Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 31 January 2025
DOI 10.3389/fenvs.2025.1506012

OPEN ACCESS

EDITED BY
Jiachao Peng,
Wuhan Institute of Technology, China

REVIEWED BY
Guoxiang Li,
Nanjing Normal University, China
Wei Li,
Taiyuan University of Technology, China

*CORRESPONDENCE
Huang Shanshan,
huangss4771@163.com

RECEIVED 04 October 2024
ACCEPTED 13 January 2025
PUBLISHED 31 January 2025

CITATION
Zhongxin Y, Shanshan H, Jing M, Ceyuan S and Shujing X (2025) The impact of digital infrastructure on urban total factor carbon emission performance: evidence from enterprise production and household consumption in China.
Front. Environ. Sci. 13:1506012.
doi: 10.3389/fenvs.2025.1506012

The impact of digital infrastructure on urban total factor carbon emission performance: evidence from enterprise production and household consumption in China

Yang Zhongxin[1,2], Huang Shanshan[3]*, Ma Jing[3], Song Ceyuan[1] and Xu Shujing[1]

[1]School of Economics and Management, China University of Geosciences (Wuhan), Wuhan, China, [2]Hubei Regional Innovation Capacity Monitoring and Analysis Soft Science Research Base, Wuhan, China, [3]School of Economics and Management, Ningxia University, Yinchuan, China

Digital infrastructure, serving as the fundamental carrier of data elements, allows China to balance economic growth with reduced carbon intensity, opening new pathways for sustainable economic development globally. This study employs a Difference-in-Differences (DID) approach to investigate the impact of digital infrastructure on urban total factor carbon emission performance, and extend the research perspective to a micro level, focusing on mechanisms involving household consumption and enterprise production. The results demonstrate that (1) Digital infrastructure can enhances urban carbon performance by promoting green product innovation of enterprises and changing consumers' consumption patterns (2) Heterogeneity analysis indicates that cities with higher income and educational levels among residents experience a more significant improvement in carbon performance, and digital infrastructure's impact varies when combined with enterprise characteristics and technological capabilities, with non-state-owned enterprises and high-tech enterprises having relatively higher carbon-saving effects. The research results of this paper emphasize role of micro-subjects in the process of digital infrastructure affecting total-factor carbon emission performance, which has important theoretical and practical significance for guiding future economic policies and strategies.

KEYWORDS

digital infrastructure, total factor carbon emission performance, green consumption, green product innovation, green market

1 Introduction

Sustainable development is a common goal of all countries in the world, and finding the balance between economic development and environmental protection is a challenge for all countries. Total factor carbon emission performance is an evaluation metric that comprehensively assesses expected economic output and unintended carbon dioxide emissions, accurately reflecting the coordination between economic growth and carbon emissions (Bai et al., 2019). This metric not only serves as a crucial assessment tool for

China but also for sustainable development globally. As the world's second-largest economy, China is also committed to promoting global climate governance while promoting economic development. Its balanced strategy has had a profound impact on green economic growth at home and abroad. At the same time, China is increasingly concerned about the improvement of domestic "digital power" and "computing power" (Gong et al., 2023).

With the advent of the digital economy, data elements have emerged as key production factors, profoundly influencing total factor carbon emission performance. Data elements, characterized by their inherent cleanliness, have partially replaced traditional production factors, bridging the gap between economic growth and reduced carbon intensity and optimizing the input structure of production factors (Aghion et al., 2005). Digital infrastructure, as the core application of data elements, reshapes the allocation of production factors and promotes digital production methods, stimulating new productive forces and thereby enhancing total factor carbon emission performance. However, the potential high-emission characteristics associated with the construction and operation of digital infrastructure may pose constraints on its role in improving carbon performance. Thus, this paper seeks to address a core question: Can digital infrastructure effectively enhance urban total factor carbon emission performance?

Enterprises and residents, as key market players, contribute to economic growth through their production and consumption activities, but they also inevitably exacerbate urban carbon emissions. Which are important factors affecting the performance of total factor carbon emission, but often be ignored in previous studies. During the digital economic development phase, enterprises and residents are inevitably affected by the input of data elements. As the cornerstone of the digital economy, digital infrastructure fundamentally transforms production and consumption patterns, thus influencing carbon emission performance on a macro-regional scale.

Specifically, during the construction and improvement of digital infrastructure, enterprises and consumers—its direct beneficiaries—can leverage the information advantages it provides to enhance efficiency and optimize the entire chain from production and distribution to consumption (Chang et al., 2024). Through digital platform, enterprises can optimize resource allocation and internal management, which helps to improve enterprise efficiency; at the same time, it can help enterprises to learn new technologies and promote production change. For consumers, through information sharing, the use of digital infrastructure will affect consumers to change their preferences, influence their consumption concepts, and encourage consumers to pursue online and offline actions for environmental protection (Ge et al., 2022). This transformation not only promotes green products and green consumption but also facilitates a low-carbon transition in economic growth.

The construction of broadband network infrastructure is an important representative of the digital infrastructure construction, as a strategic public infrastructure of national importance, it plays an essential role in economic and technological advancements. To further promote broadband network construction and achieve sustainable socio-economic development, the State Council issued the "Broadband China" strategy and implementation plan in 2013, followed by the approval of 120 "Broadband China" pilot cities in 2014, 2015, and 2016. Supported by policy, these pilot cities significantly enhanced their digital infrastructure construction levels, potentially influencing the behavior of market participants and urban green development.

Therefore, this study adopts the "Broadband China" strategy as a policy experiment, employing a DID method to explore the influence effect of urban digital infrastructure development on the performance of urban total factor carbon emission in China. At the same time, unify the enterprise and consumers into the same research system, from the perspective of micro market, through the mechanism of inspection and heterogeneity analysis to explore the influence of enterprise and consumers on the digital infrastructure to urban total factor carbon performance, explore the green supply and demand cycle in the market, carry a more comprehensive investigation about enterprise and consumer together influence in the process of carbon reduction.

As the economic resources and other conditions of developing countries differ greatly from those of developed countries, the green development path of developed countries is inapplicable to some extent. As a member of developing countries, China's green development path is conducive to its own sustainable development, and also universal for developing countries. By exploring the green economic effect of digital infrastructure, can help developing countries under the limitation of resources, they can improve domestic green development level by improving the level of digital infrastructure to achieve the effect of killing two birds with one stone, or encourage developing countries to optimize the allocation of domestic resources, reduce the digital infrastructure resource allocation to better development of green economy. Therefore, exploring how China's digital infrastructure affects total factor carbon emission performance is crucial for promoting green economic development in China and other developing countries globally.

The possible marginal contribution of this paper as follows: firstly, enrich the related research on the impact of digital infrastructure development on urban total factor carbon emission performance, provides reference value for green development in developing countries by taking Chinese cities as the research object; Secondly, to explore the role of market micro-entities in the national green development from the micro perspective of enterprises and residents, combining enterprises and residents as producers and consumers to explore the role of green product innovation and green consumption within a unified framework, Provide new perspectives and evidence for digital infrastructure influencing total factor carbon emission performance, it expanding the existing literature and has important theoretical and practical significance for guiding the future economic policy and environmental strategies.

The rest of this paper is arranged as follows: the second part is the literature review; the third part explains the theoretical mechanism and proposes the research hypothesis; the fourth part is the research design, introduces the construction of data, model and main indicators; the fifth part is empirical analysis; the sixth part is divided into mechanism inspection and heterogeneity analysis; and the seventh part is the conclusion and policy suggestion.

2 Literature review

Existing literature exploring the impact of digital infrastructure on urban carbon emission performance employs various methods and perspectives. Some studies use the "Broadband China" policy as a quasi-natural experiment case for digital infrastructure construction (Yao et al., 2023) or employ entropy methods to construct indicator systems for measuring the level of digital infrastructure construction (Kou and Xu, 2022). These studies, mostly based on panel data from Chinese cities, form two representative viewpoints. On one hand, some studies suggest that the construction of digital infrastructure can effectively enhance urban carbon emission performance and promote low-carbon development. On the other hand, some argue that the impact of digital infrastructure construction is complex, with potential differences between short-term and long-term effects. These studies provide a rich theoretical foundation and diverse analytical perspectives for this paper.

One category of literature suggests that digital infrastructure can improve urban carbon emission performance, promoting low-carbon urban development. Scholars generally believe that digital infrastructure construction can achieve urban energy-saving and emission reduction goals by enhancing green innovation levels (Sun, 2022; Han et al., 2022; Liu et al., 2024) and reducing energy intensity (Lu et al., 2023; Wan et al., 2023). Additionally, Haseeb et al. (2019) argue that digital infrastructure construction can improve urban total factor carbon emission performance through industrial structure transformation. Yu and Hu (2024) state that the aggregation of digital service industries plays a crucial role in enhancing urban carbon performance via digital infrastructure. From a micro perspective, increasing attention is being paid to enterprises and residents as users of digital infrastructure and environmental pollution contributors. Du et al. (2023) suggest that digital infrastructure can improve carbon emission performance by increasing public environmental awareness. Peng H. R. et al. (2024) posit that digital infrastructure can also promote carbon reduction by encouraging green lifestyle changes among residents. Wang and Li (2023) observe that the carbon reduction effect of the digital economy is related to residents' income levels. Li et al. (2024) find that the digital economy facilitates low-carbon development by alleviating financing constraints for enterprises. Guo et al. (2024) propose that digital infrastructure promotes enterprises' green transformation for carbon reduction.

Another category of literature argues that the impact of digital infrastructure construction on urban carbon emission performance is nonlinear. Wang C. Q. et al. (2023) state that digital infrastructure construction could increase carbon emissions for a prolonged period, inhibiting improvements in carbon performance. Lan and Zhu (2023) believe that digital infrastructure has a nonlinear relationship with carbon rebound effects and total carbon factor productivity, influencing its impact on regional carbon performance. Tang and Yang (2023) argue that digital infrastructure significantly increases carbon emissions through mechanisms such as inducing *per capita* energy consumption, total energy input, diminishing marginal productivity, and increasing energy intensity. Hu et al. (2023) suggest that regions should leverage industrial upgrades and environmentally sustainable regional cooperation to mitigate the negative nonlinear impacts of digital infrastructure on carbon reduction.

Reviewing the existing literature reveals that scholars have closely linked digital infrastructure construction with carbon emission issues, focusing on the impact of economic construction on ecological development. This provides valuable insights for this study. However, empirical research on the specific effects of digital infrastructure on carbon emission performance yields inconsistent conclusions, indicating the need for further exploration in this field. Current research predominantly adopts a macro perspective, focusing on how technological innovation, green technology development, and industrial structure upgrades affect carbon performance. In contrast, studies exploring the micro mechanisms of digital infrastructure construction's impact on carbon emission performance from the behaviors of market micro-entities—enterprises and consumers—are relatively scarce. Existing studies often analyze the carbon reduction behaviors of enterprises and consumers separately, overlooking the complex, interdependent relationships between them. This study incorporates both entities into a unified research framework for comprehensive analysis, revealing how digital infrastructure influences urban carbon emission performance and its micro-mechanisms. This approach provides a solid theoretical basis for formulating more comprehensive and effective carbon reduction strategies.

3 Theoretical mechanisms and research hypotheses

3.1 Digital infrastructure construction and total factor carbon emission performance

Total factor carbon emission performance, based on production theory, is measured by considering multiple factor inputs, evaluating the combined effects of economic output and carbon dioxide emissions. Digital infrastructure, as a fundamental carrier of data elements, can alter existing production factor configurations through the application of data elements, thus influencing expected economic outputs and unintended carbon dioxide emissions, ultimately affecting urban total factor carbon emission performance.

Due to the significant reliance of digital infrastructure on energy, which generates considerable carbon emissions, the impact of digital infrastructure on urban carbon performance is complex. On one hand, urban digitalization and intelligentization increase information accessibility, leading to efficient resource allocation and improved energy utilization. When energy efficiency improves, carbon emissions per unit of energy usage remain constant, but the generated economic increment increases, enhancing total factor carbon emission performance. On the other hand, considering the energy rebound effect, digital infrastructure might have a counterproductive impact on urban carbon performance. First, the construction of digital infrastructure itself might increase carbon emissions due to its high energy consumption during construction and operation (Avom et al., 2020). Secondly, while digital infrastructure promotes economic growth, current economic and social energy consumption mainly relies on fossil fuels. Economic growth resulting in expanded output scales and technological advancements can lead to increased energy consumption and corresponding carbon emissions (Khazzoom, 1980).

From a macro perspective, digital infrastructure construction promotes clean energy substitution for traditional energy and the replacement of material inputs with data elements, making urban activities cleaner and more efficient by mitigating factor misallocation (Ge et al., 2022). This can effectively reduce carbon emissions while fostering economic growth, thus improving total factor carbon emission performance. However, digital infrastructure requires substantial funding, and given limited resources, the initial investment costs, maintenance costs, and training costs can squeeze investments in energy-saving and carbon-reducing initiatives. The cost effect of digital infrastructure construction could hinder improvements in carbon performance (Salahuddin and Alam, 2015). On a micro level, the introduction of data elements alters enterprise production scales, and digital platforms influence how enterprises and consumers access information, affecting the traditional supply-demand chain of products in the market. The supply of green products and the green consumption chain emerging from this can further impact urban total factor carbon performance.

In summary, digital infrastructure can enhance urban carbon performance by improving energy efficiency, utilizing clean energy to replace fossil fuels, and exhibiting the energy rebound and cost effects that suppress improvements in carbon performance. Thus, the impact of digital infrastructure construction on urban carbon performance exhibits a complex bidirectional relationship. Based on this, the following competing hypotheses are proposed.

Hypothesis 1a: Digital infrastructure positively impacts urban total factor carbon emission performance.

Hypothesis 1b: Digital infrastructure negatively impacts urban total factor carbon emission performance.

3.2 Digital infrastructure construction, consumer behavior, and carbon emissions

For consumers, digital infrastructure construction can reduce carbon emissions in household activities by altering lifestyles and consumption habits, thereby enhancing total factor carbon emission performance. The rapid advancement of digitalization promotes sustainable green consumption (Peng Y. et al., 2024). Digital infrastructure construction makes life more convenient, promoting paperless learning and working methods. Internet platforms enable consumers to complete shopping, medical consultations, and other activities online, encouraging the development of second-hand markets and shared services. In 2023, the national online retail sales of physical goods reached 13,017.4 billion yuan, reflecting a notable shift from offline to online consumption, a hallmark of modern consumption modes (Ru and Deng, 2023). This convenience and resource recycling reduce consumer energy demand, particularly lowering energy use during travel, and subsequently cutting carbon emissions.

Moreover, internet applications and environmental public welfare campaigns significantly influence consumer consumption concepts, enhancing low-carbon consciousness through virtual low-carbon behaviors that translate into real-world low-carbon actions. For example, participants in the "Ant Forest" program are more likely to choose walking or public transportation over private cars to earn "energy points." Similarly, influenced by environmental awareness, consumers may prefer clean fuels when selecting energy sources, promoting low-carbon energy consumption patterns (Ma, 2020). When purchasing vehicles, consumers may increasingly prefer new energy vehicles, thus reducing the use of chemical energy and significantly lowering carbon emissions, enhancing total factor carbon emission performance. Based on this, the following hypothesis is proposed.

Hypothesis 2: Digital infrastructure construction influences total factor carbon emission performance by altering consumer consumption patterns.

3.3 Digital infrastructure construction, enterprise production, and carbon emissions

Digital infrastructure construction can transform enterprise production modes by facilitating corporate transformation and upgrading, affecting total factor carbon emission performance during production. In enterprise production, digital infrastructure construction empowers businesses to optimize resource allocation, enhance production factor efficiency, reduce unit energy consumption, and improve capacity utilization rates (Fu et al., 2024). Furthermore, digital facilities enhance enterprise information systems, prompting companies to establish databases and new digital systems that simulate production and emissions processes to improve efficiency. The lowered information acquisition threshold strengthens inter-enterprise cooperation, diversifies resources for green technology innovation, and enhances overall human capital, fostering green technology advancements driven by talent. This contributes to upgrading production processes, reducing costs, and encouraging investments in energy-saving and carbon-reducing efforts, ultimately promoting green production and product innovation.

Additionally, digital infrastructure has led to the emergence of internet-based online revenue businesses, which greatly substitute data elements for traditional energy, thereby driving economic development while significantly reducing energy consumption and carbon emissions. The appearance of these low-carbon enterprises fosters competition, influencing the flow and allocation efficiency of production factors, eliminating high-energy-consuming firms, and reducing the proportion of highly polluting enterprises. This leads to a decrease in energy consumption and carbon emissions per unit of output, ultimately enhancing carbon performance (Wang et al., 2024). Simultaneously, reallocating resources promotes investment in low-carbon technological innovation, contributing to low-carbon industrial development (Ang, 1999). Based on this, the following hypothesis is proposed:

Hypothesis 3: Digital infrastructure construction influences total factor carbon emission performance by altering enterprise production.

Based on the above analysis and hypotheses, the article proposes the theoretical framework diagram in Figure 1.

4 Research design

4.1 Model construction

Based on the approved list of cities involved in the "Broadband China" strategy by the Ministry of Industry and Information Technology and the National Development and Reform Commission of China, 82 cities implementing the strategy were selected as the treatment group, while the remaining cities that did not implement the strategy formed the control group. To examine whether the "Broadband China" strategy improved the total factor carbon emission performance of pilot cities, a gradual Difference-in-Differences (DID) model was constructed as the Equation 1:

$$UEI_{it} = \alpha_0 + \alpha_1 DID + \gamma Control_{it} + \mu_{it} + \varphi_t + \varepsilon_{it} \tag{1}$$

Where: i and t represent cities and years; The dependent variable (UEI) represents "total factor carbon emission performance"; The core explanatory variable (DID) is a dummy variable for the "Broadband China" pilot cities; *Control* variables include city-level indicators such as "government size," "city size," and "economic development level"; μ_i indicates city fixed effects, φ_t represents time fixed effects, and ε_{it} is the random disturbance term.

4.2 Variable descriptions

4.2.1 Dependent variable

Following the approach by Zhou et al. (2010), capital, labor, and energy are considered primary input factors, with CO_2 emissions as the undesirable output and GDP as the desirable output. The non-radial directional distance function (NDDF) is used to measure total factor carbon emission performance (UEI) at the city level. Capital is represented by capital stock, calculated using Zhang et al. (2004) estimation method. Labor is represented by the year-end number of urban unit employees in each city, while energy consumption is estimated using data from nighttime lighting values to decompose provincial energy consumption data into individual cities, based on the method of Shi and Li (2020). The final formula for total factor carbon emission performance is as the Equation 2:

$$\text{UEI} = \frac{\left(C - \beta_C^* C\right)/\left(Y + \beta_Y^*\right)}{C/Y} = \frac{1 - \beta_C^*}{1 + \beta_Y^*} \tag{2}$$

Where: β represents the collection of individual inefficiency factors impacting each type of input or output; The larger the UEI value, the higher the total factor carbon emission performance.

4.2.2 Core explanatory variable

Given that the "Broadband China" strategy involved pilot cities in three batches from 2014 to 2016, a multi-period DID model was used. An interaction term $DID = treat \times t$ was set, where: $treat$ is a dummy variable (1 for pilot cities and 0 otherwise). t is a time dummy variable (1 for post-policy periods and 0 otherwise). The analysis excludes sub-provincial cities and cities with severe data gaps, ultimately retaining 82 pilot cities and 103 control cities.

4.2.3 Control variables

To account for potential confounding factors, a series of control variables were included: The logarithm of *per capita* GDP ($\ln prgdp$) measures economic development levels; The ratio of local government fiscal expenditure to regional GDP represents government size (gov); Industrial structure (ui) is measured using an index that assigns scores of 1, 2, and 3 to the primary, secondary, and tertiary sectors, respectively, based on their share in GDP; Population density represents city size (dop); For mediation analysis involving enterprises, additional variables include the age of listed companies (age), growth rate of total operating revenue ($growth$), sales profit rate (ros), and debt-to-asset ratio (lev).

4.2.4 Mechanism variables

The paper explores the roles of household consumption and enterprise production in influencing total factor carbon emission performance via digital infrastructure. On the consumer side, Zhou et al. (2022) identify electrification of energy consumption as a key factor in achieving carbon peak and carbon neutrality goals. To measure shifts toward digital consumption and the use of new energy vehicles, residential electricity consumption (elc) is used as an indicator of changing consumer behaviors.

On the enterprise side, due to data limitations, annual reports of A-share listed companies were analyzed as proxies for social responsibility reports. Following Chiou et al. (2011), green product innovation (gp) was evaluated based on textual analysis of these reports. Innovation was scored on four dimensions: Use of environmentally friendly materials in product design; Adoption of degradable packaging; Assessment of product recyclability; Efficient use of resources in product design and adherence to green product labels.

Based on the level of textual description of the above indicators in the annual corporate report, each indicator will be assigned a score of 0, 1, or 2 for no description, having a description, and quantification or detailed description, respectively. The final score will be the sum of the scores for the four indicators.

4.3 Data sources and descriptive statistics

Due to data limitations on residential electricity consumption, which are only available until 2019, and the restricted number of cities with matching corporate data, this study uses panel data from 185 prefecture-level cities in China from 2010 to 2019, amounting to 1,850 observations. Data sources include the China Urban Statistical Yearbook, China Energy Statistical Yearbook, China Statistical Yearbook, the National Geophysical Data Center (NGDC), the China Emissions Accounts Database (CEADs), CSMAR, the National Bureau of Statistics, various provincial statistical yearbooks, and municipal statistical yearbooks. Missing data were supplemented using interpolation methods. Descriptive statistics of key variables are presented in Table 1.

10.3389/fenvs.2025.1506012

TABLE 1 Descriptive statistics of key variables.

Variable	Description	Observations	Mean	Std. Dev	Min	Max
UEI	Total factor carbon emission performance	1850	0.267	0.160	0.043	1
DID	"Broadband China" pilot dummy	1850	0.227	0.419	0	1
dop	City size	1850	502.861	330.097	18.46	2005.91
gov	Government size	1850	0.170	0.069	0.0734	0.4507
ui	Industrial structure	1850	2.316	0.139	2.0277	2.6949
lnprgdp	Economic development level	1850	10.774	0.582	9.436	12.0684

TABLE 2 Baseline regression results.

Variable	(1)	(2)	(3)	(4)	(5)
DID	0.017*** (3.59)	0.017*** (3.60)	0.010** (2.20)	0.010** (2.25)	0.023*** (2.76)
dop		0.0001*** (3.95)	0.0001*** (4.02)	0.0001*** (4.17)	0.0001 (1.11)
gov			−0.734*** (−12.80)	−0.740*** (−12.91)	−0.215** (−2.61)
ui				0.094** (2.13)	0.060 (0.93)
lnprgdp					0.224*** (13.72)
Constant	0.186*** (47.30)	0.122*** (7.38)	0.229*** (12.83)	0.017 (0.17)	−2.314*** (−9.44)
City FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Observations	1850	1850	1850	1850	1850
R2	0.531	0.535	0.577	0.578	0.691

P < 0.05, *P < 0.01; Values in parentheses are t-statistics.

5 Empirical results analysis

5.1 Baseline regression

The baseline regression results of the impact of digital infrastructure on urban total factor carbon emission performance are shown in Table 2. Under the control of city and year fixed effects, control variables were gradually added to the regression. From the regression results in each column, it can be observed that the estimated coefficients of the core explanatory variable *DID* are significantly positive at the 5% level, indicating that cities implementing the "Broadband China" strategy significantly enhance their total factor carbon emission performance. Specifically, from the estimated coefficient in column (5), it can be observed that after adding all control variables, the core explanatory variable *DID* is 0.0228, which is significant at the 1% level, implying that the "Broadband China" strategy increases the total factor carbon emission performance of pilot cities by 2.28% compared to non-pilot cities.

This verifies Hypothesis 1a: Digital infrastructure positively impacts urban total factor carbon emission performance.

5.2 Parallel trend test

Using the DID model requires satisfying the parallel trend assumption, which states that the treatment and control groups should exhibit parallel changes before policy implementation. Following Beck et al. (2010), the parallel trend test was conducted. The results are illustrated in Figure 2, using the year before the implementation of the "Broadband China" strategy as the base period. Before the policy implementation, there was no significant difference in total factor carbon emission performance between pilot and non-pilot cities. The differences became significant 2 years after policy implementation. Due to the time needed for digital infrastructure construction, application, and the influence on market participants like consumers and enterprises, short-term differences may not be obvious immediately after the policy announcement, indicating a lag effect in policy impact. This observation meets the parallel trend assumption, validating the use of the DID method.

5.3 Placebo test

To address potential unobserved variables at the city-year level that may confound policy evaluation effects, a placebo test was conducted. A randomly generated experimental group list for "Broadband China" pilots was created, and the baseline model was repeated 500 times. As shown in Figure 3, the kernel density distribution of estimated coefficients and their P-values approximately follow a normal distribution, suggesting robustness in the regression results.

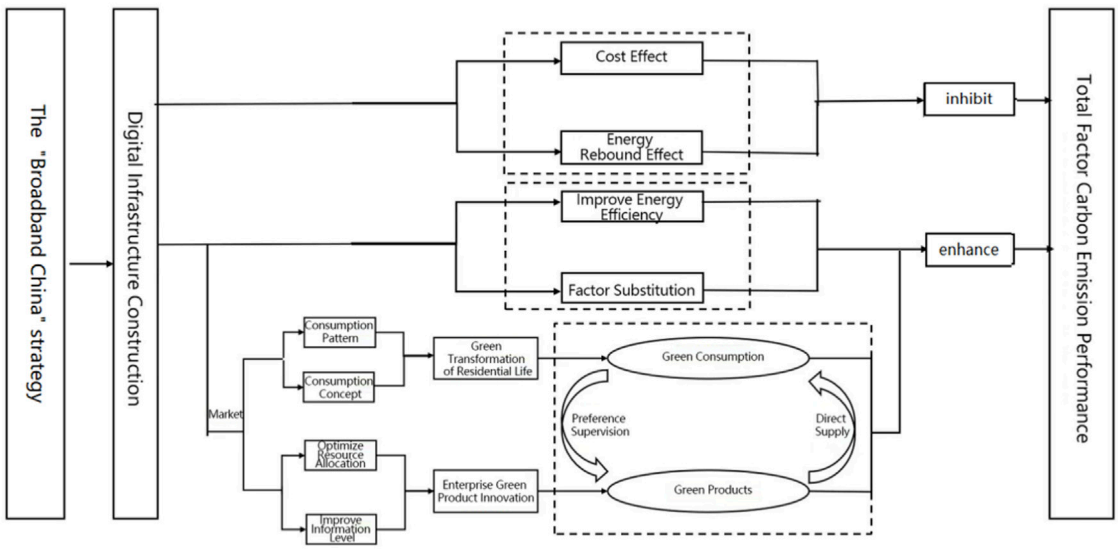

FIGURE 1
Theoretical framework diagram.

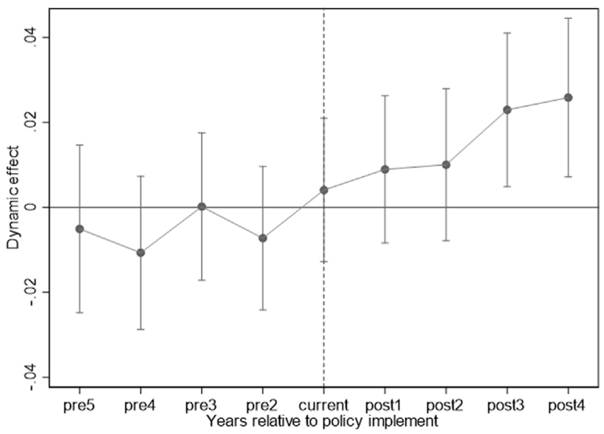

FIGURE 2
Parallel trend test.

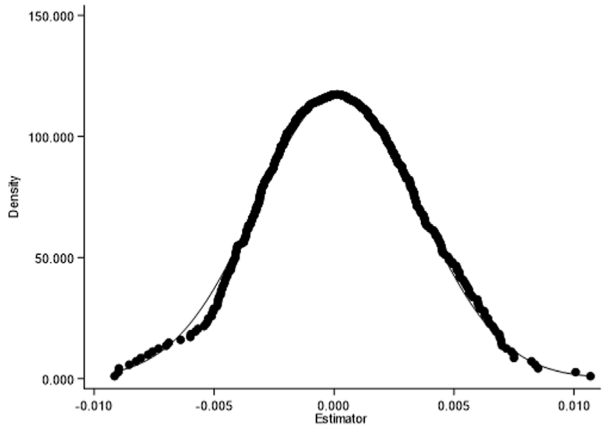

FIGURE 3
Placebo test.

5.4 Robustness test

The baseline regression results suggest that digital infrastructure construction, represented by the “Broadband China” strategy, can enhance urban total factor carbon emission performance. The robustness of these findings was further verified through various methods, including changes in model specifications, adjustments to policy timelines, exclusion of other policy interferences, removal of extreme values, and replacement of core explanatory variables.

5.4.1 Changing model specification

To mitigate potential sample selection bias, a Propensity Score Matching-Difference-in-Differences (PSM-DID) method was employed to strengthen the comparability between treatment and control groups. As shown in column (1) of Table 3, the *DID* coefficient remains significantly positive at the 1% level, confirming that digital infrastructure construction has a robust positive impact on urban carbon performance.

5.4.2 Changing policy timeline

To better verify the carbon performance effect of digital infrastructure, a counterfactual test was conducted by adjusting the policy implementation timeline. The years in which cities were approved as “Broadband China” pilot cities were shifted 2 years earlier. The results, shown in column (2) of Table 3, indicate a positive but insignificant *DID* coefficient, differing from the actual results, demonstrating that changes in carbon performance are significantly related to the “Broadband China” strategy.

TABLE 3 Robustness test regression results.

Variable	PSM-DID	Changed policy time	Excluded other policies	Excluded extreme values
	(1)	(2)	(3)	(4)
DID	0.017*** (2.10)	0.0107 (1.22)	0.023*** (2.78)	0.013** (2.37)
Smart City Dummy			−0.008 (−1.08)	
Constant	−2.344*** (−10.05)	−2.239*** (−9.18)	−2.323*** (−9.48)	−1.711*** (−9.79)
Control Variables	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	1795	1850	1850	1850
R^2	0.701	0.686	0.692	0.776

P < 0.05, *P < 0.01; Values in parentheses are t-statistics.

5.4.3 Exclusion of other policy interferences

The “Smart City” initiative, implemented from 2012, coincides with the “Broadband China” strategy. To exclude potential interference, the reform timelines of “Smart City” pilot cities were controlled. As shown in column (3) of Table 3, even after controlling for “Smart City” pilot impacts, the core explanatory variable DID remains positively significant at the 1% level, further supporting the baseline results.

5.4.4 Exclusion of extreme values

To exclude the influence of extreme values, a 5% trimming of the dependent variable UEI was performed, and the impact of pilot cities on urban carbon performance was re-evaluated. As shown in column (4) of Table 3, the core explanatory variable DID remains significantly positive at the 5% level, confirming the robustness of the baseline results.

5.4.5 Replacing core explanatory variable

To further verify the impact of digital infrastructure on urban total factor carbon emission performance, the article adopts the method of replacing core explanatory variables. Six indicators are selected from two aspects: digital infrastructure input and digital infrastructure output. An evaluation index system for digital infrastructure is constructed using the entropy method, as shown in Table 4. Simultaneously, due to the inaccessibility of data on the length of optical fiber cables and the number of internet broadband accesses at the prefecture-level cities, the article draws on the approach of Wang Q. et al. (2023) to convert the two indicators of provincial-level optical fiber cable length and internet broadband access quantity to the city level based on the proportion of total telecommunications business income of the corresponding city to that of its province. Finally, the six indicators are applied to the entropy method to form the replaced explanatory variable, the Digital Infrastructure Evaluation Index (dig).

Regression analysis was performed on the dependent variable using the replaced explanatory variable, controlling for fixed effects of city and year, and gradually adding control variables. The regression results are presented in Table 5. It can be observed that after replacing the core explanatory variable, the estimated coefficient of the digital infrastructure evaluation index (dig) is significantly positive at the 5% level, indicating that digital infrastructure still has a significant promoting effect on urban total factor carbon emission performance. This provides evidence for the article’s competitive Hypothesis 1a, which states that digital infrastructure enhances urban total factor carbon emission performance, and simultaneously demonstrates the robustness of the baseline regression results.

5.5 Endogeneity treatment

To mitigate potential endogeneity issues, the Two-Stage Least Squares (2SLS) method was adopted for testing. Following the approach of Fang et al. (2023), an interaction term was constructed using the distance from each city to Hangzhou and the time trend, and logarithmic processing (iv) was applied. This served as an instrumental variable for the “Broadband China” strategy. The results are presented in Table 6. Specifically, the results in column (1) demonstrate the rationality of selecting the instrumental variable. Additionally, cities closer to Hangzhou are more likely to become “Broadband China” pilot cities. In column (2), the coefficient of the core explanatory variable DID is significantly positive, indicating that even after considering endogeneity, digital infrastructure still enhances urban total factor carbon emission performance.

6 Mechanism test and heterogeneity analysis

6.1 Mechanism test

The above empirical results indicate that digital infrastructure can effectively improve urban total factor carbon emission performance. Based on the previously discussed mechanisms, this section further explores the roles of enterprise production transformation and consumer behavior transformation in the impact of digital infrastructure on carbon performance. Specifically, as the Equations 3, 4, following the approach of

TABLE 4 Digital infrastructure evaluation index system.

Subsystem	Indicator level	Indicator calculation	Indicator attribute
Digital Infrastructure Input	Optical Fiber Length	Length of long-distance optical fiber cables (10,000 km)	Positive
	Internet Broadband Access Ports	Number of internet broadband access ports (10,000 ports)	Positive
	Related Employees	Number of employees in information transmission, computer services, and software industries (10,000 people)	Positive
Digital Infrastructure Output	Telecom Business Volume Per Capita	Total telecom business income/total population	Positive
	Mobile Phone Penetration Rate	Number of mobile phone users/total population	Positive
	Internet Penetration Rate	Number of internet broadband access users/total population	Positive

TABLE 5 Regression results after replacing the core explanatory variable.

Variable	(1)	(2)	(3)	(4)	(5)
dig	0.550** (2.32)	0.511** (2.41)	0.451** (2.39)	0.502*** (2.66)	0.450** (2.51)
dop		0.407 (0.83)	0.0001 (0.77)	0.0001 (0.80)	0.0001 (0.99)
gov			−0.732*** (−6.76)	−0.741*** (−6.71)	−0.255*** (−3.16)
ui				0.140* (1.82)	0.101 (1.54)
lnprgdp					0.216*** (13.01)
Constant term	0.175*** (24.55)	0.125** (2.02)	0.232*** (3.26)	−0.086 (−0.46)	−2.309*** (−9.48)
City FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Observations	1850	1850	1850	1850	1850
R^2	0.538	0.541	0.583	0.586	0.692

*P < 0.10, **P < 0.05,***P < 0.01; Values in parentheses are t-statistics.

TABLE 6 Regression results of endogeneity treatment.

Variable	First stage	Second stage
	DID	UEI
	(1)	(2)
DID		0.106** (2.30)
iv	−110.420*** (−4.48)	
Control Variables	Yes	Yes
City FE	Yes	Yes
Year FE	Yes	Yes
Observations	1850	1850
Non-identification Test	13.58 [0.000 2]	
Weak Identification Test	20.09 [16.38]	

*P < 0.05, ***P < 0.01; Values in parentheses are t-statistics. In column (1) of Table 4, for the test of the null hypothesis "the instrumental variable is not identifiable," the P-value of the Kleibergen-Paap rk LM, statistic is 0.00, significantly rejecting the null hypothesis. In the weak identification test of the instrumental variable, the Kleibergen-Paap rk Wald F statistic is greater than the critical value of 16.38 at the 10% level of the Stock-Yogo weak identification test.

TABLE 7 Mechanism test regression results.

Variable	Elc	UEI	gp	UEI
	(1)	(2)	(3)	(4)
DID	2.816*** (3.03)	0.011** (2.05)	0.042** (2.04)	0.042*** (32.42)
elc		0.001*** (3.15)		
gp				0.002*** (3.46)
Control Vars	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Constant	−6.057 (−0.24)	−1.706*** (−9.86)	0.866 (1.08)	−2.079*** (−41.19)
Observations	1850	1850	23,620	23,620
R^2	0.410	0.779	0.075	0.809

P < 0.05, *P < 0.01; Values in parentheses are t-statistics.

Baron and Kenny (1986), this study tests the underlying mechanisms.

$$M_{it} = \alpha_0 + \beta DID + \gamma Control_{it} + \mu_i + \varphi_t + \varepsilon_{it} \tag{3}$$

$$UEI_{it} = \alpha_0 + \beta DID + \theta M_{it} + \gamma Control_{it} + \mu_{it} + \varphi_t + \varepsilon_{it} \tag{4}$$

Where: M_{it} represents the mechanism variables, measured by household electricity consumption (*elc*) and enterprise green product innovation (gp), reflecting green consumer behavior and green products in the market.

The results, shown in Table 7, indicate that digital infrastructure promotes household consumption transformation, thus enhancing total factor carbon emission performance. Digital infrastructure increases residential electricity consumption, and this increase contributes to better carbon performance. This suggests that as digital infrastructure construction advances, residents adopt more digitalized lifestyles, shifting from traditional chemical energy to electricity. Changes in energy consumption structures directly impact total carbon emission performance, showing that the transformation of consumer behavior acts as a partial mediator in the influence of digital infrastructure, supporting Hypothesis 2.

When exploring the mediation effect of enterprise green product innovation, the data was matched further, incorporating firm-level control variables and encompassing 185 cities with 3,203 listed companies from 2010 to 2019, totaling 23,620 data entries. The results, presented in columns (3) and (4) of Table 7, reveal that digital infrastructure fosters green product innovation among enterprises, subsequently improving total factor carbon emission performance. Thus, enterprise green product innovation partially mediates the relationship between digital infrastructure and carbon performance, confirming Hypothesis 3.

In the market, digital infrastructure enhances consumer engagement in green consumption and increases the preference for green products, reducing pollution from consumer activities. Simultaneously, it stimulates enterprise innovation in green products, reducing production-side pollution. There is a reciprocal influence between consumers' green behaviors and enterprises' green products. Enterprises' green products influence consumer purchasing behavior, reshaping consumption patterns. Conversely, consumer demand for green products drives enterprises toward transformation, increasing their investment in and output of green products. Consumer oversight also influences enterprises to adopt greener production methods. Therefore, digital infrastructure indirectly promotes urban total factor carbon emission performance by creating a self-reinforcing cycle of green production and consumption in the market.

6.2 Heterogeneity analysis

To further investigate the potential heterogeneity in the enhancement of urban total factor carbon emission performance by digital infrastructure across various levels, the article explores from the perspectives of consumers and enterprises. Considering that residents' green consumption behaviors and concepts are related to real economic conditions, the article incorporates the heterogeneity of residents' income levels for analysis; at the same time, residents' green consumption concepts and their acceptance and usage of digital infrastructure are acquired by learning, with high quality and level often achieved through learning and training, thus the level of education of residents is taken as another grouping condition for the heterogeneity analysis of consumers. From the perspective of enterprises, the extent to which enterprises accept and use digital infrastructure and their pursuit of green products are often related to corporate management and production technology levels, therefore, enterprise ownership and technological level are taken as grouping conditions for the heterogeneity analysis from the enterprise perspective.

The heterogeneous results of the "Broadband China" strategy on total factor carbon emission performance are shown in Table 8. Based on the disposable income of urban residents, cities are categorized into high-income and low-income groups. Cities with a disposable income above the mean are designated as high-income cities, while those below are considered low-income cities. Through heterogeneity analysis using interaction terms, it can be seen that digital infrastructure is more effective in improving total factor

TABLE 8 Heterogeneity analysis regression results.

Variable	Income leve heterogeneity	Education level heterogeneity	Ownership heterogeneity	Technology level heterogeneity
	(1)	(2)	(3)	(4)
DID × dpi	0.034*** (4.61)			
DID × learn		0.028** (2.05)		
DID × soe			−0.007* (−1.82)	
DID × hte				0.010** (2.57)
Control Vars	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Constant	−2.407 (−9.87)	−2.343*** (−9.65)	−0.671 (−4.18)	−0.675 (−4.19)
Observations	1850	1850	23,620	23,620
R^2	0.697	0.696	0.721	0.722

*P < 0.10, **P < 0.05, ***P < 0.01; Values in parentheses are t-statistics.

carbon emission performance in high-income cities compared to low-income cities.

Due to data availability, the number of local university students is used as a proxy for residents' education level. Cities with a student population above the mean are considered high-education cities, and those below are low-education cities. As shown in column (2) of Table 8, digital infrastructure has a more significant impact on improving total factor carbon emission performance in high-education cities compared to low-education cities. This may be because consumers' application of data elements and their low-carbon behaviors are related to their education levels. Consumers with higher education levels tend to have better low-carbon literacy and engage in more environmentally friendly behaviors.

Therefore, digital infrastructure construction can effectively improve urban total factor carbon emission performance by influencing residents' consumption behavior transformation, especially when combined with high income and education levels of urban residents. Meanwhile, higher education and income levels of residents can influence their consumption patterns in terms of thinking and behavior, further promoting green development in cities.

From the perspective of businesses, the heterogeneous effects of digital infrastructure on total factor carbon emission performance are shown in columns (3) and (4) of Table 8. Enterprises are classified into state-owned and non-state-owned enterprises, as well as high-tech and non-high-tech industry enterprises, based on ownership and industry. The results indicate that digital infrastructure has a more pronounced effect on promoting total factor carbon emission performance in non-state-owned enterprises and high-tech industry enterprises compared to state-owned enterprises and non-high-tech industry enterprises. This may be due to the higher flexibility and autonomy of non-state-owned enterprises in rule-making, allowing for more flexible application of digital infrastructure and greater carbon reduction effects. On the other hand, high-tech industry enterprises enjoy more policy subsidies and technical support than non-high-tech industry enterprises, and they have advantages in talent and technology application. Therefore, the application of data elements such as digital infrastructure has a greater impact on high-tech industry enterprises, potentially promoting green product innovation and improving total factor carbon emission performance to a greater extent.

7 Conclusion and policy recommendations

Balancing economic development and ecological protection is a critical challenge faced by countries worldwide. Digital infrastructure contributes to economic growth while simultaneously generating positive environmental effects. This study uses the "Broadband China" strategy as a quasi-natural experiment, analyzing panel data from 185 cities between 2010 and 2019. By applying the Difference-in-Differences (DID) model, the study examines the impact of digital infrastructure, represented by the "Broadband China" strategy, on urban total factor carbon emission performance. The analysis includes both enterprise and consumer perspectives to explore the internal mechanisms of this impact. The main conclusions are as follows:

(1) Digital infrastructure, represented by the "Broadband China" strategy, significantly enhances urban total factor carbon emission performance. This conclusion holds after a series of robustness tests and treatments for endogeneity.
(2) Mechanism tests indicate that the "Broadband China" strategy improves urban carbon performance by promoting green product innovation among enterprises and encouraging the green transformation of consumer behaviors.
(3) Heterogeneity tests show that from the consumer perspective, digital infrastructure more effectively enhances total factor carbon emission performance in regions with higher resident income and education levels. From the enterprise perspective, digital infrastructure has a more substantial impact on non-state-owned enterprises and high-tech enterprises compared to state-owned and non-high-tech enterprises.

Compared with previous studies, this paper through the empirical analysis affirmed the digital infrastructure in improving the positive role of urban carbon performance, which is consistent with the studies of Chang et al. (2024). The micro subject production-trade-consumption cycle process has carried on the preliminary analysis, the enterprise green product innovation and green consumption into the research framework, put forward the enterprise production and consumption micro main body plays an important role under the macro policy, which is some additions to the existing literature in this paper.

7.1 Policy implications:

Based on the above conclusions, the study offers the following policy recommendations.

(1) Strengthen Digital Infrastructure Construction to Support Green Urban Transformation: Governments should promote the construction of next-generation digital infrastructure, such as 5G, big data, and artificial intelligence. By increasing investment in digital infrastructure, governments can stimulate domestic demand and drive economic growth. Expanding support for digital resources will amplify their role as substitutes for traditional inputs. Digital infrastructure significantly boosts urban total factor carbon emission performance. Given China's industrial structure, economic growth tends to impact the environment; therefore, leveraging digital elements' environmental advantages can help achieve economic growth while reducing pollution, aligning ecological and economic goals. For developing countries, enhancing digital infrastructure can foster both digital economic growth and green development within resource constraints. China is now combining digitization with computing power and electricity, putting forward policies such as "east digitization and west calculation" to address regional differences. It means digital infrastructure construction will be conducive to urban development in the new era, and combine digital infrastructure construction with other production factors may have a more far-reaching impact on the green development of cities.

(2) Recognize the Roles of Micro-Entities in the Context of Macro Policies: In designing and implementing policies, it is crucial to consider local conditions and allow for flexibility and autonomy. Governments should support enterprises in upgrading and transitioning to greener models, enhance regulatory oversight, and offer greater support to low-energy, low-pollution companies. High-pollution enterprises should undergo targeted reforms. Increased support for non-state-owned and high-tech enterprises is essential, recognizing their vital role in digital-driven carbon reduction.

(3) Emphasize Consumer Engagement and Education for Sustainable Consumption: Governments should collaborate with community organizations to enhance residents' disposable incomes and educational levels, fostering environmental awareness and encouraging green consumption habits. Publicity efforts and incentives for sustainable consumer behavior should be strengthened to reshape consumption patterns. By influencing consumer demand, governments can phase out low-carbon performance industries and enterprises, enhancing overall urban carbon performance. The circular interaction between green production and consumption behaviors, reinforced by government influence, can significantly improve urban total factor carbon emission performance.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/supplementary material.

Author contributions

YZ: Conceptualization, Project administration, Writing–review and editing. HS: Conceptualization, Methodology, Writing–original draft. MJ: Conceptualization, Methodology, Writing–review and editing. SC: Writing–review and editing. XS: Writing–review and editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/journals/environmental-science/articles/10.3389/fenvs.2025.1506012/full#supplementary-material

References

Aghion, P., Bloom, N., Blundell, R., Griffith, R., and Howitt, P. (2005). Competition and innovation: an inverted-U relationship. *Q. J. Econ.* 120, 701–728. doi:10.1093/qje/120.2.701

Ang, B. W. (1999). Is the energy intensity a less useful indicator than the carbon factor in the study of climate change? *Energy Policy* 27, 943–946. doi:10.1016/s0301-4215(99)00084-1

Avom, D., Nkengfack, H., Fotio, K. H., and Totouom, A. (2020). ICT and environmental quality in Sub-Saharan Africa: effects and transmission channels. *Technol. Forecast. and Soc. Change* 155, 120028. doi:10.1016/j.techfore.2020.120028

Bai, C., Du, K., Yu, Y., and Feng, C. (2019). Understanding the trend of total factor carbon productivity in the world: insights from convergence analysis. *Energy Econ.* 81, 698–708. doi:10.1016/j.eneco.2019.05.004

Baron, R. M., and Kenny, D. A. (1986). The moderator–mediator variable distinction in social psychological research: conceptual, strategic, and statistical considerations. *J. Personality Soc. Psychol.* 51, 1173–1182. doi:10.1037/0022-3514.51.6.1173

Beck, T., Levine, R., and Levkov, A. (2010). Big bad Banks?The winners and losers from bank deregulation in the United States. *J. Finance* 65, 1637–1667. doi:10.1111/j.1540-6261.2010.01589.x

Chang, X., Li, J. Y., and Zheng, Q. (2024). Does new-type infrastructure improve total factor carbon productivity? Experimental evidence from China. *J. Clean. Production142620-* 460, 142620. doi:10.1016/j.jclepro.2024.142620

Chiou, T., Chan, K. H., Lettice, F., and Chung, S. H. (2011). The influence of greening the suppliers and green innovation on environmental performance and competitive advantage in Taiwan. *Transp. Res. Part E* 47, 822–836. doi:10.1016/j.tre.2011.05.016

Du, Y., Zhou, J., Bai, J. C., and Cao, Y. (2023). Breaking the Resource Curse: the perspective of improving carbon emission efficiency based on digital infrastructure construction. *Resour. Policy* 85, 103842. doi:10.1016/j.resourpol.2023.103842

Fang, F. Q., Tian, G., and Zhang, X. (2023). Digital infrastructure and intergenerational income mobility. *Econ. Res. J.*

Fu, H., Zheng, C., and Yang, P. Y. (2024). Digital inclusive finance and green transformation of manufacturing enterprises: empirical analysis based on the dual perspectives of demand and supply. *Technol. Forecast. and Soc. Change* 200, 123152. doi:10.1016/j.techfore.2023.123152

Ge, W., Xu, Y., Liu, G., Shen, B., Su, X., Liu, L., et al. (2022). Exploring the impact of the digital economy on carbon emission efficiency under factor misallocation constraints: new insights from China. *Front. Environ. Sci.* 10. doi:10.3389/fenvs.2022.953070

Gong, M., Zeng, Y., and Zhang, F. (2023). New infrastructure, optimization of resource allocation and upgrading of industrial structure. *Finance Res. Lett.* 54, 103754. doi:10.1016/j.frl.2023.103754

Guo, B., Hu, P., and Lin, J. (2024). The effect of digital infrastructure development on enterprise green transformation. *Int. Rev. Financial Analysis* 92, 103085. doi:10.1016/j.irfa.2024.103085

Han, D. R., Ding, Y. Y., Shi, Z. Y., and He, Y. (2022). The impact of digital economy on total factor carbon productivity: the threshold effect of technology accumulation. *Environ. Sci. Pollut. Res. Int.* 29 (37), 55691–55706. doi:10.1007/s11356-022-19721-x

Haseeb, A., Xia, E., Saud, S., Ahmad, A., and Khurshid, H. (2019). Does information and communication technologies improve environmental quality in the era of globalization? *Environ. Sci. Pollut. Res. Int.* 26 (9), 8594–8608. doi:10.1007/s11356-019-04296-x

Hu, J., Zhang, H., and Irfan, M. (2023). How does digital infrastructure construction affect low-carbon development? *J. Clean. Prod.* 396, 136467. doi:10.1016/j.jclepro.2023.136467

Khazzoom, J. D. (1980). Economic implications of mandated efficiency in standards for household appliances. *Energy* 1, 21–40. doi:10.5547/ISSN0195-6574-EJ-Vol1-No4-2

Kou, J. L., and Xu, X. G. (2022). Does internet infrastructure improve or reduce carbon emission performance? *J. Clean. Prod.* 379, 134789. doi:10.1016/j.jclepro.2022.134789

Lan, M. D., and Zhu, Y. K. (2023). Digital infrastructure construction, carbon total factor productivity, and carbon rebound effect. *Environ. Sci. Pollut. Res. Int.* 30 (38), 88968–88985. doi:10.1007/s11356-023-28738-9

Li, H., Zhang, Y., and Li, Y. (2024). The impact of the digital economy on the total factor productivity of manufacturing firms: empirical evidence from China. *Technol. Forecast. and Soc. Change* 207, 123604. doi:10.1016/j.techfore.2024.123604

Liu, W., Naseem, M. A. N., and Mazlan, S. N. (2024). Research on the impact of digital economy on green total factor productivity: theoretical mechanism and multidimensional empirical analysis. *Front. Environ. Sci.* 12. doi:10.3389/fenvs.2024.1383764

Lu, F. Z., Li, Z. W., and Zhang, S. (2023). Does digital finance development affect carbon emission intensity: evidence from China. *Int. Rev. Econ. Finance* 88, 1272–1286. doi:10.1016/j.iref.2023.07.036

Ma, X. P. (2020). The transformation of household consumption in the digital economy era. *Finance and Econ. Sci.*

Peng, H. R., Ke, L., and Zhang, Y. J. (2024). The carbon emission reduction effect of digital infrastructure development: evidence from the broadband China policy. *J. Clean. Prod.* 434, 140060. doi:10.1016/j.jclepro.2023.140060

Peng, Y., Wang, W., Zhen, S., and Liu, Y. (2024). Does digitalization help green consumption? *J. Retail. Consumer Serv.* 79, 103843. doi:10.1016/j.jretconser.2024.103843

Ru, H. C., and Deng, F. (2023). Economic growth effects of digital consumption. *China Circ. Econ.* 37 (11), 61–75. doi:10.14089/j.cnki.cn11-3664/f.2023.11.006

Salahuddin, M., and Alam, K. (2015). Internet usage, electricity consumption and economic growth in Australia: a time series evidence. *Telematics Inf.* 32 (4), 862–878. doi:10.1016/j.tele.2015.04.011

Shi, D., and Li, S. L. (2020). Emissions trading system and energy efficiency. *China Ind. Econ.* doi:10.19581/j.cnki.ciejournal.2020.09.001

Sun, H. Y. (2022). What are the roles of green technology innovation and ICT employment in lowering carbon intensity in China? *Resour. Conservation and Recycl.* 186, 106550. doi:10.1016/j.resconrec.2022.106550

Tang, K. J., and Yang, G. Y. (2023). Does digital infrastructure cut carbon emissions in Chinese cities? *Sustain. Prod. Consum.* 35, 431–443. doi:10.1016/j.spc.2022.11.022

Wan, S., Liu, G., and Wang, J. (2023). The impact of digital economy on total factor carbon productivity: empirical analysis based on spatial and mediating effects. *Pol. J. Environ. Stud.* 32 (4), 3809–3823. doi:10.15244/pjoes/164405

Wang, C. Q., Qi, F. Y., Liu, P. Z., Ibrahim, H., and Wang, X. (2023). The effect of the digital economy on carbon emissions: an empirical study in China. *Environ. Sci. Pollut. Res. Int.* 30 (30), 75454–75468. doi:10.1007/s11356-023-27742-3

Wang, Q., Li, J., and Ding, K. (2023). Digital infrastructure, factor allocation efficiency, and urban-rural income gap. *Statistics and Decis.* doi:10.13546/j.cnki.tjyjc.2023.09.005

Wang, W., Wang, J., and Wu, H. (2024). Assessing the impact of new digital infrastructure on enterprise green transformation. *Knowl. Econ.* doi:10.1007/s13132-024-01976-z

Wang, X. Y., and Li, J. Y. (2023). Heterogeneous effect of digital economy on carbon emission reduction. *J. Clean. Prod.* 429, 139560. doi:10.1016/j.jclepro.2023.139560

Yao, F., Lu, L., and Hong, C. (2023). Carbon emission reduction effect of digital infrastructure: from the "broadband China" strategy. *Ecol. Chem. Eng. S* 30 (2), 283–289. doi:10.2478/eces-2023-0030

Yu, J. Z., and Hu, W. Z. (2024). The impact of digital infrastructure construction on carbon emission efficiency. *J. Clean. Prod.* 448, 10. doi:10.16/j.jclepro.2024.141687

Zhang, J., Wu, G. Y., and Zhang, J. P. (2004). Estimating China's inter-provincial material capital stock. *Econ. Res. J.*

Zhou, P., Ang, B., and Han, J. (2010). Total factor carbon emission performance: a Malmquist index analysis. *Energy Econ.* 32 (1), 194–201. doi:10.1016/j.eneco.2009.10.003

Zhou, Y. C., Ma, Y. H., Jing, H. Y., Hong, Y., Zhang, Y., Ge, Y., et al. (2022). Research on the driving factors of urban electricity-related carbon emissions based on LMDI. *J. Phys.* 2401, 012028. doi:10.1088/1742-6596/2401/1/012028