National Bureau of Statistics of China, municipal statistical bureaus, the annual publications of China Urban Statistics, and the China Statistical Yearbook. To mitigate potential biases inherent in these data sources and deal with missing data points, data preprocessing measures such as linear interpolation and reference to provincial economic and social development bulletins were used. Descriptive statistics for the primary variables are presented in [Table 2](#).

Table 2. Descriptive statistics for the primary variables

Variables	Observed quantity	Mean value	SD	Min.	Max.
<i>GEE</i>	2,670	0.495	0.290	3.96×10^{-5}	1.493
<i>DID</i>	2,670	0.229	0.420	0	1
<i>PTI</i>	2,670	0.417	0.0982	0.102	0.805
<i>lnPCGDP</i>	2,670	10.73	0.561	8.842	13.06
<i>RD</i>	2,670	0.0167	0.0170	0.000568	0.207
<i>lnPD</i>	2,670	5.774	0.904	1.629	9.086
<i>ER</i>	2,670	0.0121	0.00468	0.00157	0.0298
<i>FDI</i>	2,670	0.0166	0.0175	2.40×10^{-6}	0.210

Source(s): Authors' own creation

4. Empirical results and the correlation analysis

4.1 Benchmark regression analysis

[Table 3](#) displays the findings of the benchmark regression analysis, which investigates the correlation between digital infrastructure development and urban green eco-efficiency. As evident from Column (1), when accounting for regional and temporal fixed effects, and in the absence of control variables, a statistically significant positive relationship is observed between digital infrastructure development and urban green eco-efficiency at the 1% level. In [Table 3](#), the regression estimation results for models with progressively added control variables are presented in Columns (2) through (7), and Model (7) presents the estimation results after incorporating all control variables. The results of the regression indicate that across all models, the coefficient for digital infrastructure development is markedly positive. Upon incorporating control variables, the coefficient remains significantly positive at 0.033, indicating that the regression results remain largely unchanged and consistent. The beneficial effects of digital infrastructure development on boosting urban green ecological efficiency are highlighted in this finding, implying that the Broadband China strategy, when implemented, can improve and refine this efficiency, thereby confirming *H1* proposed in the preceding theoretical analysis.

4.2 Parallel trend test

To validate that the time-staggered Broadband China policy pilot has an effective policy impact, a parallel trend test is imperative for verification. According to the pilot years of cities officially established as Broadband China, the sample interval is divided into 10 segments: the first 5 years, the first 4 years, the first 3 years, the first 2 years, the first 1 year, the second 2 years, the second 3 years, the second 4 years and the second 5 years when the sample is established as Broadband China. [Figure 1](#) displays the test results based on data from the fifth period preceding the pilot launch of the Broadband China initiative. Prior to the enforcement of the policy, the statistical significance of the estimated coefficients for policy dummy variables across pre-implementation periods is negligible, suggesting no notable distinction between pilot and non-pilot cities. The result is generally consistent with the parallel trend assumption. Furthermore, the impact of the Broadband China strategy has progressively intensified over time. This aligns with the objectives of this paper, thereby ensuring the credibility of the reference regression outcomes.

4.3 Robustness tests

4.3.1 Individual placebo test. Given that the effect of Broadband China pilot cities may be affected by other unpredictable missing variables, it will lead to errors in the enhancement of

Table 3. Empirical results of benchmark regression

Variables	GEE						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
<i>Did</i>	0.056*** (0.018)	0.056*** (0.020)	0.037* (0.020)	0.037* (0.020)	0.035* (0.020)	0.035* (0.020)	0.033* (0.020)
<i>PTI</i>		0.008 (0.113)	-0.307*** (0.138)	-0.306** (0.138)	-0.295*** (0.139)	-0.275*** (0.139)	-0.295*** (0.137)
<i>lnPCGDP</i>			0.169*** (0.033)	0.169*** (0.033)	0.170*** (0.033)	0.173*** (0.033)	0.175*** (0.033)
<i>RD</i>				-0.028 (0.577)	-0.121 (0.546)	-0.133 (0.546)	-0.066 (0.548)
<i>lnPD</i>					0.054 (0.061)	0.056 (0.060)	0.052 (0.059)
<i>ER</i>						-2.040* (1.197)	-2.113* (1.193)
<i>FDI</i>							-0.725 (0.486)
<i>Constant</i>	0.483*** (0.004)	0.479*** (0.045)	-1.197*** (0.321)	-1.197*** (0.319)	-1.523*** (0.466)	-1.548*** (0.463)	-1.535*** (0.460)
<i>Observations</i>	2,670	2,670	2,670	2,669	2,669	2,669	2,669
<i>R-squared</i>	0.009	0.009	0.038	0.038	0.039	0.040	0.041
<i>Year FE</i>	YES	YES	YES	YES	YES	YES	YES
<i>Id FE</i>	YES	YES	YES	YES	YES	YES	YES

Notes(s): (i) Significance levels are denoted by ***for 1, **for 5 and *for 10%, respectively; (ii) robust standard errors are enclosed in brackets
Source(s): Authors' own creation

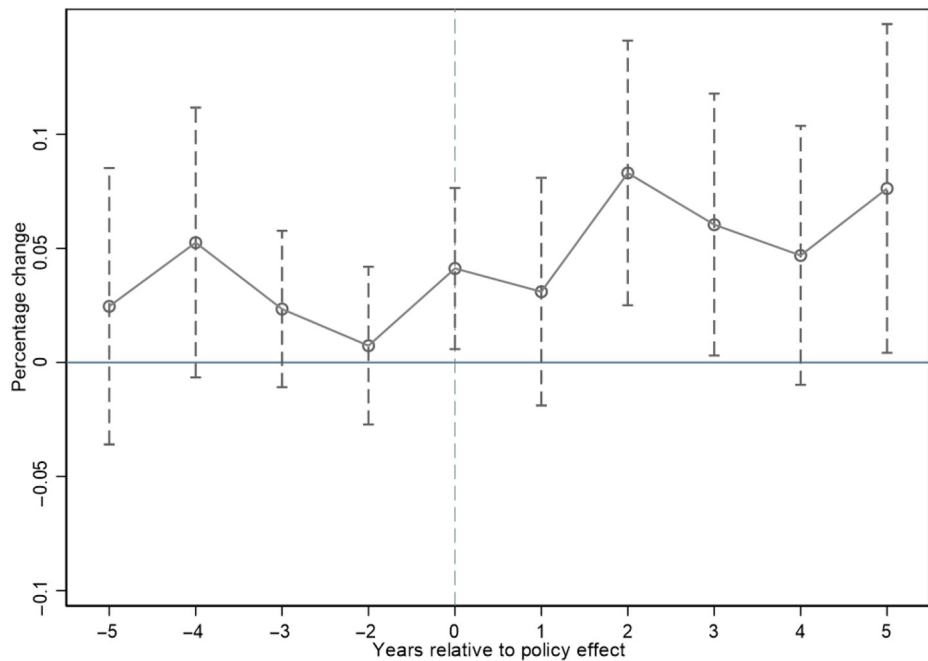


Figure 1. Results of the parallel trend test
Source: Authors’ own creation

urban green eco-efficiency, thus losing the accuracy of the conclusion. To overcome this problem, the placebo test was used to rule out other possible interfering factors. A random list is generated according to the sample of pilot cities of Broadband China, and virtual regression is repeated 1000 times, and 1000 regression coefficients and corresponding *P*-values are obtained. Figure 2 demonstrates that the kernel density of the virtual regression coefficient is approximately centered around 0 and adheres to a normal distribution, thereby confirming its successful passage through the placebo test. This further reinforces the credibility of the research findings.

4.3.2 Time-based placebo test. To reduce the potential impact of random factors on the longitudinal impacts of the Broadband China initiative, this study shifts the actual intervention years of the strategy by two and three years, respectively, producing revised estimation outcomes detailed in Table 4. The table clearly shows that advancing the implementation years of the Broadband China initiative by two or three years renders the estimated coefficients for its influence on urban green ecological efficiency insignificant. This finding suggests a lack of systematic temporal disparities between the experimental and control cities, further supporting the robustness of the estimation results.

4.3.3 Control competitive policy interference. During the rollout of the Broadband China initiative, the implementation of other policies will also affect the high-quality economic development. Therefore, this paper controls “Smart City” pilot policies that may affect urban green ecological efficiency, and the results display that did remains significant, as shown in Column (1) of Table 5, which indicate that the Broadband China strategy significantly promotes green eco-efficiency.

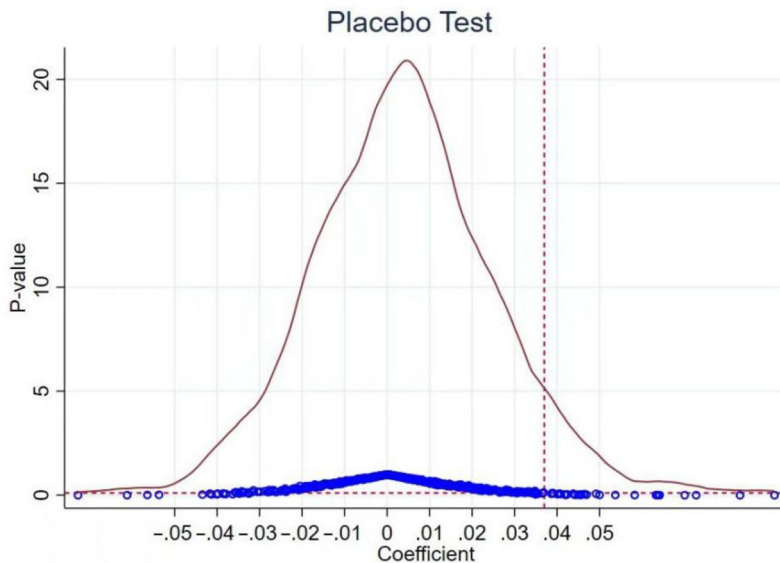


Figure 2. Results of the placebo test
Source: Authors' own creation

Table 4. Time-based placebo test

Variables	GEE	
	(1) The policy is two years ahead	(2) The policy is three years ahead
<i>Did₂</i>	0.020 (0.014)	0.003 (0.016)
<i>Controls</i>	YES	YES
<i>Observations</i>	2,669	2,669
<i>R-squared</i>	0.165	0.165
<i>Yearfix</i>	YES	YES
<i>Idfix</i>	YES	YES

Note(s): (i) Significance levels are denoted by ***for 1, **for 5 and *for 10%, respectively; (ii) robust standard errors are enclosed in brackets

Source(s): Authors' own creation

4.3.4 Indentation of core variables. To minimize the impact of extreme values on the initial regression results, the sample data underwent tail treatments of 1% and 5%, based on the variable representing urban green eco-efficiency. As depicted in Columns (2) and (3) of Table 5, the regression outcomes reveal that the Broadband China policy remains effective in enhancing urban green eco-efficiency.

Overall, the new estimated results obtained after considering the selection bias of Broadband China pilot cities exhibit good consistency in the direction of effect, significance and estimated coefficients with the previous estimation results, thereby validating the robustness of the previous estimates.

Table 5. Test results of controlling competitive policy interference and tail reduction treatment of core variables

Variables	GEE		
	(1) Control of competitive Policy interference	(2) Trapped tail 1%	(3) Trapped tail 5%
<i>Did</i>	0.038*** (0.014)	0.036*** (0.013)	0.033*** (0.013)
<i>Did₀</i>	−0.014 (0.017)		
Controls	YES	YES	YES
Constant	−1.256*** (0.383)	−1.185*** (0.378)	−1.065*** (0.360)
Observations	2,669	2,669	2,669
<i>R</i> -squared	0.167	267	267
Year FE	YES	YES	YES
Id FE	YES	YES	YES

Note(s): (i) Significance levels are denoted by ***for 1, **for 5 and *for 10%, respectively; (ii) robust standard errors are enclosed in brackets

Source(s): Authors' own creation

4.4 *Heterogeneity test*

The model research makes clear that building digital infrastructure does contribute significantly to raising urban green eco-efficiency. A noteworthy issue is the relatively uneven regional development across China, different regions have different levels of growth of the digital economy, and “high in the east, low in the west” has become a consensus. The potential diverse impacts of these spatial disparities on green eco-efficiency across various regions are worth exploring. As a result, the variability in green eco-efficiency from the perspectives of geographic location and urban scale must be investigated.

4.4.1 *Heterogeneity of geographical location.* To explore digital infrastructure’s impact on diverse cities, this paper categorizes 267 cities into four zones: east, central, west, and northeast. Columns (1)–(4) in Table 4 show a significant link between digital infrastructure and green ecological efficiency in the east, central and west, with a *p*-value < 0.10. The east outperforms other regions, suggesting a stronger Broadband China effect. Therefore, the dividends released by digital infrastructure construction in enhancing urban green eco-efficiency can be roughly ranked in descending order as east–central–west–northeast. This ranking could potentially be attributed to the following. First, the spatial hierarchy in digital infrastructure construction favors the eastern region over the central, western and northeastern regions. The latter two significantly lag behind. Second, the eastern region, with geographical and resource advantages, is more likely to see enhanced green eco-efficiency from the Broadband China policy, promoting technological innovation and industrial upgrading.

By contrast, other regions face resource scarcity, economic scale constraints and geographical limitations, lacking endogenous driving forces for ecological efficiency improvement. Northeast China, in particular, suffers from poor geographical location, severe population loss and industrial structure solidification, hindering the full realization of digital economy potential. China must therefore strive for coordinated regional development, especially by strengthening data infrastructure investment in the western region and integrating its ecological resources to foster harmonious progress among all regions in data, ecological economy and online platform economies.

4.4.2 Heterogeneity of urban scale. The impact of digital infrastructure on urban green ecological efficiency may vary by city size. Regression analysis in [Table 6](#), Columns (5) and (6), shows a statistically significant, positive 1% level correlation, suggesting that larger cities, via the Broadband China strategy, enhance ecological efficiency more than smaller/medium-sized cities. This enhancement stems from their economic scale and agglomeration benefits, facilitating advanced communication and transportation networks that integrate digital technologies across sectors. This integration fosters green tech innovation, improves resource use and minimizes environmental impact. Larger cities also attract more digital and green tech investment, nurturing an ecosystem for developing, testing and scaling cutting-edge solutions. This investment, skilled labor and research institutions favor green eco-efficiency. Policies in larger cities should therefore incentivize green ICT adoption, and develop sustainable urban digital platforms. For small- and medium-sized cities, the focus should be on capacity building, knowledge transfer, and adapting practices from larger cities.

4.5 Mechanism test

Drawing on the theoretical framework, this study postulates that the Broadband China strategy boosts urban eco-efficiency through advancements in green technology, industrial upgrading and rationalization. To test this, an intermediary effect model is used. [Figure 3](#) depicts a mechanism diagram that outlines how digital infrastructure influences the enhancement of urban green eco-efficiency.

The results of validating the influence of green technological innovation are presented in [Table 7](#), Columns (1) and (2). These indicate that the estimated coefficient of impact of the Broadband China strategy on technological innovation has achieved statistical significance at the 1% level, when incorporating the Broadband China strategy and green technological innovation into the regression analysis framework, their estimated coefficients remain significantly positive, indicating that the strategy promotes ecological efficiency via the intermediary effect of green technology innovation. As previously discussed, digital infrastructure facilitates the transcendence of geographical barriers for innovative technologies, enabling the unhindered flow of innovation factors, and augmenting the output of innovative outcomes. This integration of advanced science and technology with production and operations enables the continuous minimization of resource waste and environmental harm, ultimately enhancing urban ecological efficiency.

The outcomes of assessing the impact on industrial structure progression are displayed in Columns (3) and (4) of [Table 7](#). The research findings reveal that the coefficient for the policy indicator variable and that associated with the advancement of industrial structure exhibit notably positive values. This result suggests that the development of digital infrastructure, as exemplified by the Broadband China demonstration city initiative, holds the potential to enhance urban ecological efficiency through the acceleration of urban industrial structure upgrading. Building on the previously discussed theoretical mechanism analysis, digital infrastructure development facilitates the incorporation of novel technologies and knowledge into traditional industries, this shift redirects productive resources away from labor-intensive sectors and towards those that are knowledge and technology intensive, thereby fostering the expansion of high-tech industries.

Columns (5) and (6) of [Table 7](#) exhibit the verification results concerning the rationalization effects of industrial structure. The regression analysis indicates that the coefficient for policy dummy variables and the coefficient for industrial structure rationalization are significantly positive, indicating a substantial positive impact of digital infrastructure construction on the rationalization of industrial structure. This construction can expedite the dissemination of information, mitigate issues of information asymmetry and result in a more logical allocation of resources across various industries, thereby facilitating the coordination of energy conservation,

Table 6. Regression results for heterogeneity testing

Variables	Geographical location			Urban scale	
	(1) East	(2) Midland	(3) West	(5) Large	(6) Small and medium
Did	0.115*** (0.039)	0.059** (0.029)	-0.063* (0.033)	0.079*** (0.028)	0.000 (0.031)
Controls	YES	YES	YES	YES	YES
id="1076">Constant	-1.099 (1.166)	-0.373 (1.106)	-1.302 (0.817)	-1.045 (0.785)	-0.530 (1.000)
Observations	810	780	759	959	1,710
R-squared	0.687	0.692	0.701	0.767	0.651
Year FE	YES	YES	YES	YES	YES
Id FE	YES	YES	YES	YES	YES
Note(s): (i) Significance levels are denoted by ***for 1, **for 5 and *for 10%, respectively; (ii) robust standard errors are enclosed in brackets					
Source(s): Authors' own creation					

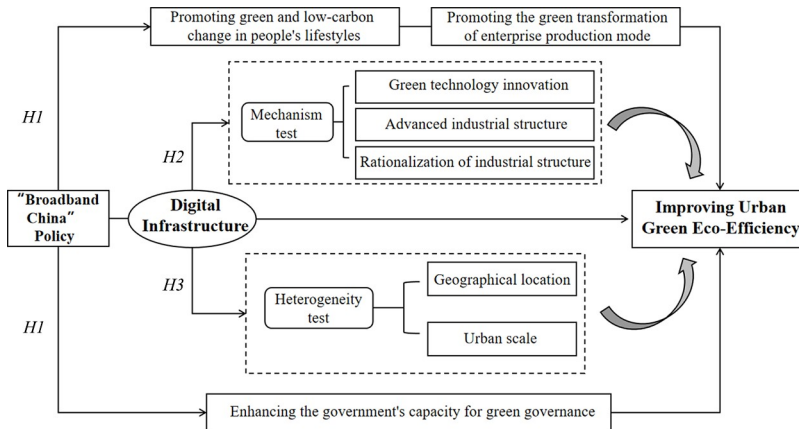


Figure 3. Mechanism diagram of the impact of digital infrastructure on urban green and eco-efficiency
Source: Authors' own creation

emission reduction, and pollution control. Furthermore, the construction enhances the degree of industrial specialization, cooperation and production efficiency, ultimately facilitating the enhancement of urban eco-efficiency.

Therefore, *H2* and *H3* are confirmed.

5. Conclusions and policy implications

Digital infrastructure construction, which emerges based on digital technology and data elements, exhibits higher economic efficiency and stronger green attributes compared with traditional economic forms. It can facilitate economic output growth while inhibiting the increase in resource consumption, thereby enhancing ecological efficiency. Consequently, using comprehensive data from 267 cities in China spanning a decade, this study draws the following specific conclusions:

- The advancement of digital infrastructure significantly boosts urban ecological efficiency, and this result remains valid after a series of robustness checks (Zhong *et al.*, 2022).
- The impact of digital infrastructure development on urban ecological efficiency varies across regions and city sizes, with eastern regions and large-scale cities benefiting the most from digital infrastructure development.
- The development of digital infrastructure enhances urban green ecological efficiency by promoting green technological innovation, advancing industrial structure upgrading and rationalizing industrial structure, serving as the mediation factors in this study.

Other scholars also assessed the effects of relevant policies on promoting sustainable urban green growth (Peng *et al.*, 2024; Niu *et al.*, 2024).

On this basis, the current study offers the following practical policy insights: First, stakeholders play a pivotal role in the green transformation of local economies, necessitating ongoing enhancements to digital infrastructure. For smaller or less-developed regions, policymakers should optimize development mechanisms based on digital economy hardware and software, accelerate digital integration in environmental governance and government services, and enhance ecological efficiency through moderate environmental regulations, ensuring the sustainability and

Table 7. Regression results of the mechanism tests

Variables	(1) NOP	(2) GEE	(3) AIS	(4) GEE	(5) TI	(6) GEE
<i>Did</i>	0.058** (0.027)	0.035*** (0.014)	0.028*** (0.008)	0.034** (0.014)	0.015** (0.007)	0.036*** (0.014)
<i>NOP</i>		0.036*** (0.010)		0.105*** (0.036)		
<i>Ais</i>						
<i>TI</i>						
Controls	YES	YES	YES	YES	YES	0.077** (0.038)
Constant	0.852 (0.749)	-1.247*** (0.383)	1.235*** (0.219)	-1.247*** (0.383)	2.368*** (0.204)	-1.247*** (0.383)
Observations	2,668	2,668	2,662	2,662	2,669	2,669
R-squared	0.802	0.171	0.281	0.172	0.092	0.169
Number of id	267	267	267	267	267	267
Year FE	YES	YES	YES	YES	YES	YES
Id FE	YES	YES	YES	YES	YES	YES

Note(s): (i) Significance levels are denoted by ***for 1, **for 5 and *for 10%, respectively; (ii) robust standard errors are enclosed in brackets

Source(s): Authors' own creation

inclusivity of digital infrastructure. Firms should embrace the “dual-transformation synergy” strategy, drive management model innovation and traditional industrial upgrading, leverage special funds, tax incentives, and technical support to incentivize digital technology adoption for optimized production, energy conservation and emission reduction, foster efficient resource utilization in intelligent manufacturing, and establish a positive cycle between digitization and green development. Policymakers should also collaborate with educational and social organizations to enhance public ecological awareness through digital skills training, particularly targeting youth and underdeveloped areas, to strengthen their capacity to engage in environmental protection using digital technologies. Second, given the heterogeneous impact of digital infrastructure on urban green ecological efficiency, regionalized and differentiated strategies should be adopted. Eastern and large cities should leverage their economic and policy advantages to strengthen intercity information flows, facilitate cross-regional sharing of large-scale digital facilities. Central and western regions can rely on national strategies to increase digital innovation investments, accelerate technological advancements and narrow the gap with eastern regions. Northeastern regions need to adjust their industrial structures, enhance competitiveness in areas like “intelligence plus heavy industry” and “intelligence plus agriculture,” redirect these toward eco-friendly sectors like services (Onwe et al., 2024a, 2024b), and develop an ecological economy based on local resources and environmental conditions, promoting renewable energy for harmonious coexistence between the economy and the environment. Finally, policymakers should strengthen support for green technological innovation research, accelerate industrial structure upgrading, particularly in circular economy, digital information and renewable energy sectors. By establishing demonstration projects for traditional industry digital transformation, driving overall green transformation of urban economies and deepening environmental awareness (Xin et al., 2023), policymakers can expedite the high-quality development process of “economizing ecology” and “ecologizing economy.”

Future research directions in this area hold promise, with several avenues worth exploring. First, while this study focuses on China given its distinctive economic and ecological traits, examining other developing countries with varying environmental challenges could offer additional policy insights. Second, considering actual indicators of digital infrastructure levels in future research will provide a more nuanced understanding of infrastructure development and its impacts. Finally, given the dynamic nature of the digital economy, incorporating more recent data beyond 2020 will enable subsequent studies to reveal the latest trends and characteristics of digital infrastructure driving ecological efficiency changes, thereby providing timelier and more precise information support for policymakers.

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