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Digital economy, technology, and urban carbon emissions nexus: an investigation using the threshold effects and mediation effects tests

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Introduction: This study aims to explore the mechanisms by which the digital economy influences urban carbon emissions in China, with a particular focus on potential threshold effects and the mediating role of technology. As the digital economy grows, it impacts various environmental metrics, including carbon emissions, necessitating a deeper understanding of its nonlinear dynamics and implications for sustainable urban development.

Methods: Using panel data from 286 prefecture-level cities in China spanning from 2012 to 2021, we apply threshold effect models and mediation effect tests. The threshold effect model is employed to investigate non-linear characteristics of the digital economy's impact on carbon emissions, while the mediation effect model assesses the role of technology as an intermediary in this relationship.

Results: The threshold effect model reveals a single threshold in the impact of the digital economy on urban carbon emissions, indicating a nonlinear relationship. Initially, the influence of the digital economy on emissions is weak, but as the digital economy develops, its effect becomes more pronounced. The mediation effect model demonstrates that technological advancement can offset the increase in emissions associated with digital economic growth, thus showcasing technology's potential to mitigate environmental impacts.

Discussion: The findings suggest that while the digital economy generally promotes urban carbon emissions, its impact is non-linear and mitigatable through technological innovation. To curb emissions in urban areas, fostering technological innovation and supporting green technology research and development are critical. Moreover, enhancing management and supervision within the digital economy sector can contribute to balancing economic growth with environmental goals. These insights are valuable for policymakers striving to harmonize digital economic expansion with sustainable environmental practices.

KEYWORDS
digital economy, carbon emissions, threshold effects, mediation effect, China

1 Introduction

As global climate change worsens, "carbon reduction" has become both a shared obligation and a challenge for nations worldwide. In recent years, with the continuous advancement of new-type urbanization and industrialization, most countries, including China, have witnessed a continuous increase in energy demand, leading to a rising trend in carbon dioxide emissions. Consequently, the Chinese government has proposed strategic goals to achieve carbon peaking by 2030 and carbon neutrality by 2060. Cities, being the "main battleground" for promoting China's green and low-carbon transformation and high-quality economic development (Zhao et al., 2023; Wang et al., 2019), have become a significant topic of concern regarding how to effectively curb urban carbon emissions (Shang and Luo, 2021).

In urban carbon emissions, academia has conducted extensive theoretical and empirical research on influencing factors. Prior studies have identified several effective means of reducing carbon emissions, including economic development level, industrial structure, population size, and energy structure. Furthermore, scholars have evaluated the carbon reduction effects of policy-related factors such as low-carbon pilot policies (Zhang and Feng, 2021), energy-consuming rights trading policies (Wang M. et al., 2024), and eco-province construction.

Recent research has expanded our understanding of various factors influencing carbon emissions. For instance, Elahi et al. (2024a) examined the decoupling of livestock and poultry pollution emissions from industrial development, while Elahi et al. (2024b) analyzed carbon emission efficiency in food production across the Yangtze River basin. Huang et al. (2024) investigated the impact of aging rural populations on agricultural carbon emissions in China, highlighting the importance of demographic shifts in land use policy. These studies underscore the complexity of carbon emission sources and the need for targeted policies across different sectors.

Concurrently, China has been experiencing rapid development in its digital economy. The digital economy, as an emerging industry, has the potential to play a crucial role in supporting carbon reduction and sustainable urban development (Yan and Zhang, 2023). However, the relationship between the digital economy and carbon emissions is complex and multifaceted, warranting further investigation. Existing literature on the relationship between the digital economy and carbon emissions presents two primary perspectives.

Firstly, the digital economy contributes to carbon emission reduction. Studies have shown that the digital economy affects carbon emissions through "digital industrialization" and "industrial digitization," with "digital industrialization" contributing more significantly to emission reduction. Research by Xie (2022) and Tian and Meng (2023) found that the digital economy can dramatically reduce carbon emission intensity across different regions by improving energy structure and technological advancement. Ge et al. (2022) noted that the digital economy promotes industrial structural transformation, thereby improving urban energy efficiency to achieve carbon reduction goals. Zha et al. (2022) highlighted how the expansion of the digital economy improves the attraction of cities to rural labor and businesses, offering advantageous economies of scale for energy conservation and emission reduction. Furthermore, Xu et al. (2022) and Xu et al. (2024a) observed that the rise of the digital economy not only supports the fall of carbon emissions locally but also helps reduce carbon emissions in surrounding cities, albeit with boundary effects in its spatial spillover effects. Recent studies have provided additional insights into this perspective. Jiang et al. (2024) explored how the digital economy encourages sustainable consumption and reduces carbon emissions. Guo et al. (2024b) examined the effect of digital infrastructure development on enterprise green transformation, while Zhao et al. (2024b) investigated enterprise pollution reduction through digital transformation in Chinese manufacturing enterprises. These studies collectively suggest that digitalization can be a powerful tool for environmental sustainability.

Secondly, the digital economy does not result in considerable environmental gains. Contrasting studies suggest that the digital economy has not led to significant environmental improvements in terms of carbon emissions. Tian and Meng (2023) found that in terms of digital products and new infrastructure, the digital economy lacks environmentally favorable characteristics such as green buildings and low carbon emissions. Qu et al. (2022) reported that the digital economy ranks 17th among 27 manufacturing industries in terms of carbon emissions intensity, surpassing conventional labor-intensive industries. Li et al. (2021) used the Environmental Kuznets Curve (EKC) as a theoretical framework to affirm the presence of an EKC curve within the realm of the digital economy. Lujun et al. (2022) pointed out that while the digital economy has a simple carbon reduction effect, it also has a "green blind spot." Wang and Zhu (2021) highlighted that while digital infrastructure development directly increases overall energy consumption, the digital economy also has the ability to conserve energy and reduce emissions at the micro level, leaving the overall influence on energy usage unclear. More recent research has added nuance to this perspective. Li et al. (2023) examined the carbon emissions of 5G mobile networks in China, highlighting the environmental challenges posed by new digital technologies. Similarly, Li and Li (2023) explored the potential of artificial intelligence in reducing carbon emissions from 5G networks, suggesting that technological advancements within the digital economy could mitigate its environmental impact.

Recent research has expanded into various aspects that indirectly influence the digital economy-carbon emissions relationship. Zhang et al. (2023) proposed a new structural economic growth model considering labor income share, which could impact carbon emissions through economic dynamics. In the realm of organizational behavior, Zhu et al. (2023) and Jabeen et al. (2024) (Jabeen et al., 2024) explored the roles of leadership and human resource management in environmental performance, highlighting the importance of human factors in sustainability efforts. Yin et al. (2019) demonstrated the application of advanced analytical methods in performance evaluation, which could be extended to assess the environmental impact of digital technologies. Feng et al. (2024) conducted a life cycle cost analysis of power generation with carbon capture and storage, providing insights into the economic feasibility of emission reduction technologies. Huang et al. (2021) and Jiang et al. (2024) focused on ecological security patterns and the digital economy's role in encouraging sustainable consumption, respectively. Li and Yue

(2024) analyzed energy demand and emissions in the urban transport sector, while Wang (2023) examined the broader implications of digitalization for climate change adaptation in China. These diverse studies underscore the complexity of the digital economy-carbon emissions nexus and the need for interdisciplinary approaches in addressing environmental challenges.

The literature also reveals emerging areas of research that bridge the gap between these two perspectives. For instance, Fan et al. (2024) analyzed how digitalization drives the green transformation of supply chains, proposing a two-stage evolutionary game analysis. Xu H. et al. (2024) investigated the influence of fintech, digitalization, and green technologies on sustainable environments in CIVETS nations. These studies suggest that the relationship between digital economy and carbon emissions is not binary but rather complex and context-dependent.

Furthermore, previous literature focused into related areas that indirectly impact the digital economy-carbon emissions nexus. For example, Zhao et al. (2024a) examined the role of CEOs' information technology backgrounds in driving digital technology innovation. Zheng and Chen (2023) revisited the linkage between financial inclusion and energy productivity, considering technology implications for climate change. These studies highlight the importance of human factors and financial systems in shaping the environmental impact of the digital economy.

Despite this rich body of research, several gaps remain. First, there is a lack of comprehensive studies that examine the threshold effects of digital economy development on carbon emissions, particularly in the context of rapidly developing economies like China. Second, while many studies have explored direct relationships, few have investigated the potential mediating role of technology in the digital economy-carbon emissions relationship. Lastly, there is a need for more research that synthesizes insights from various sectors and approaches to provide a holistic understanding of how digital transformation can be leveraged for environmental sustainability.

Given these research gaps, this paper aims to contribute to the ongoing debate by focusing on the following aspects:

- It explores the mechanism of how the digital economy affects urban carbon emissions, as well as the characteristics of the impact of different levels of digital economy development on urban carbon emissions. This provides a more complex and comprehensive perspective for understanding the relationship between the two.
- It investigates the transmission mechanism of the digital economy's impact on urban carbon emissions, selecting technology as an intermediary variable to test whether technology can offset the increase in carbon emissions caused by digital economic growth. This approach offers new ideas and methods for addressing carbon emission issues.
- By examining the impact of digital economic development on urban carbon emissions in the context of China, this paper contributes to extending China's experience to other countries and provides a reference for scientific decision-making by government departments.

While focusing on China, this study has broader international implications. As countries worldwide navigate digital transformation and climate change mitigation, understanding the relationship between digital economic growth and carbon emissions is crucial. This research provides a methodological framework and empirical insights applicable to diverse global contexts. By examining nonlinear effects and technology's mediating role, it contributes to the global discourse on leveraging digital economies for sustainable development. The findings and policy recommendations offer valuable reference points for policymakers and urban planners internationally, aiding in balancing digital innovation with environmental stewardship.

The article consists of five main sections. In the introduction, the study's background, and objectives are discussed. Following that, the theoretical analysis and hypothesis development section outlines the theoretical framework and proposes the key hypotheses that guide the research. The materials and methods section provides a detailed description of the data sources, analytical tools, and methodologies employed to conduct the study. Next, the results and discussion section presents the findings of the research and offers an in-depth analysis, comparing them with existing literature. Lastly, the conclusion and recommendations section summarize the key insights from the study, provides practical recommendations, and suggests areas for future research.

2 Theoretical analysis and hypothesis development

The relationship between the digital economy and urban carbon emissions is complex and multifaceted, as evidenced by recent literature. This complexity stems from the dual nature of digital technologies' impact on carbon emissions.

On one hand, the rapidly growing digital economy leads to widespread adoption of massive data centers, cloud computing facilities, and electronic devices. These facilities have substantial electricity requirements, primarily sourced from fossil fuels, which amplifies urban energy consumption and carbon emission levels. Li et al. (2023) quantified the carbon emissions of 5G mobile networks in China, highlighting the significant environmental impact of digital infrastructure. Additionally, the flourishing digital economy encourages the growth of carbon-intensive sectors such as transportation and industry, further raising urban carbon emissions levels (Xu et al., 2024b).

On the other hand, the growth of the digital economy also creates new opportunities to reduce carbon emissions from urban areas. Smart energy management systems, enabled by digital technologies, continuously monitor and optimize energy consumption, effectively reducing energy waste and carbon emissions (Zhao et al., 2024b). The development of the digital economy also promotes the construction of digital infrastructure, facilitating the green transformation of enterprises, thereby potentially reducing urban carbon emissions (Guo et al., 2024b). Furthermore, the digital economy fosters the creation and application of environmental protection technologies and renewable energy sources. For instance, it promotes the development of energy storage technologies and enhances the utilization of renewable energy sources such as solar and wind power, which can ultimately mitigate urban carbon emissions (Xu et al., 2024b).

Thus, the effects of the digital economy on urban carbon emissions could be both favorable and unfavorable, depending on factors such as policy reinforcement and industrial composition. This dual nature is supported by recent studies such as Jiang et al. (2024), who found that the digital economy can encourage sustainable consumption and reduce carbon emissions. Conversely, Ma et al. (2023) argued that the digital economy lacks environmentally favorable characteristics in terms of digital products and new infrastructure. Based on these contrasting findings, we propose the following competing hypotheses:

H1a: The digital economy has a positive impact on urban carbon emissions.
H1b: The digital economy has a negative impact on urban carbon emissions.

Additionally, China's stark regional development imbalance results in distinct "staircase" features at different levels of technical development across regions. This could lead to notable variations in industrial structure, degrees of digitalization, and decarbonization capabilities across different regions (Guo et al., 2024a). Such regional disparities suggest that the relationship between the digital economy and carbon emissions may not be linear. This notion is supported by studies like Li et al. (2021), who found evidence of an Environmental Kuznets Curve within the realm of the digital economy. Therefore, we posit the following hypothesis:

H2: There is a nonlinear threshold feature between the digital economy and urban carbon emissions.

The advancement of the digital economy spurs technological innovation and investment in research and development by both businesses and governments. During digital transformation, enterprises continuously explore new business models and technological applications, enhancing the quality, efficiency, and experience of their products and services through environmental information disclosure (Guo et al., 2024a). This innovation not only enhances the competitiveness of enterprises but also provides impetus for technological progress (Dong, 2023). Simultaneously, governmental intervention plays a pivotal role in fostering the digital economy's development through the formulation of pertinent policies and investment strategies (Su et al., 2021).

Digital technology facilitates collaborative research, fosters interdisciplinary cross-border innovation, and accelerates the dissemination of innovative outcomes. This open innovation model creates a more expansive platform for the advancement of scientific and technological standards. By enabling the transmission and sharing of knowledge and information, the widespread use of digital technology accelerates the diffusion and application of scientific and technical breakthroughs (Ma et al., 2024).

The development of the digital economy is largely dependent on increased investment in science and technology, innovation, and technological application across diverse domains by both governments and enterprises. This investment promotes comprehensive research, speeds up the transformation and application of scientific discoveries, and facilitates breakthroughs in key technologies within the digital economy. The resulting innovation not only creates a strong basis for the sustainable expansion of the digital economy but also enhances its industrial chain's competitiveness.

Recent studies have highlighted the role of technology as a potential mediator between the digital economy and environmental outcomes. For instance, Li and Li (2023) explored how artificial intelligence could be used to reduce the carbon emissions of 5G networks, suggesting that technological advancements within the digital economy could mitigate its environmental impact. Similarly, Fan et al. (2024) demonstrated how digitalization drives the green transformation of supply chains through technological innovation.

Considering these findings and the potential for technology to act as a bridge between digital economic growth and environmental sustainability, we propose the following hypothesis:

H3: There is a mediating effect of technology between the digital economy and urban carbon emissions.

This theoretical framework, supported by recent literature, provides a comprehensive basis for examining the complex relationship between the digital economy, technology, and urban carbon emissions in China.

3 Materials and methods

3.1 Data

The study employs panel data encompassing 286 prefecture-level cities in China spanning from 2012 to 2021. The Digital Inclusive Finance Index is sourced from the Digital Finance Research Center, Peking University. Additional pertinent data originates from the "China Urban Statistical Yearbook" (2013–2022) and statistical yearbooks of prefecture-level cities (2013–2022). Missing data are supplemented via interpolation.

3.2 Analytical framework

To investigate the direct relationship between urban carbon emissions and digital economy, this study builds the following baseline regression model (Equation 1):

$$Carbon_{it} = \alpha_0 + \alpha_1 DIGI_{it} + \alpha_2 CL_{it} + \alpha_3 EDU_{it} + \alpha_4 FGB_{it} + \alpha_5 SI_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (1)$$

where, i represents the city, t shows the year, and $Carbon_{it}$ indicates urban carbon emissions. Similarly, DIGI, CL, EDU, FGB, SI, and TECH denote the digital economy, consumption level, education, financial general budget, social insurance, and technology respectively. Moreover, μ_i represents city fixed effects, ν_t represents time-fixed effects, and ε_{it} denotes the random error term, assumed to be normally distributed at zero mean value and constant variance.

TABLE 1 Evaluation index system of the digital economy.

Index	Descriptions	Expected signs
Internet Penetration Rate	Number of internet users per hundred population	+
Number of Internet-related Employees	Proportion of employees in computer services and software	+
Output Related to Internet	Per capita total volume of telecommunications services	+
Number of Mobile Internet Users	Number of mobile phone users per hundred population	+
Development of Inclusive Digital Finance	Digital Inclusive Finance Index	+

To explore the possibility of a nonlinear threshold feature regarding the technological level between the digital economy and carbon emissions, this study establishes a threshold model based on Hansen's panel threshold model (Hansen, 1999). The single threshold model can be written as (Equation 2):

$$\begin{aligned} Carbon_{it} = \theta_0 + \theta_1 CL_{it} + \theta_2 EDU_{it} + \theta_3 FGB_{it} + \theta_4 SI_{it} \\ + \varphi_1 DIGI_{it} \times I(DIGI_{it} \leq \pi_1) \\ + \varphi_2 DIGI_{it} \times I(DIGI_{it} > \pi_1) + \mu_i + \nu_t + \varepsilon_{it} \end{aligned} \tag{2}$$

where θ *and* φ are the parameters to be estimated, π is the threshold value to be estimated, and I is the indicator function (I equals 1 if the expression enclosed in the parentheses is true; otherwise 0).

To further confirm the indirect impact of the digital economy on carbon emissions through technology, the study contruct a mediation effect model based on the baseline regression model:

$$\begin{aligned} TECH_{it} = \beta_0 + \beta_1 DIGI_{it} + \beta_2 CL_{it} + \beta_3 EDU_{it} + \beta_4 FGB_{it} \\ + \beta_5 SI_{it} + \mu_i + \nu_t + \varepsilon_{it} \end{aligned} \tag{3}$$

$$\begin{aligned} Carbon_{it} = \gamma_0 + \gamma_1 DIGI_{it} + \gamma_2 TECH_{it} + \gamma_3 CL_{it} + \gamma_4 EDU_{it} \\ + \gamma_5 FGB_{it} + \gamma_6 SI_{it} + \mu_i + \nu_t + \varepsilon_{it} \end{aligned} \tag{4}$$

where *TECH* stands for the intermediary variable technology. β *and* γ are parameters to be estimated. Equation 3 establishes the relationship between the digital economy and the intermediary variable, technology, while Equation 4 examines the combined effect of both on urban carbon emissions.

3.3 Description of variables

3.3.1 Dependent variable

The concept of "carbon emissions" encompasses both direct and indirect emissions, as defined by Kennedy et al. (2010) and Cong et al. (2014). Direct emissions occur within the accounting boundary, while indirect emissions result from inputs originating outside the boundary but are nonetheless contained within it.

For comprehensive carbon emissions accounting, the greenhouse gas accounting system delineates three distinct categories. Category 1 includes all direct carbon emissions stemming from energy-related activities within the boundary, such as construction, industrial processes, transportation, agriculture, and waste disposal. Category 2 covers energy-related indirect carbon emissions occurring outside the boundary, primarily comprising emissions from purchased electricity, heating, and cooling systems. Category 3 encompasses additional indirect carbon emissions from sources beyond the boundary not included in Category 2. These emissions typically arise from the production, transportation, use, and disposal of goods procured from external sources (Liu X. et al., 2024; Liu Z. et al., 2024).

In alignment with existing research methodologies, the present study adopts a comprehensive approach to urban carbon emissions, incorporating all three categories in its analysis. This holistic perspective allows for a more accurate assessment of the total carbon footprint associated with urban activities and provides a robust foundation for examining the relationship between the digital economy and urban carbon emissions.

3.3.2 Independent variables

To compute the Comprehensive Development Index of the digital economy, the study uses the index system proposed by Tao et al. (2022). The evaluation index system used in the study is given in Table 1.

3.3.3 Control variables

Four indicators namely, consumption, education, government fiscal expenditure, and social security are used as control variables as they may have a significant influence on urban carbon emissions. Consumption level is closely correlated with the lifestyle and resource usage of urban dwellers; the higher the level of consumption, the more will be energy consumption and carbon emission levels. Education level is a good indicator of the technological and environmental knowledge of the urban residents. Better education can encourage the use of environmental protection technology and raise environmental awareness which will lower carbon emissions. The amount of money the government spends on environmental preservation and carbon reduction is reflected in its fiscal expenditures; more fiscal expenditures may indicate the implementation of more environmental projects and carbon reduction initiatives. Social security may have complicated effects on carbon emissions due to its influence on people's lifestyle and productivity. A more accurate assessment of the impact of digital economy on urban carbon emissions can be obtained by controlling these variables, providing scientific support for policy formulation.

3.3.4 Mediating variables

Technology is used as a mediating variable in the study as it can help explain the mechanism through which the development of the digital economy affects urban carbon emissions. The development of a digital economy may indirectly affect urban carbon emissions by influencing technological innovation and progress (Hu et al., 2024;

TABLE 2 Descriptive statistics.

Variables	Mean	Standard deviation	Minimum	Maximum
Carbon	3,926.2845	5,086.8889	663.9600	62,600.0000
Digital economy (DIGI)	0.2363	0.0959	0.0143	0.7140
Consumption level (CL)	1,128.2893	1,617.3743	0.0238	18,080.0000
Education (EDU)	7,848.1926	10,082.3489	0.0037	114,782.9300
Financial general budget (FGB)	462.6522	688.7615	19.6245	8,430.8562
Social insurance (SI)	61.7637	126.2304	0.4000	1,359.0157
Technology (TECH)	13.0022	40.5220	0.0753	554.9817

TABLE 3 Parametric results using regression analysis.

Variables	Fixed effects	Threshold effects
Digital economy	0.5156*** (0.0430)	
Consumption level	0.0836*** (0.00919)	0.0845*** (0.00917)
Education	−0.0315** (0.0125)	−0.0298** (0.0125)
Financial general budget	0.2688*** (0.0128)	0.2649*** (0.0128)
Social insurance	−0.0965*** (0.0137)	−0.0997*** (0.0137)
C (Digital economy ≤ 0.3604)		0.4618*** (0.0453)
C (Digital economy>0.3604)		0.5661*** (0.0450)
Constant	−0.1218*** (0.0103)	−0.1114*** (0.0106)

The given values in parentheses are the standard errors. ***, and ** show significance at $p < 0.01$, and $p < 0.05$, respectively.

Xu H. et al., 2024; Dong et al., 2022; Hu et al., 2023). By offering a more thorough analysis for comprehending the mechanics behind carbon emissions, technology as a mediating variable can help uncover the pathways by which the digital economy affects urban carbon emissions.

4 Results and discussion

4.1 Summary of basic statistics

The given results in Table 2 offer an overview of various variables, focusing on their average values. Carbon emissions have an average of 3,926 units, suggesting a considerable level of emissions across the regions or sectors in question. The digital economy (DIGI) shows an average of 0.236, indicating a modest level of digitalization in the sample. For the consumption level (CL), the mean is 1,128, reflecting average consumption patterns. Education (EDU), on the other hand, stands out with a high average value of 7,848, indicating substantial investments in or access to education in some areas.

The financial general budget (FGB) averages 462, suggesting moderate financial resources across the sample, while social insurance (SI) shows a lower average of about 61, reflecting relatively limited coverage or access. Lastly, technology (TECH) averages around 13, highlighting the level of technological development within the regions being studied. This table provides a concise picture of how these variables perform on average, giving a sense of the general landscape without delving into variability or extreme values.

4.2 Baseline regression

The findings of the regression analysis presented in Table 3 indicate a considerable positive correlation between urban carbon emissions and the digital economy. Urban carbon emissions are also substantially positively associated with the level of consumption and government spending. Urban carbon emissions, on the other hand, are inversely correlated with social security and the level of education. Combining existing research, the rapid development of the digital economy often accompanies industrial expansion and increased energy consumption, especially in the production and service processes of digital technologies, which may lead to significant carbon emissions. Additionally, the rapid development of the digital economy may drive population growth and accelerate urbanization, thereby increasing urban carbon emissions.

Higher consumption levels are often associated with increased production and activities such as transportation and tourism, which can lead to greater energy use and higher carbon emissions (Tang et al., 2017). Additionally, increased fiscal expenditure tends to promote investment in urban infrastructure and the provision of public services, further driving energy consumption and contributing to carbon emissions (Elheddad et al., 2020).

TABLE 4 Results of the threshold effect test.

Variable	Type	F-value	Threshold
DIGI	Single	14.36 (0.073)*	0.3604
	Double	6.37 (0.423)	1.2839

The values in parentheses represent p-values. Moreover, * shows a significant level of parameter at $p < 0.10$.

Education is frequently linked to an individual's capacity for technological innovation and environmental awareness. People with higher levels of education are more likely to adopt cleaner energy sources, lead low-carbon lifestyles, and use environmentally friendly technologies (Sovacool et al., 2022). Moreover, a strong social security system can help reduce social instability, improve living standards, and lower excessive carbon consumption, ultimately contributing to a reduction in carbon emissions (Zhang et al., 2022).

4.3 Threshold effect

Based on the empirical analysis, it is evident that the growth of the digital economy contributes to increasing carbon emissions in cities. However, this conclusion assumes a linear relationship between the digital economy and urban carbon emissions, overlooking potential differences at various stages of economic growth. The impact on urban carbon emissions during the early and mature stages of digital economy growth may vary. To account for this, the study considers the digital economy as a threshold variable, allowing for an examination of its threshold effect on urban carbon emissions.

The results of the threshold effect test, shown in Table 4, indicate that after controlling for relevant variables, the digital economy is significant in a single threshold test. With a threshold value estimated at 0.3604, the digital economy can be categorized into a primary stage when it is below this value and into intermediate or advanced stages when it exceeds this threshold.

Threshold regression, conducted for both the primary and advanced stages of the digital economy (as seen in Table 3), reveals that the digital economy promotes urban carbon emissions in both stages. This demonstrates a nonlinear relationship between the digital economy and urban carbon emissions, supporting hypothesis H2. In the initial stages, the digital economy drives the modernization and transformation of traditional industries, leading to increased energy and resource demands, which result in higher carbon emissions. As the digital economy develops further, the adoption of clean energy and green technologies improves energy efficiency and optimizes industrial structures, gradually reducing carbon emissions. However, as the digital economy expands further, the scale of the digital industry itself may introduce new sources of energy consumption and carbon emissions, thereby amplifying its impact on urban carbon emissions once again.

4.4 A test of mediation effect

The digital economy can have both a direct and an indirect impact on urban carbon emissions, with technology serving as an intermediary (Li and Zhou, 2024). However, when using the stepwise regression method, the indirect effects of variables like technology may be underestimated, leading to bias in their estimation. To address this issue and assess the robustness of the indirect effect of technology, the Sobel-Goodman mediation effect model has been employed. The results of this mediation model, shown in Table 5, indicate that the coefficients from the Sobel, Aroian, and Goodman tests are all 0.004, confirming that the indirect effect of technology is robust and consistent with the findings from the stepwise regression method.

The analysis reveals a total effect value of −0.135, signifying a shift in the overall impact of the digital economy on urban carbon emissions when technology is considered as a mediating factor. This shift occurs because the digital economy influences technology, and the positive impact of technological advancements can offset the negative effects of the digital economy on carbon emissions (Ma et al., 2022). In other words, the overall influence of the digital economy becomes negative when accounting for technology. Technological progress can enhance urban productivity, helping to mitigate carbon emissions and counterbalance any potential increases in emissions caused by the growth of the digital economy (Wang L. et al., 2024).

With a mediation effect of approximately 2.96%, technology plays a crucial role as a mediator between the digital economy and urban carbon emissions. This underscores the importance of considering both the digital economy and technological advancements when developing policies aimed at reducing carbon emissions in urban areas. Implementing targeted policy measures that promote technological innovation is essential for addressing the environmental impacts of the digital economy and achieving sustainable urban development.

4.5 Robustness test

Robustness tests were conducted by altering econometric methods, performing trimming, and substituting core explanatory variables to more thoroughly examine the nonlinear influence of the digital economy on urban carbon emissions. Specifically, the original digital economy index was replaced with one derived through principal component analysis, and the ordinary least squares method was used for analysis instead of the fixed effects model. The robustness test results, presented in Table 6, show that the signs and significance levels of the estimated coefficients for each variable are largely consistent with the original regression results, reinforcing the reliability of the previous findings.

TABLE 5 Results of mediation effects test.

Mediation effect test	Estimate	Standard error	Z-value	*P*-value
Sobel	0.004	0.002	1.770	0.077
Aroian	0.004	0.002	1.765	0.078
Goodman	0.004	0.002	1.775	0.076
Digital Economy→Technology	0.003	0.002	1.786	0.074
Technology→Carbon	1.267	0.097	13.038	0.000
Indirect Effect	0.004	0.002	1.770	0.077
Direct Effect	−0.139	0.009	−15.989	0.000
Total Effect	−0.135	0.009	−15.121	0.000
Proportion of Mediation Effect to Total Effect			2.96%	

TABLE 6 Results of the robustness test.

Variables	Replacement of the core explanatory variables	Change measurement method	Trim treatment
Digital economy	0.0558*** (0.0041)	1.2148*** (0.1619)	0.7630*** (0.0427)
Consumption level	0.0828*** (0.0091)	−0.4916*** (0.0853)	0.1036*** (0.0091)
Education	−0.0325*** (0.0124)	0.124 (0.1812)	0.018 (0.0117)
Financial general budget	0.261*** (0.0127)	1.3971*** (0.1562)	−0.0147 (0.0151)
Social insurance	−0.0946*** (0.0135)	−0.2996*** (0.1139)	0.1093*** (0.0116)
Constant	0.0000 (0.0015)	−0.2870*** (0.0401)	−0.1966*** (0.0103)
R^2	0.5749	0.7819	0.4936

The given values in parentheses are the standard errors. Moreover, *** shows a significant level of parameters at $p < 0.01$.

5 Conclusion and recommendations

This study aimed to investigate the complex relationship between the digital economy and urban carbon emissions in China, focusing on potential threshold effects and the mediating role of technology. Using panel data from 286 prefecture-level cities in China from 2012 to 2021, we employed threshold models and mediation effect tests to analyze this relationship.

The empirical findings reveal several key insights. First, the growth of the digital economy is associated with an increase in urban carbon emissions. However, this relationship is not linear. The threshold effect model indicates a nonlinear threshold characteristic between the digital economy and urban carbon emissions, exhibiting a pattern that is initially weak and then strengthens. This suggests that the impact of digital economic development on carbon emissions varies at different stages of digital maturity.

Furthermore, the analysis demonstrates that technology plays a significant mediating role between the digital economy and urban carbon emissions. This finding suggests that technological advancements have the potential to offset the increase in carbon emissions caused by the growth of the digital economy. This highlights the crucial role of innovation and technological progress in mitigating the environmental impact of digital economic development. These results have important implications for policymakers and urban planners in China and potentially other rapidly digitalizing economies. To counteract the nonlinear influence of the digital economy on urban carbon emissions, we propose several focused intervention measures:

Governments should vigorously promote the development of the digital economy while simultaneously optimizing the performance of digital infrastructure and specialized equipment. This should be coupled with increased investment in green technology research and development, encouraging firms to adopt clean production technologies and environmentally friendly equipment. Policymakers should formulate and implement policies that encourage the use of renewable energy sources such as solar and wind power. Financial incentives and favorable policies should be offered to lower the cost of renewable energy adoption.

A reasonable system of carbon emission trading and quotas should be established, along with an integrated energy management and control platform to strengthen the supervision of corporate carbon emissions behaviors. This platform should leverage digital technologies for monitoring, measurement, prediction, and efficiency enhancement of carbon emissions. Urban planning should be optimized to carry out green transformations in key carbon emission sectors such as transportation and industrial manufacturing. Public awareness of environmental protection should be enhanced through the promotion of green and low-carbon travel and products.

To address the mediating impact of scientific and technological factors, governments and enterprises should increase investments in scientific and technological innovation and green technologies. This involves fostering a symbiotic relationship between the digital economy and scientific advancements to achieve carbon emission reduction. A comprehensive system for the precise transformation of traditional industries with high energy consumption should be established. This includes regulating the direction of technological innovation, establishing a technology assessment mechanism, and evaluating the environmental impact of digital economy projects.

This study's insights extend beyond China, offering global relevance. The findings and recommendations can inform international policies balancing digital economic growth with environmental sustainability, especially in rapidly developing economies facing similar challenges.

While the study provides valuable insights, it is not without limitations. Firstly, due to data availability, our analysis is based solely on data from China. The applicability of our findings to other countries with different economic and environmental conditions remains to be tested. Secondly, while we focused on the mediating effect of technology, there may be other potential influencing factors that were not considered in this study.

For future research, we recommend several directions. The scope of the study should be expanded to include data from other countries, allowing for comparative analysis and assessment of the validity and universality of our conclusions across different economic and environmental contexts. Other potential mediating or moderating factors in the relationship between the digital economy and urban carbon emissions, such as institutional quality, industrial structure, or urban density, should be investigated.

In-depth case studies of cities that have successfully balanced digital economic growth with carbon emission reduction could be conducted to identify best practices and transferable strategies. The long-term dynamics of the relationship between digital economy development and carbon emissions should be explored, potentially using longer time series data and more advanced econometric techniques. Lastly, future research could investigate the specific mechanisms through which different aspects of the digital economy (e.g., e-commerce, smart city initiatives, Industry 4.0) impact carbon emissions.

By addressing these research directions, future studies can build upon our findings and provide a more comprehensive understanding of how to leverage digital economic development for sustainable urban growth and effective carbon emission reduction. This knowledge will be crucial as countries worldwide strive to balance economic development with environmental sustainability in an increasingly digital age.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

PS: Writing–original draft, Writing–review and editing. UN: Writing–original draft, Writing–review and editing. ZQ: Writing–original draft, Writing–review and editing. SA: Writing–original draft, Writing–review and editing. KK: Writing–original draft, Writing–review and editing. AAB: Funding acquisition, Writing–original draft, Writing–review and editing. MA: Conceptualization, Formal analysis, Writing–original draft, Writing–review and editing.

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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.

Publisher's note

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