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Can the Digital Economy Enable Carbon Emission Reduction: Analysis of Mechanisms and China's Experience

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Abstract: With the continuous advancement of global scientific and technological capabilities, the issue of global warming caused by greenhouse gas emissions has received widespread attention from countries worldwide. Promoting carbon reduction and curbing the trend of global warming have become urgent and significant challenges for China and the world. Therefore, it is of great practical significance to explore the impact and mechanism of the digital economy on carbon reduction. This paper empirically analyzes the impact and means of the digital economy on carbon emissions using panel regression models and mediation effect models. The research indicates that the digital economy significantly impacts carbon emissions, and the following main conclusions are drawn: (1) The influence of the digital economy on carbon intensity exhibits an inverted U-shaped curve, starting with promotion and then inhibition. (2) The digital economy can affect carbon emissions through industrial structural upgrading and technological innovation. (3) Regions with a relatively high level of digital economy development also tend to have higher energy utilization efficiency, leading to a more pronounced impact of the digital economy on carbon emissions levels.

Keywords: digital economy; carbon reduction; mediating effects; heterogeneity

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1. Introduction

The world is entering a new era of vigorous development in science, technology, and the digital economy. The continuous growth of the digital economy not only strengthens political, economic, and cultural exchanges between countries but also enhances the level of digital industrialization in each nation [1]. Simultaneously, Digital technologies combined with the workforce, capital, and land as a new factor, gradually transforming traditional industries into digitalized and intelligent ones [2,3]. China has formed a horizontally interconnected and vertically integrated strategic system for the digital economy. According to the "China Digital Economy Development Report" published by the China Academy of Information and Communications Technology in 2022, China achieved breakthroughs in digital economy development in 2021. The scale of the digital economy has reached 45.5 trillion yuan, with a year-on-year nominal growth of 16.2%, surpassing the nominal GDP growth rate by 3.4 percentage points. Its share of GDP has reached 39.8% [4]. It is evident that the position of the digital economy in China's national economy is more solid, and its supportive role is more prominent. In the same year, China's digital industrialization scale reached 8.4 trillion yuan, with a year-on-year nominal growth of 11.9%, accounting for 7.3% of GDP, which remained relatively stable compared to the previous year. Therefore, the development of China's digital economy has significant implications for the digital transformation of traditional industries [5]. In the face of the flourishing development of the digital economy worldwide, General Secretary Xi Jinping has repeatedly emphasized the need to "expand and strengthen the digital economy" and accelerate the construction of a "Digital China" [6].

With the rapid development of the digital economy, many countries have completed their industrialization tasks. However, at the current stage, China is undergoing urbanization and industrialization, characterized by high energy consumption. Although China's economic development has entered the "new normal" stage, it is increasing. As a result, the energy demand brought about by industrialization and urbanization is still growing, leading to long-term pressure on carbon emissions reduction in the country [7–9]. To reduce carbon emissions, the country has set numerous strategic goals. For instance, General Secretary Xi Jinping proposed the "dual carbon" goal during the general debate of the 75th session of the United Nations General Assembly in September 2020. The goal is to strive for peak carbon dioxide emissions before 2030 and achieve carbon neutrality by 2060 [10]. The "dual carbon" goal presents a formidable challenge for China and the world at this stage, holding extraordinary significance for developing China's green economy and establishing a community with a shared future for humanity. Achieving this goal requires a series of extensive and profound economic transformations and the collective efforts of the entire society and even the entire human race. Meanwhile, the digital economy is accelerating its integration with traditional industries and playing a crucial role in addressing climate change and resolving the contradictions between economic growth and environmental constraints [11]. The digital economy can leverage digital technologies such as big data and artificial intelligence to facilitate green industrial transformation and address carbon emissions issues. With the innovation and advancement of digital technologies, the digital economy also plays a crucial role in energy conservation and emission reduction. Therefore, the role of digitization in achieving the "dual carbon" goals has gradually garnered widespread attention [12–14]. So, can the digital economy drive carbon reduction? If so, what is the mechanism behind its role? In addition, does the carbon reduction effect of the digital economy exhibit heterogeneity across different spatial distributions? Addressing these questions will help us gain a deeper understanding of the relationship between the digital economy and carbon emissions and thus facilitate more efficient achievement of the "dual carbon" goals.

In summary, this article mainly explores the mechanisms and impact of the digital economy on carbon emissions from the perspectives of mechanism analysis and China's experience. Therefore, the content is divided into five parts. The first section is the introduction, which briefly describes the current development status of the digital economy and its importance to traditional industries and the national economy. It also highlights the challenges faced by carbon emissions at this stage. It emphasizes the significant potential of digital economy development in constructing low-carbon cities and promoting low-carbon urban development. The second section reviews the domestic and international literature to understand the research status of experts and scholars on this topic. Based on the theories found in the literature, reasonable assumptions are made regarding the influence and mechanisms of the digital economy on carbon emission levels. The third section selects appropriate models and variables and provides an analysis and description of the chosen models and variables. The fourth section presents empirical research, studying the impact and mechanisms of the digital economy on carbon emissions through benchmark regression and mediation effect models. It further analyses the heterogeneous effects of the digital economy on carbon emissions using heterogeneity tests. The fifth section concludes with corresponding findings and proposes practical and feasible recommendations.

2. Literature Review and Analysis of Theoretical Mechanisms

2.1. Literature Review

The digital economy, as a new form of economy, has attracted widespread attention from domestic and international experts and scholars. Prior to the implementation of the "dual carbon" targets by the country, the academic community primarily focused on studying the dividend effects of the digital economy, which are primarily reflected in its technological innovation efficiency, production efficiency, and high-quality development and employment [15]. With the successful establishment of strategic goals by the government to achieve a carbon peak by 2030 and carbon neutrality by 2060, experts and scholars have begun to explore the impact of the digital economy on carbon emissions levels [16–18].

Reviewing the relevant literature shows that the academic community has divided opinions on the role of the digital economy in carbon emission reduction into three categories. First, the development of the digital economy has a significant inhibitory effect on carbon emissions. The deepening development of the digital economy can promote the digitalization trend in a region where the digital economy will participate in the construction and governance of the region through channels such as artificial intelligence and big data, thereby enhancing regional modernization and networking [18]. Suppose a province can fully utilize big data and digital technology for real-time collection and statistical analysis. In that case, it can effectively improve the region's business, governance, and operational efficiency, thereby increasing and improving productivity at each stage of operation. This can lead to the optimal utilization of resources while reducing carbon emissions and energy consumption, ultimately achieving the goal of reducing regional carbon emissions [19].

At the same time, digital technology penetrates every sector, boosting efficiency across the board and transforming once-outdated industries into cutting-edge ones. Energy efficiency in traditional sectors has steadily improved due to improvements and upgrades to production materials and procedures [20]. Khan and Raza [21] argue that in Asia and Africa, there is a significant positive correlation between capital flows and CO2 emissions; whereas, in Latin America, the Caribbean, and Europe, the relationship between these two variables is negligible. Gavkalova, Lola, Prokopovych, Akimov, Smalskys, and Akimova [22] argue that the growth of renewable energy generation does not always lead to a reduction in carbon emissions, and the impact of the relationship between the two is relatively small for Australia, Canada, Mexico, and Poland.

Additionally, optimizing industrial structure leads to a continuous increase in the proportion of the primary and tertiary sectors, thereby reducing carbon emissions and energy consumption in the manufacturing and industrial sectors, ultimately achieving the goal of reducing regional carbon emissions [23]. Secondly, the development of the digital economy has a significant promoting effect on carbon emissions levels. The main reason is that when digital technologies integrate with the energy sector, such as electricity, it increases the demand for energy consumption [24]. Currently, China's urbanization and industrialization require a continuous increase in energy demand, which may lead to higher carbon emissions levels on the output side [25]. There is a non-linear relationship between the development of the digital economy and carbon emissions levels. Based on panel data from Chinese cities, Li et al. found that the digital economy's development exhibits an inverted "U" shaped relationship with carbon emissions levels. In other words, the digital economy positively promotes carbon emissions levels in the early stages of development. However, it negatively inhibits carbon emissions levels in the later stages of development [10,23,26]. Dzwigol, Kwilinski, Lyulyov, and Pimonenko [27] confirmed that environmental regulations exhibit a U-shaped non-linear impact on the green economic growth of a country and foster gradual improvements in energy efficiency.

In summary, existing research has conducted in-depth analyses of the impact of the digital economy on society and the environment, but there are still many shortcomings. Based on panel data from 30 provinces and cities in China (excluding Tibet, Hong Kong, Macau, and Taiwan) from 2012 to 2021, this study empirically examines the impact and specific mechanisms of the digital economy on carbon emissions. Therefore, this study may have two potential innovations: Firstly, existing research mainly relies on a single indicator to measure the digital economy. In contrast, this study constructs a comprehensive indicator system for the digital economy. It evaluates the development level of the digital economy in each Chinese province using the "Topsis Method", breaking through the limitations of a single indicator and avoiding the bias that may arise from simple measurement methods. Secondly, this study introduces innovative research perspectives by considering industrial structure upgrading and technological innovation as mediating variables, acknowledging the mediating effects of industrial structure upgrading and technological innovation on the relationship between the digital economy and carbon emissions.

2.2. Mechanism Analysis and Research Hypothesis

2.2.1. Digital Economy and Carbon Emission Reduction and Its Regional Heterogeneity Analysis

With the continuous development of the digital economy, the optimized allocation of resources across different industries will become more effective, thereby improving energy efficiency, reducing energy consumption, and lowering carbon emissions. On the one hand, the ongoing development of the digital economy has driven the enhancement of industrial digitization [28]. Due to the adoption of advanced technologies in production, traditional enterprises have greatly enhanced their capabilities in acquiring, organizing, storing, and analyzing information throughout the entire production and operational processes [29]. While traditional industries are merging with the digital economy, industries and developing sectors that adopt digital technology early can optimize their resources more efficiently. Alternatively, as digital industrialization and industrial digitalization advance, the government and market sectors can allocate resources more rationally, reducing energy waste caused by inefficient resource distribution. In turn, this increases energy efficiency and decreases carbon emissions levels [30].

There is a specific sequence of events in integrating the digital economy with traditional industries. On the one hand, early adoption of digital technologies can improve production capacity for traditional industries that urgently need to integrate with the digital economy due to high consumption, emissions, and pollution. The application and promotion of the digital economy can significantly enhance the production efficiency of these industries. As a result, not only will the energy demand of these industries increase, but the carbon emissions levels will also rise rapidly [25]. Meanwhile, as the digital economy converges with the energy industry, including power generation, it enables technological innovation in the predominantly thermal power sector, thus enhancing electricity production in the thermal power industry. However, in the current stage, China still relies mainly on coal-fired power for its energy structure, and the increased coal consumption will inevitably lead to higher carbon emissions [31]. On the other hand, the promotion and increasing popularity of the digital economy have sped up the process of digital industrialization and industrial digitization, consequently continuously boosting the quality of national economic development. The inhibitory effect of the digital economy on carbon emissions levels will gradually become apparent. By utilizing digital technology in the carbon trading market, real-time and precise measurement, reporting, and verification of carbon emissions can curb carbon efficiency losses, enabling emission entities to reduce carbon emissions as required quickly. By applying digitization to the entire production process of traditional industries and improving production steps through big data, it is possible to increase the output of enterprise energy, enhance energy utilization efficiency, and thereby have a negative impact on industrial carbon emissions [32]. Therefore, we can formulate the first hypothesis of this article:

Hypothesis 1 (H1). *The impact of the digital economy on carbon intensity follows an inverted U-shaped curve of promotion followed by suppression.*

Currently, China has introduced a series of policy guidelines to promote the continuous development of the digital economy. The digital economy continuously integrates with traditional industries, and digital technologies are widely applied in society's production processes and economic activities. This has positively impacted accelerating urban industrial structure upgrading and promoting low-carbon green development. It also holds significant importance in achieving the goals of peaking carbon emissions and achieving carbon neutrality [16]. In integrating the traditional physical economy with digital technology, digital industrialization can provide the necessary digital technologies, products, services, infrastructure, and solutions. Within enterprises, the digitalization brought about by the development of the digital economy can not only enhance the management level during the production process but also enable real-time monitoring of energy consumption and carbon emissions across various departments in the production and operation chain.

The industrialization of the digital sector and the digitization of urban industries rely greatly on the application and development of digital technology. Digital technologies may efficiently integrate with high-carbon emitting sectors such as power, industry, construction, and transportation, lowering energy consumption and encouraging energy optimization in conventional businesses [33]. While each city in China is connected to others through its unique landscapes, there are significant differences in the level of digital economic development and the application and innovation of digital technologies across different regions. Specifically, the level of digital economic development in the eastern coastal areas is noticeably higher than in the western inland regions. Consequently, the application of digital technologies to drive the transformation of traditional enterprises and the efficiency of energy conversion and utilization are also significantly higher in the eastern coastal areas compared to the western inland regions. Furthermore, the process of industrial digitization and digital industrialization resulting from the development of the digital economy is faster in regions with higher urbanization levels than those with lower urbanization levels [34]. From this, we can conjecture that regions with relatively high levels of digital economy development may also be relatively more efficient in their energy use, and the effect of the digital economy on carbon emission levels will be more pronounced. It is, therefore, possible to derive the second hypothesis of this piece:

Hypothesis 2 (H2). *There is significant regional heterogeneity in the effectiveness of the digital economy in enabling carbon emissions reductions.*

2.2.2. Analysis of the Mechanism of Digital Economy Empowering Carbon Emission Reduction

Technological innovation can also reduce carbon emissions levels [35]; the relevant studies indicate that the development of the digital economy has a positive promoting effect on technological innovation [36–38]. Therefore, this article speculates that the digital economy will impact technological innovation, reducing regional carbon emissions through the innovation effects of technology. The influence of the digital economy on technological innovation can be mainly reflected in the following aspects: Firstly, the digital economy can lower the cost of research and development by providing technological support to industries. Big data and artificial intelligence are two examples of digital technologies that can be used in the research and development process to help companies more accurately analyze the needs of specific consumers and plan the direction of innovation and development based on technological advancements, making innovation more focused. Additionally, digital simulation technology can anticipate test results and reduce unnecessary resource consumption through "virtual trial and error," thereby lowering research and development costs [39]. Secondly, developing the digital economy facilitates exchanging and sharing of technological innovation resources among regions and industries. On the one hand, the digital economy accelerates the integration and dissemination of information through digital online platforms, effectively addressing the time and space constraints that hinder the allocation of innovative resources, thereby promoting the exchange and distribution of innovative resources among enterprises. On the other hand, the digital economy plays a significant positive role in reducing the cost of information acquisition and learning for higher education institutions, enterprises, and other innovation entities, thereby driving technological innovation. Thirdly, with the continuous development of the digital economy, the financing pressure for technological innovation can be alleviated. Technological innovation often faces significant financing pressure due to its long period, high upfront costs, and risks [36]. Research suggests that a lack of financing is one of the main barriers to technological innovation, and many innovative activities are terminated due to bottlenecks encountered during the fundraising process. Digital inclusive finance is one of the typical products of the digital economy. It not only overcomes the limitations of traditional financial forms but also significantly reduces the barriers to financial services. Moreover, it enhances the possibility of financing technological innovation, effectively alleviating the financial pressure on innovative activities and providing financial security for technological innovation in industries [40]. The inhibitory effect of technological innovation activities on carbon emissions is mainly manifested in the following aspects: Firstly, the continuous development of technological innovation activities can lead to a qualitative leap in production technology, thereby improving energy efficiency in the production process and reducing unnecessary energy consumption. As a result, the emission of carbon dioxide can be reduced. Secondly, the higher the level of technological innovation applied in production activities, the greater the ability and possibility to explore renewable clean energy sources. Using clean energy can reduce fossil energy consumption in industries, reducing carbon emissions at the production end [38]. Finally, the higher the level of technological innovation, the more strategies it will have for the end-of-site management of carbon dioxide emissions, thus achieving effective treatment of the end of carbon emissions and reducing carbon emissions from the release side. The third hypothesis of this paper can therefore be derived:

Hypothesis 3 (H3). *The digital economy indirectly empowers carbon reduction through increased STI capabilities.*

According to related studies, upgrading industrial structures also exerts a restraining effect on regional carbon emissions [41–43]. The development of the digital economy also has a positive promoting effect on upgrading industrial structure [44]. Therefore, the digital economy will likely impact the upgrading of industrial structure, leading to a reduction in regional carbon emissions through the upgrading effects of industrial structure. The digital economy will primarily influence the upgrading of industrial structure in the following aspects: Firstly, the digital economy can provide particular technological support for the transition from traditional industries to digital industries [45]. With the integrated development of digital and physical economies, cutting-edge digital technologies such as big data and artificial intelligence are applied in every aspect of traditional industry production, operation, and sales. This integration has reduced time requirements for each process, decreased costs for each operation, and improved coordination between different stages. Consequently, it has enhanced the efficiency of resource allocation and had a positive impact on product quality [46]. Furthermore, the product's added value will also transition from low to high, ultimately completing the task of transitioning from traditional to digital industries. Secondly, the digital economy can promote integrated development among multiple industries. Media channels based on the digital economy can accelerate the speed of information dissemination, reduce the search and transaction costs generated during the process of information dissemination, and to some extent, address the problem of information asymmetry between the information suppliers and demanders [47]. This promotes interactive communication across industries, connecting the value chains of different sectors and thereby facilitating the integrated development of diverse industries [48], promoting the upgrading of industrial structures. Thirdly, the continuous development of the digital economy has expanded the scope of online trading platforms. In contrast, the form of online transactions overcomes the time and space limitations of traditional transaction forms, thereby broadening the scope of resource allocation [49]. Industrial structural upgrading is spurred due to reallocating production components to sectors with significantly greater productivity. At the same time, upgrading the industrial structure has a pronounced negative effect on the level of carbon emissions. Its inhibiting effect on carbon emissions is mainly manifested in the following two aspects: First, there are many energy-intensive industries, such as manufacturing and industrial sectors, in the secondary industry, so their carbon emissions account for the most significant proportion of the total carbon emissions of the three industries. The upgrading of the industrial structure as a whole shows a shift from the industrial sector of the secondary industry to the service sector of the tertiary industry, which means that the industry starts to upgrade from the inefficient and energy-intensive heavy industry to the low-energy, high-efficiency and environmentally friendly industrial structure [42]. In this process, a dampening effect on the level of carbon emissions can be achieved. Secondly, the upgrading of the industrial structure is also reflected in the logical flow and allocation of resources, such as workforce and capital, among the three industries, which can promote technological progress and improve the efficiency of energy use [50,51]. In this process, the improvement of industrial structure upgrading requires a higher level of development in the digital economy, which in turn will further enhance the digital economy's capacity to enable carbon emissions reduction. The fourth hypothesis of this paper can therefore be formulated:

Hypothesis 4 (H4). *The digital economy indirectly enables carbon emissions reduction through industrial structural upgrades.*

3. Research Design

3.1. Model Setting

3.1.1. Model Testing

The main purpose of this study is to explore the impact of the digital economy on entrepreneurial activity using an ordinary panel regression model. However, the ordinary panel regression model can be classified into fixed effects, random effects, and pooled effects. Therefore, before constructing the panel regression model, it is necessary to test the effects of the model. The Hausman test is primarily used for this purpose, and the results of the Hausman test are presented in Table 1 as follows.

Table 1. Table of Hausman test results.

Testing Models	Test Methods	Outcome	Conclusion
Mixed and fixed effects	Hausman test	25.71 ***	Fixed effect
Mixed and random effects	Hausman test	26.93 ***	Random effects
Fixed and random effects	Hausman test	17.60 ***	Fixed effect

Note:*** indicate statistical significance at the 1% level, based on significance testing.

The analysis of the Hausman test results in Table 1 reveals that the chi-square values are 25.71, 26.93, and 17.63, respectively. All of these values pass the significance test at the 1% level, rejecting the null hypothesis. Therefore, based on the combined results of the three tests, it is inferred that a fixed effects model should be chosen for the analysis and exploration when constructing the panel regression model in this study.

3.1.2. Model Construction

Based on the above theoretical analysis, The discovered data for this article are panel data, so the selection of the model in this article should fully consider the temporal and spatial variations of the data. Therefore, this paper uses a panel regression model with double fixed effects to study the effect of the development of the digital economy on regional carbon emissions and constructs the following regression equation:

$$Y_{it} = \alpha_0 + \alpha_1 De_{it} + \alpha_2 De_{it}^2 + \beta Control_{it} + \mu_{it} + \sigma_{it} + \varepsilon_{it} \quad (1)$$

In Equation (1), the subscripts i and t denote region and year, respectively, Y_{it} denotes the carbon emissions of the area i in a year t. Y_{it} represents the explanatory variable, and De_{it} denotes the core explanatory variable, refers to the development of the digital economy in the region i in the year t; α_1 is the coefficient on which this paper focuses. If α_1 it is significantly negative, then it proves that an increase in the level of the digital economy can significantly curb the level of regional carbon emissions. Join the Square Project to investigate the non-linear impact of the digital economy on regional carbon emissions. $Control_{it}$ is all control variables at the district level for the region in which it is located? μ_{it} indicates area-fixed effects, σ_{it} denotes a time-fixed effect, σ_{it} is the random error term.

In order to deeply analyze the mechanism of the role of the digital economy on the level of carbon emissions and to test the mediating effect of the improvement of science and technology innovation capacity and the upgrading of industrial structure, verifying the validity of Hypotheses 3 and 4, this paper constructs the mediating effect model, whose regression equation is:

$$Uis_{it} = \alpha_0 + \alpha_1 De_{it} + \beta Control_{it} + \mu_{it} + \sigma_{it} + \varepsilon_{it} \tag{2}$$

$$Y_{it} = \alpha_0 + \alpha_1 De_{it} + \eta Uis_{it} + \beta Control_{it} + \mu_{it} + \sigma_{it} + \varepsilon_{it} \tag{3}$$

$$Sia_{it} = \alpha_0 + \alpha_1 De_{it} + \beta Control_{it} + \mu_{it} + \sigma_{it} + \varepsilon_{it} \tag{4}$$

$$Y_{it} = \alpha_0 + \alpha_1 De_{it} + \eta Sia_{it} + \beta Control_{it} + \mu_{it} + \sigma_{it} + \varepsilon_{it} \tag{5}$$

The above equation Uis_{it} represents the upgrading of the industrial structure of the region i in a year t. Sia_{it} indicates the level of STI capacity of the region i in the year t. Other symbols have the same meaning as in Equation (1).

3.2. Variable Selection and Data Sources

3.2.1. Dependent Variable

This article is based on the energy consumption data from 30 provinces and cities in China (excluding Tibet, Hong Kong, Macau, and Taiwan) during the period from 2012 to 2021, as well as the energy reference coefficients from IPCC (2006). It determines the selection of nine primary energy sources to estimate carbon dioxide emissions, as shown in Equation (2).

$$CO_2 = \frac{44}{12} \times \sum_{i=1}^{9} K_i E_i \tag{6}$$

The above equation: i represents the energy category, K_i represents the carbon emission factor for i energy source (as shown in Table 2), E_i is the amount of energy used for i.

Table 2. Carbon emission factors by type of energy.

	Raw Coal	Coke	Crude	Gasoline	Kerosene	Diesel Fuel	Fuel Oil	Natural Gas	Electricity
Converted to standard coal (t standard coal/t)	0.714	0.971	1.429	1.471	1.471	1.457	1.429	1.330	0.345
Carbon emission factor K_i (million tonnes per million tonnes of standard coal)	0.756	0.855	0.586	0.534	0.571	0.592	0.619	0.448	0.272

3.2.2. Independent Variables

Through a review of the relevant literature, this paper selects indicators in five dimensions: the level of digital infrastructure, the level of digital industrialization, the level of industrial digitization, the level of digital technological innovation, and the level of digital financial development, and uses the superiority-disadvantage solution distance method to measure the regional digital economy development index. The specific indicators for measuring the digital economy development index are shown in Table 3:

Table 3. Digital economy measurement indicators.

Level 1 Indicators	Secondary Indicators	Tertiary Indicators	Unit
Digital economy	The level of digital infrastructure	Number of mobile phone base stations	10,000
		Cable line length	kilometers
		Number of domain names	10,000
		Postal outlets	place
		Number of Internet broadband access ports	10,000
		Mobile phone penetration	ministry/hundred
	The level of digital industrialization	Number of ICT industry companies	piece
		The average number of employees in the ICT industry	person
		ICT industry revenue	billion
		Total postal business	billion
		The total volume of telecommunications services	billion
		Software business revenue	billion
	The level of industrial digitalization	The proportion of enterprises with e-commerce transaction activities	%
		Enterprise e-commerce sales	billion
		Number of websites per 100 businesses	person
		Number of computers used per 100 people	platform
		Number of electronic reading room terminals	person
	The level of digital technology innovation	Technology market turnover	billion
		The full-time equivalent of R&D personnel	year of the man
		R&D funding	million
		Number of valid invention patents	item
		Unit employees	person
		Information transmission, software, and information technology services	person
	The level of development of digital finance	The breadth of digital financial inclusion	-
		Deep use of digital financial inclusion	-
		Digital financial inclusion is digital	-

3.2.3. Intermediate Variables

Based on the previous analysis of the mechanism, it can be observed that the digital economy may impact carbon emissions by enhancing technological innovation capabilities and upgrading industrial structure [50,51]. Therefore, this study selects technological innovation capabilities and industrial structure upgrading as the mediating variables for this research.

3.2.4. Control Variables

By consulting the relevant research literature by domestic and international experts and scholars on the impact of the digital economy on carbon emissions, this paper takes four dimensions as control variables in the model [44]: fiscal expenditure, population density, level of economic development, and foreign direct investment. Fiscal expenditure is measured by the ratio of general public budget expenditure at the local level to GDP. Population density is measured by the ratio of year-end population to administrative area. The level of economic development can be measured by the logarithm of per capita GDP. The level of foreign direct investment is measured by the proportion of foreign investment to GDP.

3.2.5. Data Sources

This article uses 30 provinces (municipalities directly under the central government and autonomous regions) in China as research samples. The data for the years 2012–2021 were collected from various sources, including the "China Statistical Yearbook," "China Energy Statistical Yearbook," "China Science and Technology Statistical Yearbook," "China

Environmental Yearbook," as well as provincial and municipal statistical yearbooks and the Wind database. Data preprocessing was conducted, and provinces with significant data gaps were excluded. A total of 30 provinces (municipalities directly under the central government and autonomous regions) were included, resulting in 300 valid data points from 2012 to 2021. The data do not include Tibet, Hong Kong, Macau, and Taiwan regions.

3.3. Descriptive Statistics of Variables

The data obtained were processed, and the processed data were subjected to a descriptive statistical analysis summarized in Table 4:

Table 4. Descriptive statistical analysis.

Variables	Obs	Mean	Std. dev	Min	Max
Carbon emissions	300	4.811	4.111	0.448	24.174
Digital economy	300	0.196	0.094	0.046	0.592
Financial expenditure	300	0.250	0.103	0.107	0.643
population density	300	7.906	0.396	6.939	8.620
Foreign direct investment	300	0.699	3.261	0.048	45.106
Level of economic development	300	10.912	0.428	9.889	12.123

The data in Table 4 shows that the dependent variable, carbon emissions, has a maximum value of 24.174, a minimum value of 0.448, a mean of 4.811, and a standard deviation of 4.111. The difference between the maximum and minimum values exceeds 50-fold, indicating significant carbon emission level variations among different provinces. The key independent variable, digital economy, has a maximum value of 0.592, a minimum value of 0.046, a mean of 0.196, and a variance of 0.094. The difference between the maximum and minimum values is more than 10-fold, suggesting notable disparities in digital economy development across regions. Analyzing the descriptive statistics of the control variables reveals that fiscal expenditure, population density, foreign direct investment, and economic development level all have normal ranges without any outliers, enabling further analysis and research.

To explore the impact of the digital economy on carbon emissions, this article calculates the average digital economy and carbon emission values for each province from 2012 to 2021. It produces a time–series graph of the digital economy and carbon emissions, as shown in Figure 1. The examination of Figure 1 reveals that the digital economy has been on a gradual ascent while carbon emissions have fluctuated. By analyzing the changing trends of the digital economy and carbon emissions, it is possible to conclude that the digital economy and carbon emissions both increased during the years 2012–2014 and 2016–2018, whereas the impact of the digital economy on carbon emissions decreased during the years 2014–2015 and 2018–2020. Therefore, a non-linear link may exist between the digital economy and carbon emissions, revealing an inverted "U"-shaped relationship in which the digital economy initially boosts carbon emissions and eventually inhibits them. This article builds a panel regression model within the fixed effects framework to study the causal pathway of the digital economy's influence on carbon emissions and further analyze its effect on carbon emissions.

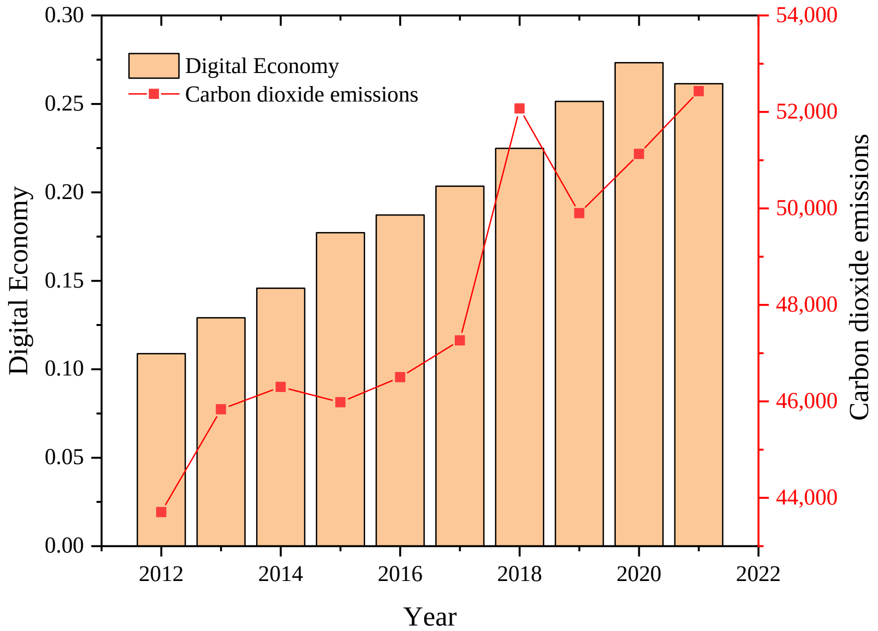

Figure 1. Time–series diagram of the digital economy and carbon emissions.

4. Empirical Analysis

4.1. Baseline Regression Analysis

Based on panel data from 30 provinces and cities in China (excluding Tibet, Hong Kong, Macau, and Taiwan) from 2012 to 2021, this study employs a fixed effects model with individual and time dimensions to investigate the impact of the digital economy on carbon emissions levels, using Equation (1). The baseline regression results are shown in Table 5. Columns (1) and (2) represent the regression results without and with control variables, respectively, primarily testing the impact of the first-order term of the digital economy index on carbon emissions. The table shows that the digital economy's coefficient in the baseline regression is 3.231, which is statistically significant at the 1% level, indicating that the digital economy significantly promotes carbon emissions. Columns (3) and (4) include the quadratic term of the digital economy development index based on Columns (1) and (2). According to the table, the coefficient of the first-order term of the digital economy development index is 3.128, which is positive and statistically significant at the 1% level. The coefficient of the quadratic term of the digital economy development index is −1.243, which is negative and statistically significant at the 5% level. This indicates that the digital economy and carbon emissions relationship is not a simple linear one but rather an inverted "U" shaped curve, with a promotion effect followed by a suppression effect, confirming Hypothesis 1. Therefore, when studying the impact of the digital economy on carbon emissions, it is necessary to simultaneously consider both the first-order and second-order terms of the digital economy. It is not sufficient to analyze only the first-order term, as it may lead to a misjudgment of the mechanisms through which the digital economy affects carbon emissions. Furthermore, comparing the data in Columns (3) and (4), it can be observed that after controlling for variables, the baseline regression coefficient of the first-order term of the digital economy development index decreases from 3.128 to 2.847. In contrast, the quadratic term baseline regression coefficient decreases from −1.243 to −1.957. Comparing the inflection points of the two models' inverted "U" shaped curves, it is evident that the influence on the inflection point is minimal, whether control variables are added or not. Analysis of the regression results in Column (4) reveals that the foreign direct investment baseline regression coefficient and economic development level are negative and statistically significant at the 1% level. Comparatively, the fiscal spending and population density baseline regression coefficients are positive and statistically significant at the 1% level. This suggests that foreign direct investment and economic development levels significantly reduce carbon emissions, whereas government spending and population density significantly increase them.

Table 5. Table of results of baseline regression tests.

Variables	**(1)**	**(2)**	**(3)**	**(4)**
Digital economy	3.231 *** (7.92)	2.177 *** (4.76)	3.128 *** (3.30)	2.847 *** (4.83)
Digital economy square			−1.243 ** (−2.12)	−1.957 ** (−2.59)
Financial expenditure		2.255 *** (4.34)		2.205 *** (4.58)
Population density		0.242 *** (3.12)		0.232 *** (2.81)
Foreign direct investment		−0.240 *** (−3.13)		−0.220 *** (−2.93)
Level of economic development		−7.666 *** (−5.68)		−8.474 *** (−6.18)
Constant	1.190 *** (14.87)	0.640 *** (3.46)	1.181 *** (11.12)	0.750 *** (3.90)
Observations	300	300	300	300
R-squared	0.572	0.787	0.573	0.795
Number of ids	30	30	30	30

Note: (1) T-value statistics in parentheses; (2) *** and ** indicate significance at 1% and 5% significance levels, respectively.

4.2. Mechanism Test

An empirical analysis was conducted using the mediation effect model to investigate the mechanisms through which the digital economy affects carbon emissions. The statistical results are presented in Table 6. Analyzing the data in Columns (1) and (3) of the table, it can be observed that the regression coefficient of the digital economy on industrial structural upgrading is 0.952, and it passes the significance test at the 1% significance level. The regression coefficient of the digital economy on technological innovation is 1.361, and it passes the significance test at the 10% significance level. These findings indicate that the development of the digital economy positively promotes industrial structural upgrading and technological innovation. Analyzing Columns (3) and (4) of the table, it can be observed that after incorporating the mediating variable of industrial structural upgrading, the regression coefficient of the digital economy on carbon emissions is −1.358, passing the significance test at the 5% significance level. After including the mediating variable of technological innovation, the regression coefficient of the digital economy on carbon emissions is −1.998, passing the significance test at the 1% significance level. These results indicate that the development of the digital economy inhibits carbon emissions by accelerating industrial structural upgrading and promoting technological innovation. This validates Hypotheses 3 and 4. Among the control variables, only foreign direct investment (FDI) significantly positively affects the mediating variables of industrial structure upgrading and technological innovation. This is mainly because FDI intensifies competition among domestic market industries, leading to technological innovation for improved productivity and industrial structural upgrading to enhance competitiveness in low-carbon and environmentally friendly industries. Other control variables do not significantly affect the promotion of industrial structure upgrading and technological innovation. Consistent with the baseline regression results, fiscal expenditure, and population density have positive regression coefficients, passing the significance test at the 1% significance level. This indicates that foreign direct investment and economic development have a significant inhibitory effect on carbon emissions, while fiscal expenditure and population density significantly promote carbon emissions.

Table 6. Table of mechanism test results.

Variables	(1) Industrial Structure Upgrading	(2) Carbon Emissions	(3) Scientific and Technological Innovation	(4) Carbon Emissions
Digital economy	0.952 *** (5.77)	−1.358 ** (−2.41)	1.361 * (1.77)	−1.998 *** (−4.65)
Industrial structure upgrading		−0.860 ** (−2.47)		
Scientific and technological innovation				−0.132 * (−2.01)
Financial expenditure	0.048 (0.18)	2.296 *** (3.65)	0.892 (1.03)	2.373 *** (4.55)
Population density	0.000 (0.01)	0.243 *** (2.86)	0.058 (0.53)	0.250 *** (3.25)
Foreign direct investment	0.089 *** (4.31)	−0.163 * (−1.95)	0.887 *** (7.12)	−0.123 (−1.32)
Level of economic development	−0.256 (−0.53)	−7.886 *** (−5.17)	1.223 (0.40)	−7.505 *** (−6.48)
Constant	2.203 *** (27.61)	2.536 *** (3.07)	−6.125 *** (−20.40)	−0.169 (−0.37)
Observations	300	300	300	300
R-squared	0.732	0.800	0.253	0.797
Number of ids	30	30	30	30

Note: (1) T-value statistics in parentheses; (2) ***, ** and * indicate significance at 1%, 5%, and 10% significance levels, respectively.

4.3. Heterogeneity Test

Analysis of benchmark regression results reveals that the development of the digital economy has an overall inhibitory effect on carbon emissions. However, does this carbon reduction effect have universality across different regions? According to the relevant literature, the level of digital economic development and carbon emissions differ due to variations in urban resource endowments and stages of economic development. Therefore, differences in resource endowments and economic development levels among cities may affect the carbon emissions effect of the digital economy. The geographical location of a city is an essential factor influencing its resource endowment. Based on this, this study divides the samples for discussion according to cities' geographical location and economic development level, as shown in Table 7. According to the analysis of the table's data, the regression coefficients of the digital economy on carbon emissions in the east, central, and west regions are all negative and statistically significant at the 1% level. In particular, the coefficient for the east region is −2.933, the coefficient for the central region is −3.541, and the coefficient for the west region is −3.391, showing that the digital economy suppresses carbon emissions significantly in the east, central, and west regions. However, the influence is stronger in the central and western regions than in the eastern region. One possible reason for this phenomenon is that after the development of the digital economy in the east reached a certain level between 2012 and 2021, it began to generate spillover effects on adjacent regions, driving the development of the digital economy in those regions and thereby amplifying the inhibitory effect of the digital economy on carbon emissions in the central and west regions. The regression coefficients of the digital economy on carbon emissions are also negative and significant at different levels in the north and south regions. Specifically, the coefficient in the north is −2.083, while in the south, it is −4.054, indicating that the digital economy significantly inhibits carbon emissions in both the north and south regions, with a more substantial effect in the south. This difference is because the level of digital economic development in the south from 2012 to 2021 was higher than in the north. The south region demonstrated a higher level of digital technology application and technological innovation, and it started its industrial and manufacturing sectors earlier, enabling faster upgrading of its industrial structure. As a result, the inhibitory effect of the digital economy on carbon emissions is more pronounced in the south. Moreover, the regression coefficients of the digital economy on carbon emissions are negative and significant at the 1% level for both coastal and inland regions. Specifically, the coefficient for the coastal region is −2.453, while for the inland region, it is −3.793, indicating that the digital economy has a significant inhibitory effect on carbon emissions in both coastal and inland regions, with a more substantial effect in the inland region. The reason for this phenomenon is that after the development of the digital economy in the coastal region reached a certain level between 2012 and 2021, it began to generate spillover effects on the inland region, driving the development of the digital economy in the inland region and thereby amplifying the inhibitory effect of the digital economy on carbon emissions in that area, thus validating Hypothesis 2.

Table 7. Table of heterogeneity test results.

Variables	East	Central	Western	North	South	Coastal	Inland
Digital economy	−2.933 ***	−3.541 ***	−3.391 ***	−2.083 **	−4.054 ***	−2.453 ***	−3.793 ***
	(−4.89)	(−4.30)	(−4.36)	(−2.82)	(−9.08)	(−6.14)	(−6.44)
Constant	0.908 ***	1.190 ***	1.456 ***	1.368 ***	0.978 ***	0.858 ***	1.372 ***
	(5.87)	(9.27)	(11.42)	(10.24)	(10.37)	(9.09)	(13.48)
Control variables	Control	Control	Control	Control	Control	Control	Control
Observations	110	80	110	150	150	110	190
R-squared	0.603	0.620	0.528	0.271	0.828	0.613	0.592
Number of ids	11	8	11	15	15	11	19

Note: (1) T-value statistics in parentheses; (2) *** and ** indicate significance at 1% and 5% significance levels, respectively.

4.4. Robustness Tests

The robustness test was conducted to demonstrate the evaluation method's reliability and the indicators' interpretability. It aims to examine whether the evaluation method and indicators still provide consistent and stable explanations of the evaluation results when specific coefficients are changed. In this study, a stepwise regression analysis was performed to investigate the impact of the digital economy and various control variables on carbon emissions levels. Table 8 presents the regression results used to demonstrate the robustness of the selected variables and the constructed model. First, a regression analysis was conducted between the explanatory variable, the digital economy, and the core explanatory variable, resulting in the construction of Model 1. The data analysis revealed that the digital economy's regression coefficient on carbon emissions was −3.231, which passed the significance test at the 1% level. This indicates that the digital economy has a significant inhibitory effect on carbon emissions, consistent with the baseline regression results. Next, control variables were successively added to construct Models 2 to 5. The data analysis showed that even after including various control variables, the regression coefficient of the digital economy on carbon emissions remained negative and passed the significance test at the 1% level. Thus, it can be concluded that the digital economy significantly inhibits carbon emissions regardless of including multiple control variables. Moreover, when regressing the explanatory variable, the digital economy, with the dependent variable, carbon emissions, the R-squared value was 0.572. As each control variable was added sequentially, the R-squared value gradually increased and reached 0.787 in the final model. This indicates a better fit of the model when control variables are included, compared to the R-squared value of 0.572 without including control variables. Therefore, it can be inferred that the model better captures real-world situations when incorporating control variables.

Table 8. Robustness tests.

Variables	(1)	(2)	(3)	(4)	(5)
Digital economy	−3.231 *** (−7.92)	−3.638 *** (−11.18)	−3.845 *** (−12.18)	−3.828 *** (−11.97)	−2.177 *** (−4.76)
Financial expenditure		3.654 *** (7.59)	3.792 *** (8.99)	3.784 *** (8.96)	2.255 *** (4.34)
Population density			0.276 *** (3.01)	0.277 *** (3.03)	0.242 *** (3.12)
Foreign direct investment				−0.215 ** (−2.60)	−0.240 *** (−3.13)
Level of economic development					−7.666 *** (−5.68)
Constant	1.190 *** (14.87)	0.353 ** (2.75)	0.484 ** (2.53)	0.583 ** (2.53)	0.640 *** (3.46)
Observations	300	300	300	300	300
R-squared	0.572	0.713	0.738	0.739	0.787
Number of ids	30	30	30	30	30

Note: (1) T-value statistics in parentheses; (2) *** and ** indicate significance at 1% and 5% significance levels, respectively.

5. Conclusions and Recommendations

5.1. Conclusions

Based on panel data from 30 Chinese provinces and cities (excluding Tibet, Hong Kong, Macao, and Taiwan) from 2012 to 2021, this paper uses a panel regression model with double fixed effects and a mediating effects model to make an empirical analysis of the effects and mechanisms of the impact between the digital economy and carbon emissions:

(1) The impact of the digital economy on carbon emission intensity shows an inverted U-shaped curve of promotion followed by suppression. As there are traditional industries with high energy consumption, high emissions, and high pollution, they need to be integrated with the digital economy. The application and promotion of the digital economy increase the efficiency of these industries while also increasing the energy demand of these industries, which in turn leads to a rapid increase in carbon emissions. As the digital economy continues to develop, digitalization is being applied to the entire production process of traditional industries and improving their production processes through big data, thereby increasing the efficiency of energy use, which negatively affects industrial carbon emissions. The impact of the digital economy on carbon emissions is, therefore, an inverted U-shaped curve, with the digital economy first contributing to and then inhibiting carbon emissions.

(2) Mechanism analysis shows that the digital economy can influence carbon emissions through industrial restructuring and technological innovation. The optimization of the industrial structure as a whole manifest itself in a shift from the secondary industry's industrial sector to the tertiary industry's service sector. This also means that industries upgrade from inefficient and energy-intensive heavy industries to low-energy, high-efficiency, and environmentally friendly industrial structures, reducing carbon emissions. The digital economy can accelerate the integration and dissemination of information through digital online platforms, effectively solving the time and space problems that constrain the allocation of innovation resources. Digital technologies such as artificial intelligence and big data play an essential role in the digitization of industries, thereby reducing carbon emissions at the output and processing ends.

(3) Heterogeneity analysis reveals that regions with a relatively high level of digital economy development will have a relatively higher energy use efficiency, and the effect of the digital economy on carbon emissions will be more obvious. The effect of the digital economy on carbon emissions is initially more evident in developed regions such as the eastern coast. Once the effect reaches a certain level, it will significantly impact carbon emissions in neighboring regions.

5.2. Discussion

From the existing literature, it can be found that socio-economic development is the key factor that causes carbon emissions to increase year by year, and many studies have confirmed this. However, from the results of this paper's analysis, there is a significant inhibitory effect of the digital economy on carbon emissions, but with the upgrading of industrial structure and the level of technological innovation, there will be a mediating effect of the digital economy on carbon emissions with the above two variables as mediating variables, i.e., the upgrading of industrial structure and the level of technological innovation will significantly contribute to the degree of the digital economy's inhibitory effect on carbon emissions. Even in regions with a low level of digital economy development, the impact of the digital economy on carbon emissions is still influenced by a complex mechanism of multiple factors such as the regional resource and environmental base, and there are significant differences in the direction and intensity of the impact of the digital economy on carbon emissions. Therefore, discussing the means to curb the increase in carbon emissions is not the same as curbing economic and urban development in a comprehensive manner. It is necessary to accelerate the development of a regional digital economy based on the current characteristics of regional development based on the comparative explanation of the correlation between socio-economic factors and carbon emissions, and yet seems that the focus and orientation of remediation.

By compiling the aforementioned data, we may conclude that China's digital economy growth is correlated with a corresponding increase in carbon emissions, following the pattern of an inverted "U" curve typical of environmental Kuznets analysis. By analyzing the non-linear relationship between the impact of the digital economy on carbon emissions, it can be found that the development of the digital economy in most regions of China still needs to be. In other words, China's economy will not be able to grow in the future. In other words, for some time in the future, economic development in China will continue to have both coercive and retarding effects on the ecological environment. Therefore, the key to eliminating the contradiction between economic development and increasing carbon emissions is to bring the level of digital economy development in most regions past the curve's inflection point within a short period. In this process, the negative impact caused by the development of the digital economy, to the maximum extent possible, is to completely transform the development of the digital economy, relying on the upgrading of industrial structure driven by scientific and technological innovation, and accelerate the construction of a resource-saving and environment-friendly development model, so that the phenomenon of mutual promotion and the achievement of harmonious development between the development of the digital economy and the environment can be formed.

5.3. Recommendations

(1) Handling the relationship between the digital economy and carbon emissions is essential. In regions where the digital economy is relatively new, the digital economy may have a positive promoting effect on carbon emissions, and this should not negate the inhibitory effect of the digital economy on carbon emissions. The development speed of the digital economy should be accelerated, and traditional enterprises should be encouraged to transition faster to the digital industry, swiftly surpassing the turning point of the digital economy's impact.

(2) The government should formulate corresponding preferential policies to promote industrial structure optimization and consider that the digital economy can impact regional carbon emissions by optimizing industrial structure. At the same time, traditional enterprises may exhibit passive and inefficient behavior during the integration with the digital economy; it is necessary to encourage traditional enterprises to actively and effectively utilize digital technologies to transform into the digital realm by providing welfare incentives. This will have an effect on carbon emissions in the region.

(3) The government should increase investment in technological innovation and optimize the environment for foreign investment. Considering that the digital economy can impact regional carbon emissions through technological innovation, there should be a bias toward funding and policies that support technological innovation. This will accelerate the empowerment of the digital economy in the energy sector, leading to improved production efficiency. On the other hand, foreign direct investment intensifies competition among domestic market industries, prompting them to enhance production efficiency through technological innovation and upgrade their industrial structures to enhance their competitiveness in the low-carbon and environmental protection industries. Therefore, optimizing the environment for foreign investment is essential, fostering fair competition and accelerated innovation in the economic market.

(4) Implement region-specific strategies to promote carbon emission reduction in the digital economy. In regions with a lower level of digital economy development, it is essential to establish a digital industry that reflects their resource endowments and economic development advantages. Additionally, there should be more substantial control over foreign investment, directing it towards low-pollution and low-emission industries. In regions with a higher level of digital economy development, continuous industrial structure optimization should be pursued, along with improving energy utilization efficiency to stimulate the carbon emission reduction effects of the digital economy.

5.4. Future Perspectives and Limitations

As an emerging economic form, the digital economy will permeate all industries in the future. This paper takes 30 provinces (municipalities and autonomous regions) in China as the research object to prove the role of the digital economy in empowering carbon emission reduction pathways, providing a new perspective on the development pathways of carbon emission reduction in China. However, there are still some shortcomings in this study: firstly, due to the limitation of the number of specimens, the summary analysis of the driving pattern of the impact of the digital economy on carbon emissions in each province of China is only based on the data of 30 provinces across China, and the relationship between the two is not explored from the perspective of prefecture-level cities. The role of the digital economy in carbon emission reduction needs to be further examined. Secondly, the empirical research conducted in this paper may be biased due to the lack of academic agreement on the measurement scale of both the digital economy and carbon emissions, as well as the limitations of the available data. Finally, a comprehensive verification of the impact of the digital economy on carbon emissions is a systematic project that requires long-term stable data accumulation and continuous methodological innovation.

The role of the digital economy in enabling carbon emissions reduction is complex, so this paper divides it into two aspects: direct and indirect. In the indirect analysis, only two mediating variables are introduced in this paper, namely the upgrading of industrial structure and the level of science and technology innovation. There may be other mediating variables in the role of the digital economy in enabling carbon emissions reduction, so more in-depth analysis can be conducted on this issue in the future. Meanwhile, this study is mainly conducted from a national perspective, and the next step will be to investigate whether the pathways of the digital economy-enabled carbon emission reduction are consistent with the national perspective specifically from a regional perspective.

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